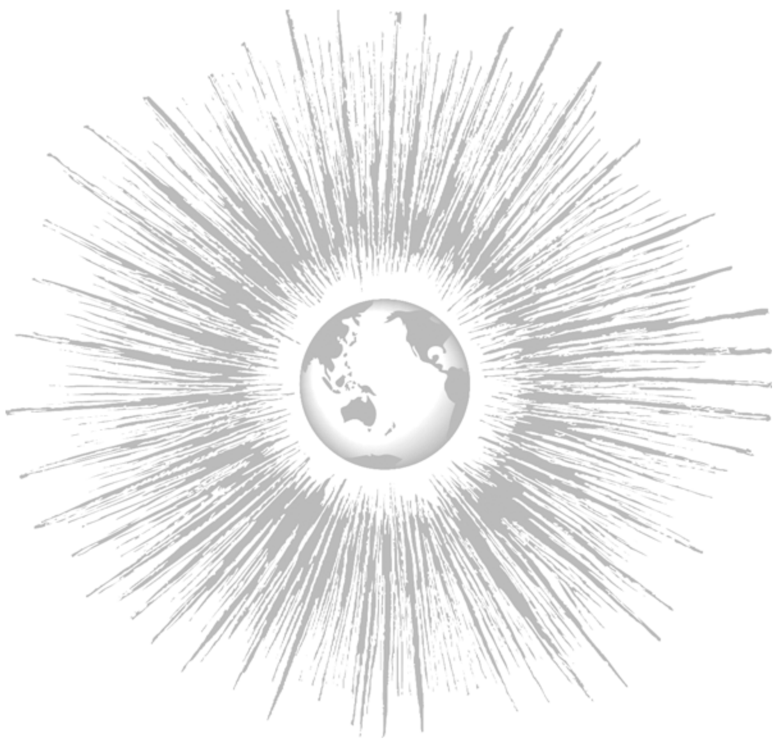

ABSTRACT

This paper reports on research in population ecology and suggests ways it might be useful in explaining spatial dynamics of states, groups, and world-systems. In particular it focuses on how and why populations at opposite of ends of Afroeurasia come to rise and fall simultaneously over long periods of time. We call for exploration of research in population ecology for understanding world-system evolution and suggest directions for possible future research.

Spatial Synchrony Among and Within World-Systems: Insights From Theoretical Ecology*

Peter Turchin
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INTRODUCTION

Political processes within world-systems are often characterized by cycles or waves. Chiefdoms cycle (Anderson 1994, 1996), empires rise and fall, and the modern state system undergoes "power cycle" or "hegemonic sequence." Furthermore, all world-systems "pulsate"—expand rapidly, then more slowly, or even contract (Chase-Dunn and Hall 1997, 2000). Because spatial waves of expansion/contraction occur across all types of world-systems, such pulsations cannot be rooted in a specific mode of production or mode of accumulation. Rather, these cycles are themselves evidence that polities and world systems are dynamical systems with various feedback loops.

Afroeurasia (in conventional terms Asia, Europe, northern Africa) has been linked, at least at the information and luxury goods exchange levels (Chase-Dunn and Hall 1997), for two and a half millennia or more. Thus, events and processes in Europe cannot be explained solely by examining European processes, a conclusion strongly supported by Pomeranz (2000). On the other hand, the degree of Afroeurasia-wide linkage fluctuated, so that world-systems at opposite ends of Afroeurasia were nearly isolated for long periods of time. One interesting puzzle is why there is a substantial linking of rise/fall processes at the western and eastern ends of Afroeurasia during the last two millennia (Teggart

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1939; Frank and Gills 1993; Frank 1992, 1993; Chase-Dunn and Hall 1997, 2000; Denemark et al. 2000). For example, increases and decreases in the territorial sizes of empires and the population size of cities correlate between East Asia and West Asia/Mediterranean (e.g., Chase-Dunn, Manning, and Hall 2000). Yet, there appears to be little linkage to cyclical processes in South Asia (Chase-Dunn, Manning, and Hall 2000). Interestingly, archaeologists have noted seeming parallels in rise and fall of ancient cultures in what is now southeastern and southwestern United States (Neitzel 1999).

There has been much speculation about what processes drive various cycles within world-systems, what mechanisms may lead to (partial) synchrony between some world-systems separated by great distances, and why there is little or no synchrony between others (Denemark et al. 2000; Frank 1993; Grimes 2000). The current state of the field bears a striking similarity to the debates that occurred among population ecologists a few decades ago. Ecologists also found that many population systems go through regular oscillations, and that these population cycles are synchronized across distances of hundreds, and sometimes thousands of kilometers. We argue in this paper that there is much to be learned from what ecologists have found from their studies, analyses, and models of oscillatory population systems. While ecological models and analytical approaches cannot be imported wholesale, or without adjustment, into world-system problems, they do offer a number of useful insights, and suggestions for future research.

Many ecological studies are highly analytical, and current standards of scientific rigor in the discipline (especially in the study of population oscillations and spatial synchrony) require translation of verbal hypotheses into mathematical equations. The benefits of this approach are the ability to subject predictions from rival hypotheses to rigorous quantitative tests. However, model construction requires making simplifying assumptions. Surprisingly, however, the resultant models are often quite robust with respect to these initial assumptions. That is, "first-cut" models can be investigated mathematically as to the consequences of relaxing the initial assumptions for theoretical predictions. Repeated applications of this process can extend theory and simultaneously increase confidence in the answers that it provides. The conditions under which population cycles become synchronized have been a focus of an intense theoretical (and empirical) investigation over the last several decades, leading to a fairly mature state of understanding of synchrony.

A key insight from ecological theory is that the processes driving oscillations (the rise/fall dynamics) and the processes causing large-scale synchrony need not be the same. In fact, current empirical research shows that in ecological systems they are typically distinct. Ecological models show that if two (or more) systems separated in space are driven by largely endogenous dynamics, and if their endogenous dynamics are broadly similar (e.g., have approximately the same period), then their cycles may be synchronized by a variety of shared exogenous perturbations, and these perturbations need not be very strong. The process of bringing spatially distant oscillations into phase by weak exogenous influences is sometimes called "entraining" or "phase-locking." This insight, in particular, is suggestive for possible explanations for the synchrony of population and city-size changes in east and west Asia.

Our goal in this paper is to review recent developments in ecological theory of spatial synchrony, and discuss its possible applications in world-system research. Because the nature of endogenous processes underlying systemic oscillations is a key ingredient in the explanation of large-scale synchrony, we begin by reviewing cyclical processes affecting the dynamics of polities and world-systems. Second, we review the theoretical results from ecological models. Third, we discuss some broad patterns in the Afroeurasian history from the point of view of the theory we present here. Fourth, we conclude that this preliminary examination is sufficiently promising to warrant further theoretical and empirical investigation of this extension of ecological theory to world-systems problems. Finally, we discuss directions for future research suggested by the theory, and, in particular, how some of these hypotheses might be tested with data.

CYCLIC PROCESSES IN WORLD-SYSTEMS

For the most part world-system analysts have focused on two cyclical processes: the Kondratieff wave (K-wave) and the hegemonic cycle. K-waves are shown by approximately 50–year cycles in prices. The upswing is called the A-phase, the downswing the B-phase. K-waves are notoriously difficult to date precisely because they must be measured indirectly via trade volume and prices (Barr 1979; Boswell and Misra 1995; Goldstein 1988; Grimes 2000). The basic dynamic is that a new technology allows economic expansion. Eventually the market saturates, and competition increases, and the expansion slows until another cycle, based on yet another new or renewed technology develops. Kondratieff waves have been discussed primarily in the context of the modern capitalist world economy. However, several authors (Modelski and Thompson 1996, 2000) have traced K-waves back into the 12th century.

Hegemony, in a non-Gramscian sense, is a condition in which one state in a core region dominates a world-system through economic and political power, typically without overt coercion. Once its power peaks, hegemony is lost, or at least declines, and the core is marked by much more intense inter-state rivalry and competition. Hegemonic cycles are about a century long, and may be related to K-waves in complex ways that are currently debated (Thompson 2000).

"Secular cycles," periodic waves of state breakdown accompanied by oscillations in population numbers, are a third type of cycle (Goldstone 1991; Fischer 1996; Nefedov 2001; Turchin 2003). Secular waves arise as a prediction from demographic-structural theory, which focuses on the dynamic interaction between population numbers and sociopolitical stability. Jack Goldstone (1991) analyzed the effect of population growth on state breakdown. Briefly, population growth in excess of the productivity gains from the land leads to persistent inflation and rising real costs, which outstrips the ability of the state to increase tax revenues. Rapid expansion of population also results in an increased number of aspirants for elite positions, putting further fiscal strains on the state, and intensifying intra-elite competition and factionalism. Increased rural misery, urban migration, and falling real wages lead to frequent food riots and wage protests; expansion of youth cohorts contributes to the population mobilization potential; and elite competition and popular discontent fuel ideological conflicts. As all these trends intensify, the end result is state bankruptcy and consequent loss of military control, elite movements of regional and national rebellion, and a combination of elite-mobilized and popular uprisings that manifest the breakdown of central authority (Goldstone 1991:25).

State breakdown and resulting sociopolitical instability cause a population decline, both through their effects on demographic rates, and by damaging a society's productive capacity (Turchin 2003). First, political instability causes lower reproduction rates, because during uncertain times people choose to marry later and to have fewer children. Also, family limitation practices may be disguised as increased child mortality. Second, mortality rates rise as a result of increased crime, banditry, and internal and external warfare. Migration from war– or famine–affected areas leads to increased emigration, declining birth rates (because people on the move cannot afford to have children), and epidemics. Increased vagrancy, movements of armies, and movements of rebels spread disease by connecting areas that would stay isolated during better times. Political stability or instability can also affect the "carrying capacity." Strong states support the agricultural productivity by constructing irrigation canals and roads, by implementing flood control measures, by clearing land from forests, etc., thus increasing the numbers of people that can be gainfully employed growing food. Additionally, a strong state offers protection. In an anarchic society people can live only in natural strongholds, or places that can be made defensible. Fear of attack can lead farmers to cultivate only that proportion of productive area that is near fortified settlements. A strong state protects the productive population from external and internal (banditry, civil war) threats, and thus allows nearly all cultivable area to be put into production.

Mathematical modeling of the interaction between population dynamics and

sociopolitical instability suggests that agrarian societies should go through cycles of alternating phases of political centralization/population growth and political decentralization/population decline. A typical period of such "secular cycles" is two to three centuries (although the theory predicts that in societies characterized by widespread elite polygyny, the cycle period should be shorter, around one century—these are "Ibn Khaldun" cycles, which we will discuss in later section). A recent survey by Turchin and Nefedov (2004) suggests that secular cycles are a ubiquitous feature of Afroeurasian history during the last 3–4 millennia.

Effects of hegemonic cycles and secular waves ripple through world-systems and, perhaps, beyond. Sociopolitical cycles give rise to cycles of colonization and decolonization, war and peace, state-formation and state collapse, and a variety of social and cultural movements. These cycles do not necessarily determine or cause these processes. Rather, they may create structural conditions that facilitate, or retard, their course (see Grimes 2000; Boswell 1989; Boswell and Sweat 1991; Boswell and Chase-Dunn 2000:Ch. 2).

Arrighi and Silver (1999; Arrighi 1999) argue that globalization also has spread in waves, corresponding to cycles of hegemony. A key part of their argument is that state capacity to govern is never entirely stable but waxes and wanes with world-systemic cycles. Waves of globalization are yet another example of how these cycles shape social processes. Chase-Dunn et al. (2000) document waves of globalization in the late 19th and late 20th centuries.

We also note that a world-system typically has multiple kinds of boundaries, and except for small systems, islands, and the 20th century world-system, these boundaries do not coincide—they are nested within each other. There are at least four different types of boundaries (Chase-Dunn and Hall 1997). At the smallest scale are the bounds of bulk goods trade, the bulk goods network (BGN). Next in size are the bounds of regular political-military interaction, the political-military network (PMN). Then there are two much larger, but typically different boundaries. Often the slightly smaller of the two is the luxury or prestige good net (PGN), and the typically somewhat larger, information or cultural net (IN). All four boundaries can be fuzzy. If one thinks of a topographic map of each of these features, the "boundary" would be zone of a sharp drop off, what would look like a cliff or very steep slope. Synchronization can occur at any of these four levels. However, each level would have its own mechanisms and dynamics. These differences between networks and corresponding boundaries, of course, are more salient in ancient world-systems than they are in the contemporary world-system.

Clearly, there are many potential levels of synchrony among the various world-system cycles. As noted in the introduction, several have been documented empirically (e.g., Chase-Dunn, Manning, Hall 2000). Other than the speculations by Chase-Dunn, Manning and Hall (2000), very little has been offered by way of explanation. Furthermore, synchrony, or entraining, between east and west Asia does not extend to south Asia, which itself is another puzzle. We argue that an examination of what ecologists have found about synchrony may provide leads for exploring the mechanisms and hence explaining the causes of synchrony across world-systems. We begin that task with a brief overview of synchrony from an ecological perspective.

WHAT THE ECOLOGICAL THEORY SAYS ABOUT SYNCHRONY

Ecologists have long puzzled over why many oscillatory population systems exhibit large-scale spatial synchrony. In fact, in the very paper that inaugurated the scientific study of population cycles Charles Elton also speculated why lemming peak years should be synchronized across much of Norway (Elton 1924). An even more striking pattern of spatial synchrony was later observed in the Hudson Bay Company data on lynx pelts (Elton 1924). It turned out that the ten-year lynx cycle is synchronized over the whole taiga region of Canada. In 1953 P.A.P. Moran developed statistical approaches for analyzing spatial aspects of lynx population cycles, and proposed a formal mechanism that could explain large-scale synchrony (Moran 1953). This mechanism is currently known in the ecological literature as "the Moran effect" (Bjornstad, 1999; more on the Moran effect below). Moran's pioneering work inspired an enormous number of modeling, statistical, and empirical studies, leading to a rapid maturation of the theory of spatial population dynamics during the 1990s (for a review see Bjornstad, 1999). A key issue was determining which mechanisms may cause synchrony.

Synchronizing Mechanisms

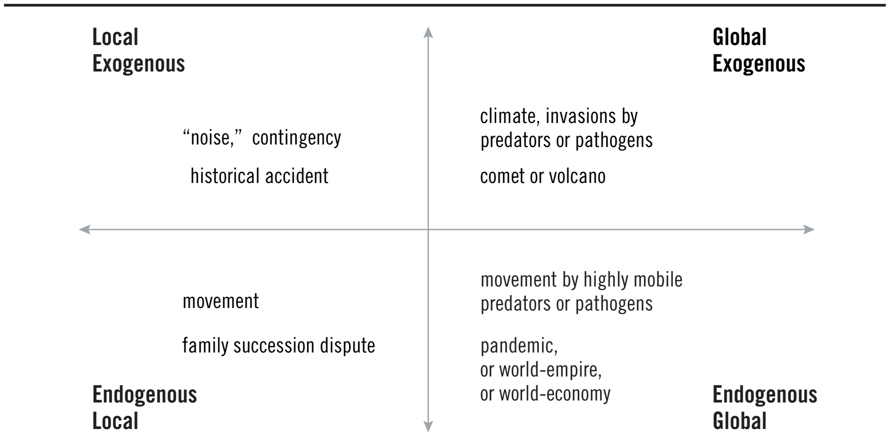
Ecologists have classified mechanisms that induce spatial synchrony along two continua: exogenous versus endogenous and local versus "global." A factor X is called an exogenous mechanism if it is not part of the feedback loop: X affects the variable of interest, while the variable of interest does not affect X. By contrast, an endogenous factor is one that is part of a feedback loop: the variable of interest affects X and then the change in X affects the variable of interest. Of course, we do not always (or even often) know all the feedback loops that affect the dynamics of the variable of interest. Thus, in practice, we call endogenous only those mechanisms, whose feedback influences are explicitly taken into account (e.g., modeled). For example, in human-dominated ecosystems the usual assumption that climate affects population, but population does not affect climate, does not necessarily hold. Chew (2001) shows that early human civilizations so denuded forests and salinized agricultural land that they may, indeed have changed local, if not regional, climates. Some of these changes may

be system-wide. Planetary changes are probably only a 20th or 21st century phenomenon (see also Crowley 2000; Hornborg 2001; Mann 2000; Thomas 1956; Turner 1990). Still, in world-system applications some climatic changes may need to be modeled as endogenous, rather than exogenous processes.

Ecological theorizing uses the terms "local" and "global" in ways that differ significantly from usage in world-systems analysis, a difference that can generate confusion. We review these differences since virtually all ecological research uses these terms in a consistent way. A "local" mechanism is one whose effects fall off with distance. By contrast, a "global" mechanism affects all points in the relevant space similarly, without any regard to how far these points are from each other. Thus, the term "global," as used in ecological literature, might be glossed as "system-wide" in world-system terms. For clarity, we use "planetary" when we mean the entire world, and "global" only as in ecological theory. The spatial scale of a local mechanism can be measured in a variety of ways. One of the most useful approaches is to calculate the spatial autocorrelation function (ACF). A typical ACF is close to 1 for small spatial lags (because points located near each other tend to be highly correlated). As spatial lag is increased, ACF declines to zero (reflecting lack of correlation between points separated by large distances). Thus, a rough measure of the spatial scale of spatial autocorrelation is the spatial lag at which ACF becomes statistically indistinguishable from zero. As the spatial scale on which a process operates increases local mechanisms grade smoothly into global. In practice, whenever the spatial scale of a mechanism is greater than the extent of the spatial domain, within which the dynamics of interest occur, it should be treated as global. ACFs of global processes remain positive (do not decline to zero) for the whole range of spatial lags possible within the spatial domain. In other words, even points situated at the opposite sides of the domain exhibit some degree of synchrony.

Given the two classificatory dimensions (endogeneity and locality), we can define four regions of a universe of potentially synchronizing processes (Figure 1). Ecologists have tended to concentrate on two: the global exogenous and local endogenous mechanisms. The most discussed global exogenous factor in ecology is climatic variation. It is a quintessentially exogenous process because variation in temperature and rainfall can have a very strong effect on survival and reproduction of organisms, while fluctuations in organism population numbers almost never have an effect on weather (although in humans this is not necessarily true, as noted above), especially on the short time scales of interest to population dynamicists. On the spatial scale at which ecologists study most populations, weather patterns are best thought of as global. For example, variations in temperature are highly cross-correlated across hundreds of kilometers. On short temporal scales, precipitation may have a distinct local character (when a summer

Figure 1– Dimensional Continua of Mechanisms of Spatial Synchronicity



thunderstorm dumps a couple of cm of water in one locality, while leaving another, only a km away, dry). On a longer time scale, however, such local effects tend to even out (wet versus dry summer conditions affect large areas, hundreds of km in extent). In any case, close examination of specific mechanisms shows that the global-local distinction defines a continuum, and not a dichotomy. For world-systems analysis, given the potential effects of human activity on climate (see Chew 2001), clearly "global" or system-wide mechanisms would be a massive volcanic eruption or collision with a sizable comet. Alternatively, if there is a truly exogenous climatic shift (due, say, to sun spot cycles or some such mechanism that humans could not affect) and if it were planetary, then we should see global synchrony, across Afroeurasia, Meso– and South America, Southeast Asia, and sub–Saharan Africa. This would still require some subsidiary explanation for the already documented lack of synchrony in South Asia.

The quintessential local endogenous mechanism is movement. It is endogenous because the number of organisms spreading from a source depends very much on the population density at the source. It is local, because organisms do not "teleport"—in order to get to there from here, an organism must travel through the intervening space. The result is a characteristic pattern of movement, in which the density of dispersers declines with the distance from source. We note that movement is not limited to the population under study; it may also refer to movement of other components in the dynamical system, such as predators or pathogens. Socially, disputes in family succession among elites, as among Mongols who had competing lines of succession (Barfield 1989; Chase-Dunn and Hall 1997: Ch. 8) would be examples (laterally and lineally). Rules of succession or descent vary by cultural group, and thus are typically highly localized. Such rules do change, but typically only very slowly, often pushed by changes in the ecology of production and adaptation.

Once again, although movement tends to the local endogenous corner of the classificatory universe, under certain circumstances it may become either exogenous or global (or both). An example of movement acting in an exogenous manner is when the area under study is subjected to recurrent invasions of predators or pathogens from outside. Movement may act globally (or in a system-wide manner), rather than locally, when the scale of dispersal is much larger than the extent of the spatial domain. In ecological applications, movements by predators often occur on a much larger scale than movements of their prey. For example, lynx—the main predator of snowshoe hares—have been known to travel over a thousand kilometers. To give another ecological example, many fungal pathogens disperse by spores that may be carried by wind over very large distances. An analogous feature among humans would be the propensity to bring small, exotic souvenirs from distant places, and/or to trade them over great distances (Helms 1988). Another example might be the appearance of new, airborne pathogen that (nearly) simultaneously affected all human populations. The diffusion of the Black Death in the 14th century, *might be* such an instance, since it appears to have spread from Central Asia to both East Asia and West Asia (and Europe) (McNeill 1976). Finally an ecumene-spanning empire, or a world-economy might be considered an endogenous global factor. Consider the widespread effects of the Roman Empire or the current effects of U.S. foreign policy, which may be the analog of "highly mobile predator." Thus, both Iraq and North Korea, separated by thousands of kilometers, are under similar kinds of pressure to change.

Finally, there is the local, exogenous corner of the classificatory universe. This is essentially the "random" corner, where noise, or contingency seems most likely. In social terms, this would be "historical accident." We note, however, that while the event(s) may be accidental or random, their consequences are not (in the sense that their effect may depend on the state of the system).

We reiterate that local-global and exogenous-endogenous are not discrete dichotomies, but rather continua between extremes. As one moves toward the center of the classificatory universe, these distinctions begin to blur and finally merge together.

Types of Oscillatory Dynamics

The efficacy of different mechanisms described above to synchronize oscillations depends on the nature of the dynamics characterizing the synchronized systems. The key distinction is between stable and chaotic oscillations. Chaos is defined as bounded oscillations with *sensitive dependence on initial conditions* (Eckman and Ruelle 1985). Sensitive dependence can be illustrated with the following mental experiment (or even better, a computer experiment). Suppose we have a dynamic system, which started from a certain initial condition and then generated a certain trajectory. Now imagine that we restart the system from an initial condition that is slightly different (on the computer, we simply rerun the program, but give it a different initial data). If the system is chaotic, then we will observe that the two trajectories starting from very similar but different initial points will diverge with time, and eventually oscillate in a completely uncorrelated fashion. If the system is stable, then the two trajectories will converge and soon become completely indistinguishable from each other; they will oscillate in perfect synchrony. Returning to the chaotic system, the faster trajectories diverge the more sensitive to initial conditions (and therefore the more chaotic) the system is.

The same argument applies to the behavior of two identical or very similar systems. If their dynamics are stable, then the two systems starting from similar initial conidtions will tend to oscillate in synchrony. Small random perturbations will keep them out of perfect synchrony but the stable nature of the two systems will act to bring the two trajectories back in synchrony. By contrast, two identical chaotic systems starting even from very similar initial conditions will rapidly diverge and oscillate asynchronously (this is sometimes known as the "butterfly effect"). Small random perturbations will make this process of divergence even faster. This is why the dynamical stability is such an important factor in allowing synchronous oscillations. It is very hard to synchronize two chaotic systems.

The Effect of Different Synchronizing Mechanisms on Spatial Dynamics

The ability of any particular mechanism to synchronize dynamics depends on its nature, as well as on the nature of local population dynamics. In general, exogenous drivers are not particularly powerful synchronizing mechanisms. A substantial degree of spatial synchrony requires, first, that local dynamics are stable (nonchaotic) oscillations and that, second, the exogenous factor acts in a global (or system-wide) manner. The mechanism of entrainment is the Moran effect, which acts as follows. Consider two stable dynamical systems driven by identical (or, at least, similar) mechanisms. For example, two spatially separate locations are inhabited by the same prey and predator species that undergo cyclic population interactions. Subjecting the two stable systems to similar perturbations from an exogenous driver is akin to starting them with similar initial conditions: eventually both systems will oscillate in synchrony. By contrast, subjecting two chaotic systems to identical perturbations will not synchronize them, because they will diverge from each other due to their sensitive dependence properties.

If an exogenous factor acts in a local manner, then its synchronizing strength will depend on how effectively the exogenous perturbations acting on each local system are cross-correlated. Furthermore, the effects of synchronizing external drivers may be degraded by other exogenous drivers, which may act independently on each system.

Note that the usual way of modeling exogenous influences in dynamical systems is by assuming that exogenous drivers affect the rate of change of a dynamic variable such as the population density of the studied organism. For example, an unseasonable freeze may impose 50% mortality on a population, which means that the population size will be halved. Such relative changes cannot synchronize chaotic systems for reasons given above. Another kind of an exogenous influence is one that "resets" each system to approximately the same value, instead of affecting its rate of change. That is, it makes the initial conditions in both systems virtually identical, hence they will be synchronized for some time, until the chaotic process begins to produce divergence. Multiple "resetting" perturbations can impose a fairly high degree of synchrony even on chaotic systems. The average degree of synchrony will depend on how frequently "resetting" events occur, and how fast trajectories of local systems diverge after each resetting event.

Endogenous factors such as movement have a greater potential for inducing spatial synchronization, especially if the local dynamics are characterized by stable limit cycles. Ranta et al. (1998) showed that even relatively low rates of movement can induce a near-perfect synchrony of local cycling populations. This property of nonlinear systems is called phase-locking (Bjornstad 1999). However, populations coupled by movement will remain uncorrelated if they are characterized by locally chaotic dynamics.

Oscillatory dynamics in ecology arise most often as a result of population interactions between predators and prey (or, more generally, between ecological consumers and their resources, see Turchin 2003). It is important to remember that both predators and prey can move around. Depending on the dynamical nature of interaction (e.g., stable equilibrium, stable limit cycles, or chaos), and on the details of movement behavior (e.g., the movement rate of predators relative to that of prey, ability of predators to track prey aggregations) predator-prey systems in space can give rise to second-order spatial covariance, which can take the form of traveling waves and static patchy patterns (Bjornstad 1999). We do not have space here to give justice to this rich and subtle theory, but wish to mention one kind of behavior, which may be of relevance to world-system dynamics —out-of-phase oscillations.

To illustrate this kind of behavior, consider a two-patch system incorporating both dispersal and local dynamics, coupling two discrete-time logistic equations (Hastings 1993). This deceptively simple system is capable of a surprising diversity of dynamical behaviors, depending on parameter values and initial conditions, but we are interested only in the out-of-phase cycles. What happens is that when patch 1 is low, patch 2 is high. On the next step, population in patch 1 grows, plus the patch gets a lot of migrants from patch 2. This causes patch 1 to overshoot its equilibrium, so on the subsequent step the population in it collapses. Meanwhile, patch 2 is affected by the same events, except they are shifted in phase with respect to patch 1. In other words, the interplay of movement and local dynamics leads to the behavior in which population size in each patch goes through recurrent cycles, while the total population (the sum of both patches) is constant.

Statistical Issues

Above we have devoted a lot of attention to the issue of what mechanisms may bring about large-scale synchrony. The implicit assumption here is that we are dealing with an empirical case of synchronous dynamics and the question is how to explain it. Given limited and noisy data, however, how do we know that there is a pattern to be explained, in the first place? Thus, we need to say something about the null hypothesis of no synchrony, and how to distinguish it statistically from cases where synchrony is present. The problem is that two unconnected systems, but with similar dynamics (for example, the same period of oscillations) may look like they are synchronized, especially in limited runs of data. If, purely by chance, the two systems are in phase at the beginning of the observed period, they will continue cycling in phase for several oscillations, simply because the endogenous dynamics of each system generate cycles of the same period. Such a spurious synchrony may continue for some time before the systems diverge, either because their periods are not exactly the same, or because each system is affected by a different set of exogenous influences (or because of sensitive dependence). If data are limited, however, it may appear as though the two processes have been synchronized by some external force. An example of spurious synchrony is Charles Elton's proposal that the lynx cycle in boreal Canada is driven by the sunspot cycle. Indeed, during the 19th century, the two series were largely in phase. However, eventually the two series diverged, so that by mid–20th century they were in a perfect antiphase! These two dynamical systems appear to be entirely unconnected, and the spurious synchrony observed during the 19th century arose as a result of very similar periods of oscillations (both slightly above 10 years).

Thus, it is important to keep in mind that simple-minded approaches, such as measuring cross-correlations and testing their statistical significance with some standard formula such as Bartlett's rule (Chatfield 1989) can be very misleading. Standard measures of significance assume that data are independent of

each other, while in an oscillatory system subsequent data points are positively autocorrelated, inflating the statistical significance of the test. Methods for correcting significance level in such situations exist (e.g., Sciremammano 1979), but perhaps the best approach is to use some version of bootstrap (Efron and Tibshirani 1993).[1]

The problem is that rigorous approaches require rather long data sets. In other words, tests for significant cross-correlation between two oscillatory time series are characterized by low power. The problem is not lack of cleverness in designing powerful tests, but in the nature of the problem. In order to be sure that two series are not spuriously correlated may require a very long wait to see if they diverge. Fortunately, mechanism-free statistical tests are not the only way to investigate spatial synchrony. An alternative (or, rather, complementary) approach is to characterize the potential mechanisms that may (or may not) bring about spatial autocorrelation. Thus, in practice the question of whether there is synchrony and what factors explain it are not completely separable, and need to be addressed jointly.

Summary

Spatial dynamical systems are capable of a very diverse spectrum of behaviors. Nevertheless, certain common themes emerge from this review. First, spatial synchrony is promoted when two local systems are driven by similar dynamical mechanisms. In fact, such systems can exhibit spurious synchrony: even though there is no synchronizing mechanism, the two systems oscillate in step because they happened to start from similar initial conditions. Second, processes that act globally (that is, on a system-wide basis) promote large-scale spatial synchrony. Third, the type of local dynamics affects very much whether any particular mechanism will induce synchrony. Systems with stable oscillations can be synchronized over vast geographic distances by global exogenous influences. The degree of synchrony will usually not be very high, because each local system will also be affected by other exogenous factors that are not highly autocorrelated

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[1] A bootstrap is a computer-intensive method for testing hypotheses. The basic idea is to construct a model for the null hypothesis—in this case, two oscillating system *without* any synchronizing connections. One then generates many data sets similar to this situation (e.g., same length of time-series and same degree of noise), and calculates the test statistic—here the cross-correlation coefficient. Then the data-base correlation coefficient is compared to the bootstrapped correlations. For example, for a p-level of 0.05, the data-based statistic should be greater than 95% of bootstrap statistics (see Efron and Tibshirani [1993] for more elaborate discussion).

across space (noise, contingency). Endogenous factors such as movement may result in a very high degree of synchrony—phase-locking, but the spatial extent of such synchronous oscillations may not be great, because the effect of movement tends to attenuate rapidly with space. Additionally, endogenous processes may cause out-of-phase cycles (anti-synchrony, so to speak).

Finally, chaotic systems are very difficult to synchronize either by exogenous or endogenous mechanisms. Only global catastrophes that reset all locations to approximately the same initial conditions can impose some (fleeting) degree of synchrony on chaotic systems. Examples include events such as collision with a large comet, like the one that is hypothesized to have led to the extinction of dinosaurs, or a massive volcanic eruption, such as Thera (see also Weiss, et al. 1993).

IMPLICATIONS FOR WORLD-SYSTEM RESEARCH

East-West Synchronicity and Global Climate

As we mentioned in the Introduction, one empirical pattern that requires explanation is synchronous changes of empire sizes in West and East Afroeurasia. Ecological theory suggests several hypotheses, the simplest one being the effect of an exogenous global factor—climate. World-system theorists (Chase-Dunn et al 2000) have already suggested this explanation, but historical demography (Galloway 1986) presents it in its most developed form. Galloway (1986: Figure 6) plotted the solar activity index (considered to be one of the most important drivers of global climate change) and populations of Western Europe and China from 400 BCE to 1800 CE. Dynamics of the solar activity index (see Eddy 1977: Table 1) suggests that there was a long-term period of warm climate with the peak around 20 BCE–80 AD (the Roman Maximum). The second such warm period was from 1120 to 1280 CE (the Medieval Maximum). Between these two maxima, there was a period of cooler temperatures (the Medieval Minimum, 640 –710 CE). After the Medieval Maximum, solar activity declined (the Spoerer Minimum, 1400–1510 CE), then increased somewhat, declined again (the Maunder Minimum, 1640–1710), and increased again in the late 19th and 20th centuries. As noted by Galloway, populations of Western Europe and China increased and decreased roughly in parallel with solar activity.

The Roman Maximum in solar activity coincides with two great empires dominating the eastern and western ends of Eurasia: Han China and the Roman Empire. However, while this is a remarkable correlation when examined at a coarse time scale, finer scale resolution does not reveal a close parallelism in the sociopolitical dynamics of the two empires. The Roman polity went through three secular cycles: the Republic, followed by the decentralization phase during the late 2nd and most of the 1st century BCE, then the Principate, followed by the troubled 3rd century, and finally, the Dominate, followed by a final collapse in the West during the late 5th century. By contrast, the first peak of the Chinese empire (Western Han Dynasty) occurred during the 1st century BCE, just when the Roman polity was convulsed by a series of civil wars. The interregnum between the Western and Eastern Han dynasties was during the 1st half of the 1st century CE, the Eastern Han peak was during the 2nd century, and the collapse of the Han dynasty occurred during the 3rd century, which coincided with the similar period of the Roman Empire. There was no third secular wave in China, however, but a long period of disunity until the Sui-Tang unification. Population fluctuations, as far as they are known, followed closely the sociopolitical dynamics. Thus, while the broad period of 200 BCE–200 CE was characterized by large empires and high population densities at both ends of Eurasia, finer dynamics within the period came into and out of phase.

A similar pattern appears to hold during the next warming period (roughly from 700 to 1200 CE). The peak of the Early Tang dynasty occurred around 700 CE. It experienced a collapse during the middle of the 8th century, a restoration (the Late Tang dynasty) during the 9th century, and a final collapse in 907. By contrast, Carolingian empire reached its peak around 800 CE, and disintegrated during the 9th century. During the same period another large Eurasian empire, the Caliphate, went through two shorter cycles: Omayyads (661–750) and the Abbasids (750 to around 860 when the dynasty became a pawn of the Turkic *ghulams* [slave-warriors]).

In the next wave, North Sung declined during the 12th century, followed by the Mongol conquest of the 13th century (South Sung fell to the Mongols only in 1279). Chinese population declined catastrophically during the 13th century dynastic collapse and nomadic conquest. By contrast, in Western Europe the population peaked around 1300 CE, and the actual collapse occurred only in post-Black Death period. Political disintegration in Western Europe, however, occurred in patchy manner. The German–Roman (later known as Holy Roman) Empire disintegrated fairly synchronously with the Sung (although the process was by far less violent). On the other hand, France experienced the worst periods of civil war around 1370s and 1420s (two peaks of the Hundred Years War), while England's turn came only in 1450–1485 (the Wars of the Roses). By that time the Chinese had already expelled the Mongols (in 1368) and unified all China under the Ming dynasty. Again, when viewed broadly, the Medieval Warm Period is the time of strong empires and dense populations, but when we consider dynamics *within* the period, synchronicity largely falls apart. This observation supports the idea that climate did not directly drive the secular wave, but rather modified it in a way that imposed a certain degree of synchrony between the East and the West.[2]

The 17th Century Crisis

What is highly interesting is that the next wave of state collapse—the so-called crisis of the 17th century—affected practically all Eurasian empires (apart from the South Asian region) essentially simultaneously (Goldstone 1991). The "long 17th century" began ca. 1570 with religious warfare in France, the Dutch Revolt, the troubled second half of Ivan the Terrible's reign in Russia, and the daimyo-led civil war in Japan. During the first half of the 17th century, Russia went through the Time of Troubles, Central Europe was devastated by the Thirty Year War (during which Germany lost a third to half of its population), the Ming dynasty fell in China and was replaced by the Manchus, Spain experienced the Portugese and Catalonian revolts, the Ottoman Empire almost disintegrated, and the English decapitated their king. The 17th century was also the period of widespread famine and epidemics. All regions of Eurasia (apart from India and Iran) experienced population declines, in some cases quite extreme (as in Central Europe).

The crisis in the 17th century was unique in the history of Eurasia. The next wave of state collapse was not as tightly bunched. Thus, the Age of Revolutions in continental Europe started with the French revolution of late 18th century, and ended with the revolutions of 1848–1849. By contrast, Russia, China, Turkey, and Iran went through their revolutions during the early 20th century. England entirely avoided state collapse during the 19th century, but had to let its empire go in the 20th century (Ireland in 1920, India in 1947, Africa in early 1960s). In fact, it appears that the revolutions in the 19th – early 20th centuries are "echos" of the 17th century; oscillations that began to diverge as a result of, perhaps, slightly different periods, and an accumulation of historical accidents peculiar to each specific polity.

Why was the 17th century crisis Eurasia-wide? One possible explanation is again the global climate. The 17th century saw a trend to lower temperatures, which in most Eurasia (apart from the Indian subcontinent) should have resulted in decreased harvests. According to the demographic-structural theory, the root cause of crisis is in the imbalance between population numbers and the productive capacity of the land. This imbalance can be achieved either by excessive population growth, or by a rapid decline in the productive capacity of the environment, for example, as a result of a string of colder, wetter years. Note that in this scenario climate change does not directly cause state collapse: its effect is, rather, mediated by social structure (population numbers in relation to the productive capacity of land).

[2] One anonymous reviewer noted that Galloway's data focuses on long-term fluctuations, of much longer period than city-size or empires. We actually concur with observation. Thus, this type of climate change may **not** be the mechanism for East—West Asia synchrony. Still, it illustrates how other climatic changes, occurring on a shorter scale, might produce such synchrony.

The Mongol conquest as a "resetting catastrophe"

Another explanation of the 17th century crisis would look back to the events during the previous secular wave. Most world-system theorists agree that the Mongol conquest in the 13th century was a key event in the Afroeurasian history. Not only did the Mongol Empire briefly connect East with the West, it also started a series of remarkably coherent oscillations in Central Asia and adjoining regions.

The huge territory conquered by the Mongols during the first half of the 13th century contained four large "cultural areas" inhabited by settled people: China, Transoxania, Persia (including Mesopotamia), and eastern Europe. From the middle in the 13th century, these four areas were ruled by four separate Chingissid dynasties: (1) Kublai and his successors (the Yuan dynasty) in China; (2) Jagataids in Turkestan (which included Transoxania); (3) Hulagu and his successors (Il-Khans) in Persia; and (4) Juchids (Batu and his successors) in the Kipchak Steppe (the Golden Horde). According to the theory advanced in Turchin (2003: Chapter 7), these four polities should be subject to the Ibn Khaldun cycles of around a century in period.

The Ibn Khaldun cycle, named after the 14th century Arab sociologist who first described it, is a variety of a secular wave that tends to affect societies with elites drawn from adjacent nomadic groups. The dynamics of the Ibn Khaldunian world-system are determined by the interaction between a sedentary, agrarian state and surrounding steppe or desert pastoral "tribes." The sedentary state region is the site of recurrent state building/collapse episodes. It is inhabited by indigenous commoner population, that provides the productive basis of the society. The steppe or desert is inhabited by stateless tribes that periodically conquer the civilized region and establish a ruling dynasty there. Steppe or desert tribes, thus, supply the elites (nobility) for the sedentary state. Ibn Khaldun cycles tend to operate on a faster time scale, so that their period is about 4 generations, or a century.

The events in Eurasia after the Mongol conquest appear to provide a reasonable fit to this theory:

1. In China, the civil war between the successors of Kublai broke out in 1328. The 1350s saw numerous revolts led by native leaders, and in 1368 one of these leaders expelled the Mongols and established the Ming dynasty.
2. Turkestan was unified until 1333–1334, when a nomad-led insurrection broke out against the Jagataid regime in Eastern Turkestan. By 1350 the power in Transoxania passed into the hands of local Turkic nobles. After a period of turmoil, Timur established a new dynasty. Timur unified Transoxania in 1379, and conquered Iran during the 1390s. The Timurids dynasty also lasted about a century. In 1469 Persia was lost to the White Sheep Horde, while Transoxania splintered between warring branches of Timur's descendants.
3. The Persia of Il-Khans underwent dissolution in 1335. After a period of civil war it was conquered by Timur (see above). When the Timurids lost Persia in 1469, another turbulent period followed, and eventually, by 1500, Persia was unified by a native dynasty (Safavids).
4. A similar course of events occurred in the Kipchak Steppe. The Juchids' rule ended in 1359, when the Kipchak steppe fell into anarchy. After a period of civil war, the Golden Horde underwent a revival under Timur Qutlugh, who re-consolidated his dominion over Russia, although a series of punitive expeditions were required during the early 15th century to keep the tribute flowing. In the middle of the 15th century, however, the revived Golden Horde began disintegrating again. The first part to secede was the Crimean Khanate in 1430. The Khanates of Kazan and Astrakhan followed (in 1445 and 1466, respectively). The Moscovite polity went through its own period of civil war during the second quarter of the 15th century, which, curiously, coincided with the civil war on the steppe that lead to the final splintering of the Golden Horde. As soon as the civil war ended, Muscovy became *de facto* an independent state (*de jure* independence had to wait until 1480).

This is an alternative way of viewing the analyses of Barfield (1989) and Chase-Dunn and Hall (1997: Ch. 8). As Barfield notes, however, the Mongol conquest was somewhat exceptional with respect to the usual strategy employed by the central–Asian nomads. First, the Mongols succeeded in capturing much vaster regions, due in the main part to innovations in organization by Chinggis. Second, instead of merely exploiting sedentary states via the outer frontier strategy, the Mongols actually conquered large empires and had to run them. Finally, the break-up grew out of Mongol rules of dynastic succession that emphasized both lateral and linear descent. These extensive Mongol conquests also disrupted the Ibn Khaldun cylces, in effect resetting them in several different areas simultaneously.

Among nomads this contradiction produced conflicts that both allowed one strong leader to emerge and tended to eliminate rivals. While useful for pastoralists, this multifaceted civil war strategy for succession is disastrous for states. Chase-Dunn and Hall (1997: Ch. 8) argue that the issue was **not** that the Mongols could not change their system of succession—they clearly knew how states worked. Rather, it was that they could not change their system and remain Mongols. To have a more orderly system of succession like those found in states, would have destroyed the very mechanisms that allowed leaders like Chinggis to emerge. The Ottomans, however, seem to have solved this problem. They institutionalized succession so that change happened very quickly—one heir wins, all others are strangled with a silken chord. As a result, the secular cycles of the Ottoman Empire were 200–300 years long.

To summarize, all Chinggisid dynasties went through typical Ibn Khaldun cycles of about a century in period, and all experienced collapse at approximately the same time. In China, a native dynasty expelled the Mongols after one cycle, while in Russia and Iran the steppe dynasties went through two cycles before giving way to native rulers. Incidentally, the central Eurasian steppes continued to undergo Ibn Khaldun cycles, until their conquest and division between the Russian and the Chinese empires (Barfield 1989). What is remarkable is the degree of synchrony in the socio-political dynamics of the settled regions initially conquered by the Mongols in the 13th century. One possible explanation of this pattern is that an initial catastrophic event—the Mongol conquest—reset all regions to approximately the same initial conditions. Thereafter, each region oscillated as a result of its endogenous dynamics, but because oscillations were driven by similar mechanisms, political collapses occurred at about the same time.

The Black Death as a Resetting Catastrophe

Returning to the fates of Eurasia as a whole, the continent-wide spread of Black Death from its endemic region (Central Asia) may have been another resetting catastrophe. The Black Death pandemic is widely credited to the Mongol conquest, and the resulting density and speed of traffic, trade, raids, and communications across Central Asia—for which the Mongols are widely famous. The increase in traffic made it possible for various vectors to survive to spread various pathogens, notably the plague bacteria, over large distances

(McNeill 1976).[3] The Mongol conquest, however, was largely complete by mid-13th century, while the Black Death struck a hundred years later. Why was there such a delay? We do not know, but one hypothesis may explain it: that disease tends to spread particularly rapidly during the decentralization phase of the secular cycle (this was mentioned above). If this hypothesis is correct, then it was not the fact of Mongol unification *per se*, but that simultaneous disntegration of various Mongol polities that threw the Great Steppe in turmoil, causing large numbers of people to move back and forth, and thus spread the Black Death to both ends of the continent. That is, as suggested earlier, these social processes transformed what might have been an exogenous-global mechanism in to an endogenous-global mechanism.

The Black Death caused Eurasia-wide turmoil simply by its terrifying impact on populations. But it also probably had an additional effect that tended to bring distant polities in phase with each other. Epidemics generally inflict a higher mortality on lower strata of society, while the elites tend to escape relatively lightly. A side effect of an epidemic, therefore, is to increase imbalance between the productive strata and elites. According to demographic-structural theory, excessive elite numbers are a highly destabilizing factor for any society. Thus, polities experiencing a severe epidemic should be more likely to go into a collapse than polities avoiding such a fate. Note that the logic of this argument is similar to the hypothesized connection between climate change and sociopolitical stability made above: both disease and climate are assumed to act indirectly, by affecting social structure.

The 14th century, therefore, was similar to the 17th century in that much of Eurasia was in crisis, and in that it was the century of widespread population decline. (Additionally, it was the time of decreasing temperatures, leading to the Spoerer minimum). This raises the possibility that the crisis in the 17th century was simply an echo of the 14th century. A more wholistic view, however, would be to consider the Black Death and the two minima of solar activity as repeated

[3] Chase-Dunn and Hall (1997, Chs. 6 and 8) present this argument. They further note (p. 116) contra to Goldstone's claim that there is little or no world-system effect here, that the Black Death spread precisely along the pathways of trade that formed the Afroeurasian-wide world-system. In situations like this where world-systems that were either isolated, or only connected at the two widest levels (information and prestige goods), begin to merge, the endogenous—exogenous distinction becomes particularly muddy. This is where a more quantitative (and dynamical) approach is called for. For example, we need to obtain numerical estimates of how the spatial scale of information and prestige goods exchange fluctuated during this period.

shocks, global in their effect on most of Eurasian polities, that caused secular oscillations across the continent to get in phase. The repeated nature of these shocks, and especially that they happened to be three centuries apart (leading to a potential resonance effect) may go a long way to explaining the remarkable degree of Eurasia-wide synchrony during the last millenium.[4]

Spread of Pathogens, Ideas, and People

The above discussion has already brought in the disease as one potentially synchronizing factor. The Black Death, however, was a rather unsual episode in the history of epidemics, because of its global (within Eurasia) effect. It was not a unique occurrence (for example, the flu pandemic of 1911 was even more global in its effect), but most diseases tend to spread in a more local fashion. Recent research on measles epidemics during the 20th century (when we have excellent data sets, e.g. for England, see Grenfell et al. 2001) has traced how disease spreads from town to town. In general, we would expect that epidemics would be an important synchronizing factor within world-systems, but except for unusual circumstances they will not spread between world-systems. One such exception, as noted above, would be the rapid spread of the Black Death within Eurasia during the 1330s and 40s (McNeill 1976).

Cultural influences, innovations, and fads could also spread in a manner similar to epidemics. A dramatic example is the wave of revolutions that spread through western and central Europe in 1848–1849. Other potential examples include the spread of agricultural innovations (which elevate the carrying capacity) and birth-control practices (which reduce population growth rate).

Finally, actual population movements between agrarian polities are probably too slow to synchronize them, although within a polity they should play an important role (e.g. migration to urban centers at the end of population increase phase). We can evaluate the rate of migration by considering historical instances of colonization movement, such as the Iberian Reconquista or the colonization of European steppe by the Russians. Incidentally, both of these examples involved interpolity migration. The Reconquista resulted in a major transplantation of Spaniards from the north into the reconquered south, but also in massive movements of the French settlers into the north (Bartlett 1993:

[4] But we should not overstate the observed degree of synchrony. Secular waves do not have very regular period of oscillations, so we should expect divergence after just one or two cycles after a resetting perturbation. Perhaps that is why the Age of Revolutions occurred in Western Europe earlier than in other parts of Eurasia.

179). Populations moving into the European steppe came from Russia, Poland-Lithuania (Ukrainians and Jews) and even Germany. Both processes were very slow, occurring on the time scale of centuries. Iberian Reconquista occurred in two main pushes, 1080–1150 and 1212–1265 (Bartlett 1993). Russian colonization started with the conquest of Kazan in 1552 and continued after the incorporation of Crimea in 1783.

Nomadic populations, however, may be an altogether different story (see Barfield 1989 and Frank 1992). McNeill (1963, 1987) suggests that differing ecological conditions created a "steppe gradient" that tended to encourage movement of Central Asian Steppe nomads to the west whenever events in the east disrupted their lifeways.[5] Such disruptions could be socio-political, for instance temporary success of Chinese military campaigns against them, or climatic, in quality of grazing, or a sudden growth in population (of animals or people or both) that strained the carrying capacity of the local environment (again, these in turn might have social and/or climatic sources). The net effect is one of many relatively short-distance movements that create a net westward migration across Central Asia toward the west. Because nomads are much more mobile than agriculturalists, disturbances at the east end of the Great Steppe can rapidly propagate to the western end, probably on the time scale of years and decades.

Asynchronous South Asia

If we consider the Steppe Gradient, along with Jared Diamond's (1999) observation that absent formidable barriers, east—west movement along similar latitudes (and therefore similar climates) is easier than north—south movement that must traverse significantly different ecological zones, we can construct one explanation for the puzzling findings of Chase-Dunn et al. (2000) that east and west Asia synchronize, but not south Asia. This is all the more so, since the Himalayas are a formidable barrier to contact and exchange. To be sure, there has been extensive traffic across the Himalayas, but it may not have been sufficient to synchronize the various systems. Steppe nomads seldom made incursions into south Asia. Central-Asian influence on India was transmitted indirectly via the Iranian plateau (for example, the Moguls, whose name is a corruption of the "Mongol," conquered India from Afghanistan).

Two additional factors give tangential support to this supposition. First, while bulk goods, large populations, and armies rarely moved between South

5. However, in the first millennium BCE the predominant direction of movement was to the east, leading to the spread of Indo-European nomads (see McNeill 1987, pp. 265-67, especially the map on p. 266).

and Central Asia, travelers and ideas did so extensively. The spread of Buddhism and of silk and other luxury goods are familiar examples. Both illustrate the critical difference between the various boundaries of world-system, bulk goods and the military-political exchanges on the one hand versus information and luxury goods on the other. Second, south Asia had tremendous effects on southeast Asia. Again there is the spread of Buddhism, but also other cultural features, and trade in luxury goods. Yet, if the east—west vs. north—south differential is at work, there should be some synchrony between south Asia and Southeast Asia, and less synchrony between Southeast Asia and east Asia. Unless, of course, the somewhat lower barriers between east and southeast Asia did allow sufficient contact and exchange to promote synchrony.

The second explanation for asynchronous dynamics in South Asia is the effect of climate. Cold, wet, climate leading to problems in most of Eurasia might have been a boon for South Asian agriculturalists. The two hypotheses, movement (of people, goods, and ideas) and global climate are not mutually exclusive.

A possible third explanation for asynchronous dynamics in South Asia is that local, i.e., endogenous, processes may have differed significantly between south Asia and the rest of Asia. This would seem less likely, but it is a possibility that warrants consideration.

Currently we do not have sufficient data to discriminate among these explanations. Still, the arguments and analyses presented here suggest ways these issues might be addressed empirically.

CONLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

Much (if not all) of our discussion of potentially synchronizing factors and their interplay with sociopolitical cycles in Eurasia is highly speculative. However, these speculations constitute a powerful argument for the relevance and utility of further systematic, theoretical and empirical extensions of ecological theories to world-systems analysis. Our key conclusion is that this synthesis of these two widely separated theoretical traditions can lead to much more rigorous exploration and testing of theories of the processes of world-systemic change.

Our goal in this paper was not to provide answers, but to generate hypotheses that can be subsequently tested with data. Thus, the last topic that we need to discuss here is how such empirical testing might be accomplished.

We argue that explicit mathematical models are necessary ingredients in this empirical program. The reason is that nonlinear dynamics such as cycles are sufficiently complex in themselves, but when we add a spatial component, the resulting problems become much too difficult to be grasped by the "naked" human mind. What is needed is mathematical formalism to be able to state the problem precisely—as models—and computers to solve the models. As we mentioned in the Introduction, some social scientists might object to mathematical models on the grounds that they oversimplify the reality. We seek to understand such complex systems by building models systematically, starting with simple assumptions and then adding more complex processes, as they are warranted by data.

The power of mathematical models is that they make quantitative predictions that can be compared to data using standard statistical methods. One statistical methodology for investigating spatial synchrony is the autocorrelation analysis. The correlation coefficients calculated by Chase-Dunn et al (2000) between empire sizes in the Central, East Asian, and Indic PMNs was a very useful step that has already yielded highly suggestive results, but it can be improved upon. First, we can estimate spatial autocorrelation functions (ACF), that is, how the correlation coefficient changes with distance between the polities. Different synchronizing mechanisms leave different "signatures" in the ACF. Thus, a local process should result in an ACF that declines with distance: high correlation between territorial dynamics if polities are located near each other, and low or no correlation for polities separated by great distances. In other words, the scale at which ACF becomes indistinguishable from 0 is related to the spatial scale at which a process operates. By contrast, a global mechanism should result in no relationship between the correlation coefficient and distance.

The approach sketched above tests a *qualitative* prediction—the question of whether the ACF declines with distance has a binary answer (yes or no). A more informative approach would address the quantitative aspects of ACF, such as the spatial scale at which it becomes indistinguishable from zero. Thus, an even stronger test would be to construct a mathematical model of synchronous oscillations, estimate the spatial scale at which the postulated factor operates (for example, how fast and how far epidemics spread), and then make quantitative predictions about the shape of the ACF.

Furthermore, spatial autocorrelation analysis is not the only statistical approach that could be used. Very useful insights can be obtained by examining cross-correlations between two or more factors. For example, we can investigate how political dynamics are correlated (in space and time) with disease dynamics. Again, qualitative predictions can be made readily (for example, no crosscorrelations between polity size dynamics and disease probably means that these two factors are unrelated to each other). However, more progress will be made if we can make quantitative predictions using explicit models.

The approach that we are advocating needs several ingredients for success. On the empirical side we need a more detailed database of territorial dynamics of all polities within the Afroeurasia (omitting, perhaps, ones that are smaller than a certain threshold).[6] We also need data on spatio-temporal dynamics of any other variables that may affect synchrony, such as epidemics and climate. Some databases already exist, e.g. Biraben's (1975) compilation of places affected by the Black Death in Europe and the Mediterranean. Certain kinds of data, such as climate change, are in the process of being developed in other disciplines and all we need to do is wait (e.g., see Mann 2000). Other data will probably need to be developed from scratch (here recent developments in historical GIS may be of great help).

On the modeling side we need a better understanding of processes that may cause oscillations and synchrony. What would be particularly useful in the study of synchrony is estimates of the rates of movement for different "things"—goods, pathogens, ideas, and people.

The research program combining mathematical theory with sophisticated statistical approaches is costly—it requires a large quantity of data and some changes in research practice. However, we think that such an investment is warranted. Recent results that suggest sociopolitical cycles and wide-scale synchronicity within the Afroeurasia are "intoxicating," to use the word of Robert Denemark (2000). If there are regular empirical patterns, then history is not just a collection of accidents. But unraveling the complex interactions causing the empirical regularities will require sophisticated quantitative tools.

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