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Here we revisit, with new data, tools, and theory, *the* classic problems engaging social and political theorists since at least the time of Hobbes (*Leviathan*, 1651): how and why, over the last few thousand years, did the relatively egalitarian foraging bands of our deep prehistory give way to larger-scale societies marked by obvious inequalities in power and wealth? Although the end points of this process may be fairly clear, what's in the middle remains a muddle. We develop our approach with reference to a specific historical trajectory, yet we suspect this model represents a common path to sociopolitical complexity in the absence of direct competition with larger, more hierarchical groups. Our proof-of-concept model

reproduces important aspects of patterns in settlement and conflict seen in the central Mesa Verde region of the Pueblo Southwest in the last half of the first millennium and the early second millennium AD.

Outputs from this model however do not map very well into the taxonomies developed by neo-evolutionary studies of the mid-twentieth century (e.g., Fried 1967; Service 1962). This is a little troubling, but on the other hand archaeologists have often lamented the poor fit of concepts like “chiefdom” or “stratified society” to what they see as the facts on the ground in the later prehispanic Southwest (Haas et al. 1994). In any case, we are more interested here in process than taxonomy.

Clarity though requires some vocabulary. The model developed here recognizes three basic kinds of groups beyond the household: simple non-hierarchical groups, simple hierarchical groups, and complex hierarchical groups composed of multiple simple groups. We build an evolving ecosystem of households within these three types of groups that has no pre-ordained endpoint. What happens in any specific run is strongly conditioned by structural factors such as resource distribution and abundance, and population sizes of groups and their distribution; “history” (here, random factors that structure subsequent development) also plays an important role. In this model the households within a group can be expected to have only modest internal differences in power or wealth even though there may be fairly marked differences in power and wealth among the simple groups making up a complex group. We show that complex groups might become large enough to dominate an area equal in size to the area we simulate, so that pauses in conflict seen in the archaeological record of this area might be explainable by suppression of conflict within such a group.

The approach we take honors both of the pathways identified by Hobbes 350 years ago by which sociopolitical complexity may increase. He believed that our basic human motivation to

acquire power could easily result in continual struggles for supremacy and possessions among individuals that in turn lead to a “solitary, poor, nasty, brutish, and short” existence in the chaos of individuals freely exercising their Natural Rights in close proximity. But of course we have not been willing victims of these circumstances. We can escape them, Hobbes said, by abdicating a portion of our individual rights to a sovereign power (Leviathan)—a “man, or ... assembly of men”—“that he may use the strength and means of them all, as he shall think expedient, for their peace and common defense” (Hobbes [1651]1957:112):

The attaining to this sovereign power, is by two ways. One, by natural force; as when a man maketh his children, to submit themselves, and their children to his government, as being able to destroy them if they refuse; or by war subdueth his enemies to his will, giving them their lives on that condition. The other, is when men agree amongst themselves, to submit to some man, or assembly of men, voluntarily, on confidence to be protected by him against all others. This latter, may be called a political commonwealth, or commonwealth by *institution*; and the former, a commonwealth by *acquisition* (1957:112-113).

Hobbes’ two alternatives for the emergence of leaders continue to structure debate in both political theory and anthropology on how sociopolitical complexity may increase. Conflict theorists (e.g., Carneiro 1970) emphasize pathways in which hierarchy is imposed. Managerial elites—voluntarily supported for the good works they achieve—are envisioned by more functionally minded scholars (e.g., Johnson 1978).

These two competing positions have been able to survive only because there is some support for each. We regard the emergence of political hierarchy as a process in which voluntaristic, small-scale “commonwealths by institution” (simple hierarchical groups) may become nested within larger-scale “commonwealths by acquisition” with the formation of

complex groups. This happens as simple groups grow in population and come into competition with other groups of similar scale. Simple groups with no leaders, however, are limited in size by their inability to coordinate their activities. Thus through time, the largest groups in the model may be, first, simple non-hierarchical groups, but as group and regional populations grow, simple groups with leaders gain an advantage, and displace many of the simple non-hierarchical groups. Eventually, simple hierarchical groups come into conflict with each other, and, typically, larger groups subsume smaller groups by force or negotiation, forming complex groups composed of two or more simple groups.

The model we propose assumes that individuals have long ago found ways to cooperate within families (households). Simple groups, internally united in our model by ties of kinship and possibly success in provisioning public goods, are allowed to grow until they encounter a numeric threshold (our `GROUP_SIZE` parameter) that corresponds, notionally, to the approximate scale of a clan or a small group of related clans (phratry). That these groups are fairly small is no accident. One of the original formulators of public goods theory, Mancur Olson, noted that small groups will deliver optimal amounts of a collective good better than large groups (1971:35). If a group is so large that each individual's actions do not make a noticeable contribution to the group, Olson argued that an individual will have no incentive to contribute unless there are "selective" positive or negative incentives (1971:50-51). Thus the simple leaderless groups we model are fairly small, with further growth only made possible by the action of leaders who (1) provide selective negative incentives against those who fail to cooperate, and thereby (2) allow for a positive return to group size through repeated collective action.

Rates for the cooperative and competitive processes in the model (and, we believe, in the world) are spatially and temporally variable, depending on the underlying productivity of the

landscapes in which they are embedded, as well as the spatial, demographic, and organizational characteristics of groups. Moreover, these processes have an inevitable historical dimension (path dependency), given their evolutionary character (in which future actions are partially conditioned by present circumstances) and some randomness in various processes.

Any attempt to endogenize rates of population growth and productivity, as we do here, must begin with realistic modeling of resource landscapes. We implement a model of self-regarding households interacting over these resources within the model for group formation and evolution described below. This mode of inquiry minimizes traditional concerns such as “do social relations prevail over technological and environmental considerations, or do these latter ‘ecological’ domains pose primary constraints on the evolution of political systems and social structures?” (Upham 1990:9). Instead we are able to ask, “how do social and ecological dynamics interact in the evolution of political systems?”

Another classic concern that we implicitly address with this approach is the notion of resistance: how is the natural reluctance of people to give up their political autonomy (or to contribute to the public good) overcome (or minimized) in increasingly hierarchical groups? The groups we model are made up of actors with differing inherited proclivities for degrees of pro-social vs. self-regarding action. The variable success of these differing strategies through time is determined by running the model, not by decisions we make in advance of the modeling, though our choices of plausible parameter values (especially for the public goods game) do influence the success of the various strategies. We propose that many such classic dilemmas of sociopolitical theorizing will dissolve as specific historical instances are modeled with adequate endogenization. Is it resource stress, or resource abundance, that is most likely to lead to institutionalized inequality? Are polities inherently born of conflict or cooperation? Which came first: control over resources, or social power? Many such questions turn out to be co-

evolutionary in nature, and small initial differences may be magnified by non-linear interactions to become eventually substantial.

The project of understanding the evolution of leadership continued here (begun in Hooper et al. 2010 and Kohler et al. 2012) starts from the construction of models that are ethnographically plausible and internally coherent. But, as Gould and Lewontin (1979:259) point out, “[p]lausible stories can always be told. The key to historical research lies in devising criteria to identify proper explanations among the substantial set of plausible pathways...”. In the deductive approach advocated here, “proper explanations” are those that are not just ethnographically plausible and internally coherent, but fit the largest possible array of data from the archaeological record we are attempting to model. This requirement encourages us to build models of change for particular portions of time and space, since, even though the models may be general, our evaluation of their goodness-of-fit requires they represent some known partition of space and time. The model in this chapter is implemented on an 1800-sq-km landscape resembling that of Southwest Colorado from A.D. 600–1280, described by Ortman et al. (2012). This is also called the Village Ecodynamics Project (VEP) I area.

What do we Mean by Sociopolitical Complexity?

“Complexity” is an unfortunate term because its inversion is “simplicity,” but no known society of *H. sapiens* is (or has ever been) simple: “The notion of complexity in anthropology makes sense only in making typological distinctions of scale and hierarchies of decision making, not with regard to the number of interactions or relationships among constituent agents or groups in a society” (Clark 2002). Nor are even small-scale human groups completely egalitarian, since they typically support socially defined distinctions along the lines of age, gender, size and ability, and kinship (Feinman 1995:256-257; von Rueden et al. 2014; Wiessner 2002:251). The

landscape in which “the road to inequality” begins is thus strewn with abundant raw materials useful (to some) for later exchanges and elaborations.

As Drennan and Peterson (2012) point out, the processes of sociopolitical evolution have been variable enough that it is difficult to agree on a general definition that adequately describes the available cases. With reference to the middle-range societies in the US Southwest that concern us here, Lightfoot and Upham (1989) defined sociopolitical complexity as including the development of hierarchical decision-making organizations, the presence of status differentiation, and the rise of inequality that limits access to economic resources and ritual information. Of course, any one of these features can be criticized. Netting (1990), for example, has demonstrated that the last character may be present among intensive cultivators in acephalous communities, and Braun (1990) notes that some delegation of authority occurs in nonhierarchical communities. Clearly it is easier to define processes of *increasing* sociopolitical and demographic scale in specific historical trajectories, as we do here, than to define invariants across cultural traditions and regions.

Recent Approaches to Understanding Emergence of Leadership

North American archaeologists in the last third of the 20th century were primarily concerned with correctly identifying complexity when they saw it, and in weighing the general role of factors such as craft specialization, sedentism, storage, long-distance exchange, population increase, and so forth in causing sociopolitical change toward greater economic or social inequality and more hierarchy in decision making (e.g., Plog 1990). Although many of these researchers criticized aspects of mid-century neo-evolutionary syntheses, on the whole, there was considerable continuity with the way the problem of sociopolitical evolution was conceptualized and addressed. Rosenberg (2009:24) has characterized the dominant approach as “progressive transformationalism.”

Some recent treatments of these issues, however, propose a radical break with this tradition via construction of formal models that focus on—

- how within-group cooperation can be achieved and maintained (known in the political science literature as the collective-action problem) given a rational-actor model. The importance of punishment in particular is becoming more obvious (Boyd and Richerson 1992), and not just within human groups. Flack et al. (2013) show that punishment is key to within-group cohesion in groups of pigtailed macaques, and that suppressing policing mechanisms destabilizes social networks;
- explicit treatment of group size and the structure of the meta-population in which groups reside and interact;
- inter-group competition and conflict (rarely mentioned by southwestern archaeologists until the mid-1990s, though see Lightfoot and Upham 1989);
- evolutionary dynamics, often employing outcomes from strategic games to drive them; see Stanish (2009) for a discussion of game theory in relation to sociopolitical evolution;
- an appreciation that hierarchy may confer advantages within groups for coordination or efficiencies in information transmission, and may be able spread, even in the absence of information effects, via demographic effects resulting from uncoupling resource availability from reproduction (Rogers et al. 2011). Researchers have also suggested that hierarchies help reduce environmental uncertainty (Flack et al. 2013);
- suggestions from numerous quarters that human social systems may become more complex in a variety of ways that do not necessarily involve greatly increased centralization and hierarchy (e.g., Mezza-Garcia et al. 2014 and references therein);
- the general rise of a complex adaptive systems perspective (Holland 2014; Kohler 2012a), with its attention to emergent properties and institutions (leadership, for example) whose description and analysis typically involves tools such as agent-based

modeling alongside traditional analytical approaches. At their best, these approaches bring in “big picture” considerations frequently missing in post-neo-evolutionary applications of evolutionary theory by archaeologists (Bettinger 2009) while honoring the micro-evolutionary processes on which such archaeologists have focused.

These discussions have become coupled with a concern for understanding how prosocial tendencies (such as a willingness to die for one’s group) could have evolved, on longer time scales, from a population of self-regarding individuals.

A review of this large and rapidly proliferating literature is well beyond the scope of this chapter. We are heavily influenced by these new directions, however, so it is essential to very briefly mention a few of these inspirations explicitly. These serve as design requirements that our model must honor to move the field forward:

1. Many small-scale human groups may be sufficiently stable and strongly enough differentiated from other groups, genetically or culturally, to support group selection (Henrich 2004). Contrasting selection pressures may thus act on the level of the individual and the group; for example, “selfishness beats altruism within groups. Altruistic groups beat selfish groups” (Wilson and Wilson 2007:335). Between-group competition is a main motor for increased social complexity and inequality (Flannery and Marcus 2012:473).
2. The first steps towards hierarchy and power inequalities must be very small and acceptable within a tradition of egalitarianism typical of small-scale societies. Clearly this must involve voluntary participation that benefits everyone in the group in some way. Rosenberg (2009:37-40; see also Feinman 1995:263) has suggested that internal peace-keeping (conflict resolution) provides a legitimate, “primitive,” general social role meeting this requirement. Explanations considering the local contexts in which

leadership first becomes evident in the archaeological record referenced in our model (Pueblo I villages, mid-to-late AD 700s) have suggested that lineage heads could have met an “original social purpose for leadership” by organizing the increasingly long-distance hunts required to return deer to the villages in an increasingly game-depressed landscape (Kohler and Reed 2011), and distributing the returns in a fair manner (i.e. conflict prevention).

3. Defense or predation (on other groups), notes Bowles (2009:1294; see also Turchin and Gavrillets 2009:169), is a public good, conferring advantages on groups at a cost to the participants. “Warfare is a [particularly] high-stakes form of cooperation” (Mathew and Boyd 2013: 58). Although the altruist as warrior is paradigmatic, a “willingness to take mortal risks as a fighter is not the only form of altruism that contributes to prevailing in intergroup contests; more altruistic and hence more cooperative groups may be more productive and sustain healthier, stronger, or more numerous members, for example, or make more effective use of information” (Bowles 2009:1294).

Taking these points into account, a useful model must (1) support a multi-level selection dynamic in which social strategies within groups can evolve; (2) build complexity from a starting point of voluntary participation, naturally modeled as a public-goods game; (3) allow for policing/punishment to maintain within-group cooperation until such point as (4) between-group competition, including conflict, allows leadership (or groups with leaders) to take on more coercive properties. Finally, it is desirable to implement the approach in a specific environment in which we explicitly evaluate the realism of the dynamics generated by the simulations. In our case this environment is spatially and temporally heterogeneous, leading us to employ agent-based models instead of formal analytical (“closed-form”) models.

A Verbal Description of the Model

The Base Autonomous-Household-Ecology Model¹

The simulation begins in “AD 600” by randomly seeding 200 households on a virtual landscape which we have endowed, to the best of our ability, with realistic levels of four resources (water, woody fuels, three species of huntable prey, and potential maize fields) whose spatial distribution varies according to edaphic factors and whose temporal distribution varies in accordance with tree-ring-proxied climates in our study area (Johnson and Kohler 2012; Kohler 2012b; Kolm and Smith 2012). Household activities for this base-level model (referred to as “Village” and described by Kohler 2012c) are incorporated in the current simulation. In brief, households myopically and approximately minimize their caloric costs for obtaining adequate supplies of all these resources through central-place foraging, prey switching, labor intensification, and household relocation, as befits their local circumstances and possibilities.

We track household composition (number of members, sexes, and ages), and household requirements scale according to size. Households move on formation, and also when their current location becomes untenable because of declining resource yields or growing household size. Since a number of households initially land in poor areas, a decrease in household number in the first 3-4 years of the simulation is typical. In the simulations reported here, we allow households to engage in time-delayed reciprocal exchanges of maize for maize and meat for meat, both with close kin (“generalized reciprocity”) and near neighbors of good standing (“balanced reciprocity”) (Crabtree 2015; Kobti 2012). Suppressing exchange would slightly decrease global household numbers and degree of aggregation in the simulations (Crabtree 2015).

Evolutionary Public Goods Game

¹ A Swarm implementation of an earlier version of this model is deposited in OpenABM (www.openabm.org/model/2518/version/2/view).

While retaining all the behaviors represented in the base simulation, we add a number of features enabling us to grow groups and leaders. Inspired by Hooper et al. (2010), we instantiate 3 social strategies typifying individuals who prefer to live in non-hierarchical groups, and 8 social strategies typifying agents willing to live in hierarchical groups (Table 1). Initially these strategies are randomly distributed among the members of each household, but as new households are formed (via marriage of a daughter) the new household assumes the social strategy of the wife's mother if she is alive; otherwise they take on the preferences of the wife's father.

Once a year all households play a public-goods game within their group. In the general game, households put a certain amount of a resource (maize in our case) into a public fund. The amount in this fund is multiplied by a factor representing the return on the public good, and then is redistributed equally to all group members (we call this augmented amount the *benefit* of the public good). If all households contribute to the public good, each gets a good return on its investment. If just a few households in a group do not contribute, those defectors not only keep what they should have donated, but share in the return accruing to each household in the group. Thus each household has a temptation to defect. Unfortunately, in fact, the unique Nash equilibrium is for all households to defect (Capraro 2013:5). Non-hierarchical groups may contain one or more “mutual monitors” who monitor and punish defectors at some cost to itself (Table 1). Hierarchical groups will contain a leader who fulfills these same functions and who is reimbursed through a tax. Such leaders can very roughly be conceptualized as “big men” with no coercive power except within the limited domain where the group voluntarily grants it. Members of hierarchical groups must pay this tax *and* contribute to the public good. Obviously, the hierarchical preference will thrive only when the tax and contribution to the public good is less than the return on that good. In the model, and we believe in the world, getting viable rewards from the public goods game requires close vigilance and occasional punishment.

Households can exist in three states: 2 (thriving), 1 (just getting by), and 0 (perishing). The default value for state is 2, but this gets lowered to 1 if the current maize in storage is less than that needed for the current year plus that expected to be needed for the following year *or* if the maize just harvested is less than next year's anticipated needs. Households in state 1 reproduce according to a life table that provides for an approximately stable global population.

We define a parameter "STATE_GOOD" that determines the degree to which natality and mortality are affected by the household's state. When STATE_GOOD = 1—the value we apply here—the probabilities of giving birth are incremented by 10% for women in a household in state 2 (from probabilities in an empirically-derived life-table; Kohler 2012c:68; Weiss 1973:156), and the probabilities of dying are decremented by 10% for members of that household. A household's hierarchical preference and strategy for playing the public goods game affects its maize storage and perhaps its state, and may therefore increase, or decrease, its relative number of offspring, who inherit the parent's strategy, providing a slow evolutionary dynamic to strategy change in the population. Optionally, but implemented here, we define a faster social learning dynamic in which agents emulate the propensity of the "richest" household (that with the most storage) to work in a hierarchical setting, though not its other behaviors related to the public-goods game. This is a model of indirect bias as defined by Boyd and Richerson (1985:241–259).

Up to this point, the model corresponds to that implemented and analyzed by Kohler et al. (2012). Among other findings, Kohler et al. (2012) reported that most households preferred to live in nonhierarchical groups initially, but as those groups grow in size (which happens first in the most productive regions), "mutual monitors"—who begin to pay more for these activities than they receive as their share in the public good—are at a competitive disadvantage compared to other agent types, and decline in frequency. As this happens, non-hierarchical

group members will receive less return from the public good as more and more members of their group fail to contribute, and are not punished for this failure.

Conversely, members of hierarchical groups will not do very well when their groups are small, but prosper more as they increase in size, taxes paid to support a leader insure that everyone contributes to the public good. Accordingly, hierarchical groups continue to grow in size and dominate the most productive areas. Non-hierarchical groups remain small and dominate only areas with poor production.

Four Weaknesses in the Previous Model

Kohler et al. (2012:12-24) report more details on the implementation of the public-goods game than we have space to review. Below, we describe four modifications to that model that address its main weaknesses as we see them.

First, whereas groups were formed in the earlier work by assignment of nearby households, in the work reported here households track their lineage and grow groups based on kinship. These lineages are the original “groups” in the simulation, and grow (or not) according to how well their constituent households thrive on a variable landscape (which is in part determined by the social strategies of the households). The founding households seeded on the landscape are assigned unique lineage identifiers that are inherited matrilineally by daughter households.² No new lineage identifiers are created during the simulation, nor do we model any immigration,

² We take no position here on whether the kinship system in the world we model is unilineal, and if so, whether it employed a matrilineal/matrilocal or patrilineal/patrilocal bias. In the model as it presently exists, this distinction between biases is somewhat irrelevant, except that in warfare, because only males die in battle, we expect a much faster pruning of patrilineal than matrilineal from the population. In the real world, however, these systems do have differing characteristics. Matrilineal societies rarely have internal warfare; they may fight as much, but their warfare tends to be external. Since even in such communities men are frequently the decision makers, they try to live close by their own kin when they move at marriage and hence matrilocal communities are rarely exogamous but tend to be formed of different kin groups (see Ember and Ember 1971).

so each surviving agent household tracks its heritage back to its founding household. As groups grow, they may fission if they reach maximal group size. This can be considered a “span of control” measure; it forms an assumption as to how big a group can become and still act as a single (simple) group. For the Hopi, Levy (1992:20) describes cases where groups exceed in size the carrying capacity of farmland, in which case extended families bud off to form new groups.

Second, a group now decides whether to be hierarchical or non-hierarchical based on the majority preference of its constituent households. In earlier simulations, groups were formed only of households with the same preferences (Kohler et al. 2012:13). This led to the strong selective dynamic noted by Hooper et al. (2010) and Kohler et al. (2012) whereby larger groups preferred hierarchical agents. Our groups are now determined by kinship, so while kin will tend to have similar preferences through inheritance, there are often groups with mixed preferences. All households have *all* behavioral preferences required to play either the hierarchical or non-hierarchical public goods game; for example, a household with a hierarchical preference may be in a non-hierarchical group, in which case its hierarchical-type preferences (willingness to be a leader, tax rate, and whether or not they are a reluctant taxpayer) will not be activated, while its non-hierarchical preferences (willingness to be a mutual monitor) will be expressed. As we discuss below, this dynamic of majority-rules play and ecologically-determined expression of preferences has a large impact on the resilience of specific—and even non-adaptive—preferences in agent populations.

Third, these groups are now territorial, in contrast to groups in the earlier simulation that could intermingle with no restrictions. Not only is there a great deal of evidence suggestive of territoriality from spatial distributions of dwellings in our study area (e.g., Reese 2014; Varien 1999), but defended claims to territory also figure prominently in most explanatory models for

sociopolitical evolution (e.g., Boone 1992; Gibson 2008; Hooper et al., this volume; Maine 1861; Smith and Choi 2007).

Fourth, we add two mechanisms—merging and fighting—by which the simple groups described above may form a complex group composed of two or more simple groups. The importance of inter-group competition in current theory has already been noted; Kohler et al. (2014) summarize and analyze evidence for violence through time in the study area referenced here. We now provide a more detail on each of these modifications.

Territoriality, Merging, and Warfare

Groups in the model are corporate: they maintain and defend claims to the core portion of their territory used for growing maize. (They do not own or defend the larger territories usually necessary to acquire other resources.) As some of the initial 200 groups prosper and grow on the landscape, a convex-hull polygon is drawn around their member households, and no other group is allowed to plant within or move into that polygon. As daughter households bud off of the original household, the polygon grows to encompass those daughter households and their fields. Currently, fields must be either in the same 200-m cell where the household resides, or in one of its 8 neighbors (its Moore neighborhood).

At the beginning of the simulation 200 households are seeded randomly on the landscape and told to move to the best available location within the `MOVE_RADIUS` parameter (here, 40 cells, or 8 km) subject to the rules governing territoriality noted above. Households then annually re-evaluate their locations and attempt to move if their anticipated needs are not likely to be met. Not all desired moves are allowed, however. Cells that are in other groups' territories, that would result in overlap of group territories, or that would require crossing another group's territory to access are disallowed. Each time a household cannot move to a cell to which it would like to move tracks the group that impeded its move. We call these "frustrations." If a

household cannot move to *any* cell that is higher ranking than its home cell, its group records this as a “frustration that hurts.” Frustrations that hurt can lead to merger or warfare. Frustrations (including those that hurt) are tracked at the group level.

When a group has a frustration that hurts, it has the opportunity to relieve frustration by tendering an offer to subsume another group as its subordinate (to “merge” and thus form a complex group), or, if that offer is rejected, to fight. Each group archives a list of groups that have frustrated it. This list is sorted according to a function that considers the distance between the two groups and the quantity of frustrations incurred. The focal group will then iterate through its frustrations, calculating its likelihood of winning a battle against each group. Specifically, the focal group will compare its likelihood of winning battle against a random number between 0 and 1. If the random number is less than its probability of winning in battle, the focal group will decide to tender an offer of merger and potentially to fight.

Let’s call the aggressing group m and the defending group n . Group m will always first tender an offer of merger. Group n will then calculate its probability of winning a potential fight (see *Warfare: Stochastic Lanchester Laws*, below); this proportion is compared against a random number between 0 and 1 as above, and group n accepts the merger if the random number is less than or equal to its own probability of winning (p_n). In that case, group n will become subordinate to group m , forming a complex group. Smaller groups are more likely to accept an offer of merger than larger groups, whereas evenly matched groups have even odds of accepting or rejecting an offer to merge. Each group can accurately estimate the size of opposing groups. Simple groups within complex groups will be able to count some warriors from their larger groups in these size estimates (see *Warfare: Stochastic Lanchester Laws*). Numerous ethnographic accounts of groups such as the Shoshone, who would occasionally group together to show their strength to an enemy (D’Azevedo 1986), or the Maori whose *Haka*

dance could allow warriors to show their strength (Ka'ai-Mahuta 2010:106) suggest that this assumption is plausible.

If group n does not accept the offer to merge, then a decision as to whether to *actually* fight is made by the group m . Group m uses the same logic presented above: it calculates the probability of winning a fight against group n (this will be $p_m = 1 - p_n$), and makes a stochastic “decision” based on that probability. Stronger aggressing groups are more likely to decide to fight (Manson and Wrangham 1991).

Should group m decide to fight, the probability of m or n winning is once again calculated (p_m , as before). The outcome of the fight is determined by probabilistically sampling the uniform distribution $[0,1]$ twice (call these d_m and d_n), and comparing each draw to p_m and p_n . If $[p_m \geq d_m \text{ AND } p_n \geq d_n]$ or $[p_m < d_m \text{ AND } p_n < d_n]$, the fight is considered a “draw”, and each group walks away from the battlefield, wounded but not entering into a complex group; otherwise, the group whose probability of winning met or exceeded its random draw will attempt to subsume the defeated group as a subordinate (see *Complex Groups and Tribute*, below).

Regardless of whether a complex group is formed, fights always generate casualties (the removal of a fighter from the battle due to injury or death), a portion of which can result in fatalities. Lanchester showed that in hand-to-hand combat, the number of casualties is approximately equal to the size of the smaller group engaging in battle (Lanchester 1916). We stochastically calculate fatalities for each group independently as a function of the minimum group size $f_{mn} = \min(f_m, f_n)$ by simulating f_{mn} coin tosses weighted by a factor s , or the probability that a casualty will result in a fatality. Thus, on average, $2sf_{mn}$ deaths will occur in any given fight between groups of sizes f_m and f_n .

To summarize, merging and fighting occurs in the following order. The focal group (1) tenders an offer of merger to the frustrating group; (2) if that offer is rejected, it decides

whether to attack the frustrating group; (3) if deciding to attack, it fights the frustrating group (suffering casualties and possibly fatalities); (4) if successful, it subsumes the frustrating group as its subordinate in a complex group, but only if the frustrating group is not already subordinate to another group.³ A complex group can only have one dominant group at a time, but can have multiple subordinate groups. We do not have an upper cap for the number of subordinate groups in a complex group; theoretically all groups in Village could be contained in one complex group, and in fact this does happen in some of the simulations presented here.

Complex Groups and Tribute

We call groups in dominant/subordinate relationships “complex groups.” They can become much larger than simple groups, but are distinctive in two other ways as well. They require their subordinate groups to pay tribute to the dominant group, and they enable some their constituent groups to call on larger pools of warriors for offense or defense.

Tribute flow is one of the defining characteristics of power in complex societies (Steponaitis 1981); in our model each subordinate group must pay a tax to its dominant group. Steponaitis proposes that degree of political centralization can be determined from the amount of tribute collected in each hierarchical level, and how that tribute flows between the levels in the hierarchy. While he considers the easiest way to measure levels of hierarchy to be the appearance of monumental architecture (which we would consider to be materialized public goods), in this simulation we model flows of tribute in maize, in keeping with Steponaitis’ estimates of comestibles and how their flow allows for growth of hierarchy. This is a stylized assumption, which is non-problematic if labor having an equivalent caloric value was the actual currency employed in our reference context.

³ It “makes sense” to attack a much smaller group, even if it already has a dominant, because it is likely to wipe some households off the landscape, thus (potentially) relieving frustrations.

Steponaitis assumes that groups consist of producers (farmers) and non-producers (administrators) and that the job of administrators in a hierarchical society is to ensure the flow of tribute. “In any settlement: (1) the number of producers is directly proportional to the annual yield of that settlement’s catchment, minus the food that is allocated as tribute; and (2) the number of non-producers is directly proportional to the amount of tribute in food to which that settlement has access” (1981:325). As more layers of hierarchy are added, administrative centers keep a portion of tribute from lower levels within the hierarchy, some or all of which is distributed along with the shares of the public good originating within that group itself. Steponaitis calculated that, generally, some 16 percent of produced comestibles was passed up the hierarchy as tribute, although the percentage could be as high as 22 in some cases. In our case it seems unlikely that 16-22 percent of individuals would be non-producers and, in fact, even leaders of hierarchical groups still farm in our simulation. Nevertheless, it seems likely that in the most complex societies in the Pueblo Southwest there was at least some tribute flow—as Mahoney and Kanter (2000:10) argue for the Chacoan system.

In the organizational scenario that Steponaitis envisions, multiple lower-level sites (whose number is limited by the “span of control” variable in Gavrillets et al. 2010) channel tribute to a higher-level site. If there are sites at a still higher-level in the hierarchy, this organization can be scaled accordingly, so that several intermediate-level sites may channel tribute to a paramount site. We note in advance that the model we simulate here is somewhat more likely to form chains of dependency more than clusters of sites at the same level channeling tribute to a single site at the next-higher level. Whether this is realistic will be discussed below.

We define β as a tax on a subordinate group’s net benefit from the public goods game, and μ as the proportion of the tribute from a subordinate group passed through an intermediate group to a dominant group ($1 - \mu$ therefore being the tax kept on that pass-through). Consider a

complex group consisting of four groups ($a \rightarrow b \rightarrow c \rightarrow d$), where arrows indicate the flow of tribute up the hierarchy from a to b , b to c , and c to d . Let H_i be the net benefit from the public goods game paid to group i , and let μ be a possible compounding factor as tribute moves up the chain. Group a will pay $\beta \cdot H_a$ to group b ; group b will pay $\beta \cdot H_b + \mu \cdot \beta \cdot H_a$ to group c ; and group c will pay $\beta \cdot H_c + \mu (\beta \cdot H_b + \mu \cdot \beta \cdot H_a)$ —this pattern will continue up the chain. More generally, the tribute, T_g , that any group g will pay to their dominant group may be calculated as a function of the benefits from the public goods game of all groups *lower* on the hierarchy than group g and their distance from group g in the hierarchy graph:

$$T_g = \beta \sum_{i=0}^n (H_i \cdot \mu^{d_i}) \quad (1)$$

where i indexes the groups in the subordinate neighborhood n of group g , including group g itself, and d_i is the graph distance between group g and group i . Here, following Gavrillets et al. (2010:64), we allow the fixed parameters of β and μ to take on values (0.1|0.5|0.9, Table 2). Gavrillets and colleagues explored values of 0.1, 0.2 and 0.3, while Steponaitis derived values of 0.16-0.22 from empirical data.

Groups also call on their directly dominant and subordinate groups (but not groups from more distant portions of the complex group) for help in both attacking other groups and in defense. As complex groups are likely to have more fighters than groups that are not in complex hierarchies, being in a complex group is beneficial because more warriors leads to a greater chance of success. When fatalities occur, dead warriors are removed randomly from among all groups participating in the fight.

Warfare: Stochastic Lanchester Laws

The models of group formation, tribute, and fighting we have described require a relevant model for the mechanics of ancient warfare to produce accurate probabilities of success for the

aggressing or defending groups. The questions of how wars are fought and battle outcomes predicted have received ample attention elsewhere (e.g., Kress and Talmor 1999). Here, we employ a set of models developed by Frederick Lanchester (Adams et al. 2003; Artelli and Deckro 2009; Kress and Talmor 1999; Lanchester 1916). Lanchester, an engineer in the British army, developed these equations to determine outcomes of air battles during World War I (Lanchester 1916) but also sought a more general description of two primary classes of warfare: “ancient” and “modern”. In ancient warfare, battles were fought primarily in one-on-one duels with similar technologies (Lanchester’s Linear Law) while in modern warfare, fighters from one team may have superior weaponry resulting in one side winning easily (Lanchester’s Square Law). Lanchester initially derived sets of differential equations describing rates of attrition from each group under each class of warfare. These equations—now called the *Deterministic Lanchester Laws*—showed that, given equal skill of individual fighters, the larger team should win any given battle (Kress and Talmor 1999 provide a mathematical overview). These equations provide a useful means for simulating casualties in models of conflict (see, for example, Turchin and Gavrillets 2009). However, the Deterministic Lanchester Laws present a problem as, intuitively, we know that a smaller group must have *some* chance of winning a battle, and that its chances of winning are enhanced as the size of their forces approaches that of their enemy.

Therefore we employ probabilistic modifications of Lanchester’s Linear Law—the *Stochastic Lanchester Linear Law*—to derive the probability that a given battle will be won by a given group, following the description and formula presented by Kress and Talmor (1999). Imagine two groups (m and n) arrive at a duel-style battle (an “ancient” battle in Lanchester’s estimation). Fighters on both teams possess a certain level of skill (α_m, α_n) , such that a fighter with twice as much skill as its opponent will have twice the chance of winning a duel than if they were evenly matched. Each team also has an acceptable level of *attrition* (m_0, n_0) , or

number of casualties they are willing to endure before ceding the battle. At any given point in the battle, the number of concurrent duels in progress is equal to the minimum of the number of surviving fighters on each side. Duels take place between individuals with outcomes dependent on relative fighting skill. A new opponent from the opposing team soon thereafter meets the winner of each duel, if one is available. Fighting continues until the team with a lower attrition threshold reaches their attrition level. Thus, the probability of m winning a battle (P_m) is a function of each team's attrition thresholds and the relative strength of the fighters—the probability that team n will reach its attrition threshold before team m .

Formally, the probability that team m will win a battle may be represented as:

$$P_m = \left(\frac{1}{\alpha + 1}\right)^{n_0} \sum_{i=0}^{m_0-1} \binom{n_0 - 1 + i}{n_0 - 1} \cdot \left(\frac{\alpha}{\alpha + 1}\right)^i$$

where $\alpha = \frac{\alpha_n}{\alpha_m}$, and the rest of the variables are as above. Clearly, $P_n = 1 - P_m$. In all of the simulations reported here, we assume the skill of the fighters to be even ($\alpha = 1$), and that battles will be fought until annihilation (i.e., m_0 and n_0 are equal to the sizes of groups m and n , respectively).

Of course, it should be noted that with few exceptions ancient warfare was in practice *not highly lethal*. That is not to say that violent conflict did not result in deaths—as Keeley states, “adult males who fell into the hands of their enemies were usually immediately dispatched” (1996:83)—but that in non-state warfare, fighting usually ceased once a group suffered a relatively small number of fatalities (Keeley 1996:91). According to Keeley, “given a high frequency of warfare ... no small group could afford to accept losses in battle exceeding 2 percent” (1996:91). Here, instead of setting attrition thresholds to such low numbers, we test the impact of different fatality rates on our simulated populations by defining a parameter s

(0.02|0.05, Table 2) to represent the acceptable proportion of fatalities to the total expected in a war of attrition (i.e., a proportion of the size of the smaller group, or sf_{mn} as above). An alternative approach might be to explore different attrition thresholds for each group, perhaps as a proportion of population, or even to “evolve” attrition threshold preferences given group experiences.

Results

What are the effects of these specifications in the long run? We ran a sweep defined by the parameters in Tables 1-3, searching the small space of possibilities defined by the changing parameter values in Table 2. Where applicable we contrast three kinds of runs: those with territorial groups engaging in merging and fighting; those with territorial groups but no merging or fighting; and those with no group structure, merging, or fighting. The runs with no group structure, merging or fighting instantiate “Village” as described by Kohler (2012c); the other two run types add dynamics described here for the first time. Videos of the tribute structure, group size, and group-type dynamics for each run are available at <http://village.anth.wsu.edu/BH/>. Simulation output is archived at Washington State University.

Population Size

Figure 1 shows that the base autonomous-household-ecology model (Village) generates fewer households through time on average than do the other run types. The lack of constraints on movement enjoyed by Village households is more than balanced by the benefits received from playing the public goods game in the other two run types. The “Groups Only” models produce the most households because these benefits are not partially undone by mortality from warfare. (As an aside, it is likely that warfare reduces population more in our model than it would in real populations, since it creates a sex imbalance [only males die in warfare] that is not compensated by polygyny, as it might be in reality.) Considering just the runs with fighting and

merging, none of the parameters listed in Table 2 has a significant effect on numbers of households through time, although higher levels of μ (proportion of the tribute from a subordinate group passed through an intermediate group to a dominant group) and lower levels of β (tax on a subordinate group's net benefit from the public goods game) are weakly associated with higher populations. We were surprised that choice of s did not significantly affect population size. These results are likely influenced by the high degrees of path dependence that we discuss next.

Path Dependence

In most cases we performed only one run for each combination of parameters. However, we also experimented with three runs, one for each run type, duplicating parameter combinations while using different random number streams. Total populations through time for these duplicate runs are shown by run type in Figure 2 and the difference between the two duplicates is shaded in each case.

By far the least path dependence is found in the base autonomous-household-ecology model. These two runs do not diverge noticeably through time. Much more path dependence is visible in the two groups-only runs, with even more produced by the duplicated runs with both groups and warfare/merging. Variability between duplicate runs of both types increases markedly around AD 1000. We can infer that around this time households become numerous enough that the processes involving territoriality and merging/warfare introduced in these models begin to have a marked effect.

This result has two implications. First, with respect to our methods, it suggests that we will need to perform many simulations for each combination of parameters to be able to differentiate the effects of parameter choices and the effects of path dependence: our conclusions here with respect to the effects of parameter choice must be regarded as tentative

and exploratory. Second, as we will briefly argue below, these results have ramifications for our understanding of the relative importance of history and process in the analysis of historical systems, and how we approach this issue.

Lineage Survival Through Time

Not surprisingly, the three runs with groups but no fighting or merging tend to have a higher number of surviving lineages ($\bar{x}=32, \sigma=1$) than do the 37 runs with groups that fight and merge ($\bar{x}=26.3, \sigma=3.7$), although both outcomes represent a radical decrease from the initial 200 lineages. Considering just the runs with fighting and merging, lower values for Group_size (50 vs. 100) significantly increase the number of surviving lineages ($p = 0.02$), perhaps because the greater number of groups that bud off when the span of control parameter is lower allow lineages to spread and diversify their spatial holdings. Lower values for s have an almost significant effect on increasing the number of surviving lineages ($p=0.12$), presumably since these lower values decrease the possibility for extinction via warfare.

Group Types Through Time

Figure 3 shows the number of (simple) groups with hierarchical vs. non-hierarchical preferences through time. Not surprisingly, the three runs with groups but no fighting or merging produce far more groups by the end of the simulation ($\bar{x}=252, \sigma=47.8$) than do the 37 runs with groups, fighting, and merging ($\bar{x}=150.5, \sigma=57.4$). Although one might predict that fighting would increase the proportion of groups that are hierarchical, the proportion of hierarchical groups is similar for groups with no fighting or merging ($\bar{x}=0.39, \sigma=0.1$) and for groups with fighting and merging ($\bar{x}=0.36, \sigma=0.1$).

Complex groups, of course, can be produced only with fighting and merging. By the end of the simulation the 37 runs with fighting and merging have an average of only 2.1 complex

groups each ($\sigma=0.9$). None of the parameters varied here has a significant effect on this outcome. At year 1299 (the end of the simulation) the average number of simple groups in each complex group is 117.8 ($\sigma=64.8$). Figure 4 shows the proportion of groups through time in the largest complex group and demonstrates that this measure of concentration can wax and wane over the course of a simulation. None of the parameters varied in these runs has a significant effect on the proportion of simple groups in the largest complex group in year 1299 ($\bar{x}=0.75$, $\sigma=0.19$), although lower values of β are weakly associated with higher proportions ($p=0.41$), probably because lower values of β (the tax on the net benefit from the public goods game) increase the survival of subordinate groups in complex groups.

Effects of Warfare and Merging on Agent Types

Compared with the results in Kohler et al. (2012), in most runs a surprising number of households end up in non-hierarchical groups (Figure 5). This is partially due to the group fissioning dynamic we implement here. Single households on the periphery of a group that has reached its maximum size will “bud off” from the parent group to start their own groups. These new groups are very often non-hierarchical (or become so quickly), and in many of the runs reported here these small groups proliferate on the landscape and rarely grow to be very large as they are almost immediately coerced into merging and paying tribute to larger groups around themselves. These small groups may also simply have no room to grow.

Figure 6 displays the population-level distribution of agent types through time in runs with (top) and without (bottom) fighting/merging. Once again, there is surprisingly little difference between the two run types, suggesting that this model does not adequately represent the conditions under which group selection for pro-sociality is expected; non-hierarchical (i.e., non-cooperative) types are also surprisingly numerous in almost all runs, a result radically different from those presented by Hooper et al. (2010) and Kohler and colleagues (2012). As noted

above, the key difference between those earlier efforts and the simulations presented here is that here groups are formed from kin relations, and that the *type* of group (hierarchical versus non-hierarchical) is determined by majority rule—all members of each group play the public goods game by the dominant preference. This allows minority preferences to be *insulated* from selection when selection is acting at the group level as in our models. Non-hierarchical reluctant taxpayers and reluctant cooperators are unable to exercise their preferences when they are in the minority, but because they are forced to play the majority's position, they never feel the pain of playing their own preferences. Thus, their preferences are never selected against. In a group-selection scenario, these preferences (“non-adaptive” in circumstances of dense populations and high intergroup conflict) are able to piggyback on the more-adaptive preferences of the majority. Furthermore, there is little to no pressure to change one's preferred strategy. Minority-preference individuals receive the benefit of playing the majority's rules, but may continue “believing” that if their own preference were in the majority they would achieve more success. It is also the case that high amounts of tribute flow can overcome the negative effects of being in a large non-hierarchical group; groups at the top of a hierarchy receiving large amounts of tribute are less likely to feel the negative effects of what would be maladaptive behaviors were they not able to rely on the productivity of their subordinate groups. Finally, because these groups are spatially constrained they are somewhat insulated from information about the success of other strategies that might persuade them to change their minds—most nearby agents are in their own group and thus will be performing equally as well or as poorly as themselves, giving them little cause to change their preference via social learning.

These observations challenge the notion that larger group sizes must select for prosocial preferences among individuals; a majority rule allows for the persistence of non-adaptive *preferences* among individuals so long as they are the minority. These traits are therefore

maintained in populations and are readily available (and appropriate) when small groups fission from a parent group and non-hierarchical preferences result in higher returns.

Realism (Validation)

It is premature to fully evaluate the goodness-of-fit between these simulations and their reference context at this exploratory stage, but for illustrative purposes we put a measure of similarity in the rightmost column of Table 2 between the warfare histories and demographic histories of those runs with fighting and merging, and the reference context. For each series (warfare and demography), we first took the mean across each of 14 periods for which we have accurate reference data (derived from Varien et al. 2007 and Kohler et al. 2014), and then calculated the Euclidean distance between each simulated run and the reference. We standardized each series of distances independently to have a mean of zero and a standard deviation of one, then took the average of the standard distances, so that similarity in the time series of population and warfare are weighted equally. To reflect similarity (as opposed to dissimilarity indicated by Euclidean distance), we negated each mean standardized distance.

None of the parameters is significantly associated with this measure of fit, though there is a very weak tendency ($p=0.48$) for the higher level of s to be associated with better fits. The best-fitting run, 22, was produced by setting $s=0.05$, $\text{Group_size}=50$, $\mu=0.5$, and $\beta=0.9$ (Table 2). The conflict series generated by Run 22 is shown in Figure 7. We emphasize, though, that another run with the same parameters but a different random number series would generate a sequence that is somewhat and possibly even substantially different.

Discussion and Conclusions

This chapter illustrates how we can begin to move beyond verbal models—with their convenient ambiguity—that have dominated archaeological discourse on the processes by

which sociopolitical scale increases, to proof-of-concept computational models that unambiguously illustrate the consequences of specific models for sociopolitical evolution through time. Such models show what large-scale patterns emerge from clearly specified micro-scale processes. We do not have to ignore one level to study the other, and indeed we must not.

We should not assume that the complex groups modeled here are historically correct. The better question is: in what ways they do seem to be approximately correct for this reference setting, and in what ways they could be improved? On the empirical side, we should ask what we would expect to see in the archaeological record were these models approximately correct. These lines of inquiry will be pursued elsewhere, by us and by others.

One result of specific culture-historical interest is that if the model *does* reflect sociopolitical processes approximately correctly, it is plausible to conclude that the entire VEP I area could have consisted of a single polity by the latter portions of the sequence, if we are willing to consider the somewhat loose webs of dependencies and taxation flow we model across groups as forming polities. This possibility has also been suggested by the surprising cessation of violence as reconstructed from trauma to human bone in the late AD 1100s and early-to-mid 1200s (e.g., Kohler and Varien 2010). The present model suggests that political entities of this scale are indeed plausible for this period.

As with any model, we should also be careful to avoid misplaced concreteness in our interpretations. Some southwestern archaeologists who might be skeptical of “polities” in this record might be willing to entertain the possibility that what we have modeled is the emergence of networks of ceremonial dependencies and obligations, for example centered on great kivas. Ceremonial practices and obligations in these (and many other mid-range) societies do seem to entail what might be considered political relations, and what we have called “leaders” here can possibly be conceptualized as leadership offices variably including priests, clowns, and other

“officials.” To explore this interpretation of the model we need to analyze the empirical record through time to determine the number and spatial distribution of great kivas (for example), their size hierarchy and relation to population aggregates, and the prehistory of sodalities and religious offices (see Ware 2014 for a good start).

For either the “ceremonial” or the “political” interpretation of this model we also need to characterize the quantitative structure of the hierarchical branching networks, or “Horton orders,” describing regularities in the scaling relations as we move from individuals, households, extended households, roomblocks, villages of multiple roomblocks, groups of villages, and perhaps higher orders. This is feasible for areas such as Mesa Verde National Park where we have virtually complete survey. This exercise would assist on two fronts, since it should help estimate appropriate measures of span of control for the model, and should help assess the realism of the *other* processes assumed by the model, once those estimates are correctly specified in the model. Examples for these sorts of analysis can be found in Grove (2011), Hamilton et al. (2007) and Rodriguez-Iturbe and Rinaldo (1997).

More generally, it is intriguing to consider the contributions of various processes and constraints to the high degrees of path dependence in the “histories” simulated here. The base autonomous-household-ecology model exhibits little path dependence (Kohler 2012c:71 and above). The addition of group-level territoriality considerably increases path dependence, since it introduces significant constraints on household movement that depend on who controlled a particular patch of land previously, and that prevent households from achieving an ideal free distribution. The addition of conflict and merging introduces a number of additional probabilistic processes that deeply affect subsequent sizes of groups, their locations, and the prominence and timing of conflict. (Modeling revenge as an additional motive for conflict would introduce even more path dependence.)

A core ambition for all historical social scientists is to weigh the relative importance of history and process. Modeling appears to be the only rigorous way to eventually move beyond vacuous statements such as “history matters” to study the *precise* ways in which history matters, and how much. Our results here seem to suggest that the one-off run of history we see in any specific prehistoric sequence may indeed be exceptional, and if the “tape of life” were to be rewound and replayed that history would not create the same record twice. If correct, this suggests limits on our ability to retrodict (or explain) outcomes from analysis of the processes that affect structure, and suggests that apparently random factors early in an historical sequence cannot be ignored. From the point of view of the players in the historical drama, it suggests that they may experience “lock in” to specific trajectories that may ultimately prove to be inefficient (Arthur 1994; Hegmon submitted; Pierson 2000).

Another general issue raised by our approach is whether “complex groups” as modeled here would tend to become chiefdoms under other conditions, and if so, what would those be. Are “complex groups” a temporary halfway house between tribes and chiefdoms, or a relatively stable organizational system that we ought to be looking for in other areas? They bear some resemblance to the “intergroup collectivity” described by Newman (1957; Johnson and Earle 1987:165-171) for the Northwest Coast, except that in our model the hierarchical groups headed by “Big Men” are explicitly ranked relative to each other if they are in the same complex group. Our intuition is that rather small changes in the model, for example allowing leaders in groups at the top of complex groups to accumulate storage and use that to manipulate labor and obligations, would generate a system recognizably similar to a chiefdom, and perhaps such changes would result in structures more reflective of the political reality in the VEP I area during the Chaco hegemony—though the organization of that system remains controversial. There is obviously much to be done to construct models that adequately represent the

processes of social construction in historical political systems, but the way forward is becoming increasingly clear.

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Table 1. Agent types and approximate payoffs related to their participation in the public-goods game. Payoffs are approximate since it cannot be known in general whether reluctant cooperators (in both group types) or reluctant taxpayers (in the hierarchically inclined groups) will need to be punished in any given year. Payoffs to leaders refer to agents actually acting as leaders; potential (latent) leaders receive payoffs appropriate to their actions as regular members of their hierarchical group. When agents are non-hierarchically inclined p = fraction of pure cooperators; q = fraction of monitors; r = fraction of reluctant cooperators; $p + q + r = 1$. When agents are hierarchically inclined u = fraction of pure cooperators; v = fraction of willing taxpayers; y = fraction of individuals willing to lead. From Kohler et al. (2012), modified from Hooper et al. (2010).

| Type | Approximate Payoffs |
|--|---|
| NH.ALLC (non-hierarchic, always cooperate) | $V(\text{ALLC} p, q, r) = (1 + (p + q + Qr)(n - 1))b / (n - c)$ where Q represents probability that at least one other member of the group is a monitor ($Q = 1 - (1 - q)^{n-1}$). |
| NH.MM (non-hierarchic, mutual monitor) | $V(\text{MM} p, q, r) = [(1 + (p + q + r)(n - 1))b / (n - c - c_m(n - 1))] - rc_s(n - 1)$ |
| NH.RC (non-hierarchic, reluctant cooperator) | $V(\text{RC} p, q, r) = [(Q + (p + q + Qr)(n - 1))b / (n - Qc)] - sq(n - 1)$ |
| H.ALLC.T.L (hierarchical, always cooperate, taxpayer, leader) | $V(L u,v) = uvtn - c_m n - (1 - u)c_s n - (1 - v)\hat{c}_s n + (tb - c_m)n$ |
| H.ALLC.T.UL (hierarchical, always cooperate, taxpayer, not leader) | $V(\text{H.ALLC.T} u, v) = [1 + u(n - 1)](1 - t)b / n - c + [(1 - t)b - c]$ |
| H.ALLC.RT.L (hierarchical, always cooperate, reluctant taxpayer, leader) | Same as for H.ALLC.T.L |
| H.ALLC.RT.UL (hierarchical, always cooperate, reluctant taxpayer, not leader) | $V(\text{H.ALLC.RT} u, v) = [1 + u(n - 1)]b / n - c - \hat{s} + [(1 - t)b - c]$ |
| H.RC.T.L (hierarchical, reluctant cooperator, taxpayer, leader) | Same as for H.ALLC.T.L. |
| H.RC.T.UL (hierarchical, reluctant cooperator, taxpayer, not leader) | $V(\text{H.RC.T} u, v) = u(n - 1)(1 - t)b / n - s + [(1 - t)b - c]$ |
| H.RC.RT.L (hierarchical, reluctant cooperator, reluctant taxpayer, leader) | Same as for H.ALLC.T.L |
| H.RC.RT.UL (hierarchical, reluctant cooperator, reluctant taxpayer, not leader) | $V(\text{H.RC.RT} u, v) = u(n - 1)b / n - s - \hat{s} + [(1 - t)b - c]$ |

Table 2. Parameters varied in this study. Run 39 duplicates run 38, and run 42 duplicates run 41, except for the random number streams they sample. Standard fit is calculated as the negated mean of the standardized Euclidean distances in population and warfare between each run and the empirical record. The highest standard fit (in bold) indicates the best-fit run.

| Run | S^a | Group Size ^b | μ^c | β^d | Type | Standard Fit |
|-----|-------|-------------------------|---------|-----------|----------|--------------|
| 1 | 0.02 | 50 | 0.1 | 0.1 | Warfare | 0.331 |
| 2 | 0.05 | 50 | 0.1 | 0.1 | Warfare | 0.576 |
| 3 | 0.02 | 100 | 0.1 | 0.1 | Warfare | -0.148 |
| 4 | 0.05 | 100 | 0.1 | 0.1 | Warfare | 0.084 |
| 5 | 0.02 | 50 | 0.1 | 0.5 | Warfare | -2.666 |
| 6 | 0.05 | 50 | 0.1 | 0.5 | Warfare | -0.271 |
| 7 | 0.02 | 100 | 0.1 | 0.5 | Warfare | 0.327 |
| 8 | 0.05 | 100 | 0.1 | 0.5 | Warfare | 0.117 |
| 9 | 0.02 | 50 | 0.1 | 0.9 | Warfare | 0.353 |
| 10 | 0.05 | 50 | 0.1 | 0.9 | Warfare | 0.026 |
| 11 | 0.02 | 100 | 0.1 | 0.9 | Warfare | -0.183 |
| 12 | 0.05 | 100 | 0.1 | 0.9 | Warfare | 0.585 |
| 13 | 0.02 | 50 | 0.5 | 0.1 | Warfare | 0.056 |
| 14 | 0.05 | 50 | 0.5 | 0.1 | Warfare | 0.443 |
| 15 | 0.02 | 100 | 0.5 | 0.1 | Warfare | -0.179 |
| 16 | 0.05 | 100 | 0.5 | 0.1 | Warfare | -0.077 |
| 17 | 0.02 | 50 | 0.5 | 0.5 | Warfare | 0.335 |
| 18 | 0.05 | 50 | 0.5 | 0.5 | Warfare | 0.106 |
| 19 | 0.02 | 100 | 0.5 | 0.5 | Warfare | 0.583 |
| 20 | 0.05 | 100 | 0.5 | 0.5 | Warfare | -0.170 |
| 21 | 0.02 | 50 | 0.5 | 0.9 | Warfare | 0.028 |
| 22 | 0.05 | 50 | 0.5 | 0.9 | Warfare | 0.891 |
| 23 | 0.02 | 100 | 0.5 | 0.9 | Warfare | -0.594 |
| 24 | 0.05 | 100 | 0.5 | 0.9 | Warfare | 0.157 |
| 25 | 0.02 | 50 | 0.9 | 0.1 | Warfare | 0.266 |
| 26 | 0.05 | 50 | 0.9 | 0.1 | Warfare | -0.323 |
| 27 | 0.02 | 100 | 0.9 | 0.1 | Warfare | -0.021 |
| 28 | 0.05 | 100 | 0.9 | 0.1 | Warfare | 0.213 |
| 29 | 0.02 | 50 | 0.9 | 0.5 | Warfare | 0.317 |
| 30 | 0.05 | 50 | 0.9 | 0.5 | Warfare | -0.048 |
| 31 | 0.02 | 100 | 0.9 | 0.5 | Warfare | 0.386 |
| 32 | 0.05 | 100 | 0.9 | 0.5 | Warfare | -1.153 |
| 33 | 0.02 | 50 | 0.9 | 0.9 | Warfare | -0.005 |
| 34 | 0.05 | 50 | 0.9 | 0.9 | Warfare | 0.059 |
| 35 | 0.02 | 100 | 0.9 | 0.9 | Warfare | -0.161 |
| 36 | 0.05 | 100 | 0.9 | 0.9 | Warfare | -0.646 |
| 37 | 0.05 | 50 | 0.9 | 0.5 | Warfare | 0.407 |
| 38 | — | 50 | — | — | Groups | |
| 39 | — | 50 | — | — | Groups | |
| 40 | — | 100 | — | — | Groups | |
| 41 | — | — | — | — | Economic | |
| 42 | — | — | — | — | Economic | |

^a probability that a casualty will result in a fatality

^b how big a group may become before fissioning

^c proportion of the tribute from a subordinate group passed through an intermediate group to a dominant group

^d tax on a subordinate group's net benefit from the public goods game

Table 3: Static parameters in this sweep. All other parameters set to those used in run 230 in Kohler and Varien (2012).

| Parameter | Value | Description |
|------------------|-------|---|
| HUNT_RADIUS | 20 | Radius for hunting (in cells; 20 cells = 4 km) |
| PROTEIN_PENALTY | 1 | Removal of STATE_GOOD bonus if protein needs not met (reversion to rates in life table) |
| NEED_MEAT | 0 | Agents can move to a cell even if they cannot get enough meat via hunting |
| STATE_GOOD | 0.1 | When an agent is good, increments birthrate by 10%, and decrements death by 10% |
| DOMESTICATION | TRUE | Agents can domesticate turkey |
| ALLIANCES | FALSE | Will groups track daughter groups and not attack them |
| COOP | TRUE | Agents engage in GRN and BRN exchange networks |
| GROUP_BENEFIT | 2 | Growth rate for benefits as group size increases |
| GROWTH_RATE | | |
| B_BENEFIT | 73 | maximum benefit produced by contributing to the public good |
| C_COST | 37 | maximum cost of contributing to the public good |
| S_SANCTION | 56 | cost imposed on defectors. Same cost for taxation and public good defectors |
| CM_MONITOR COST | 4 | cost of monitoring one group member |
| CS_SANCTION COST | 11 | cost of sanctioning one individual, tax or public good |

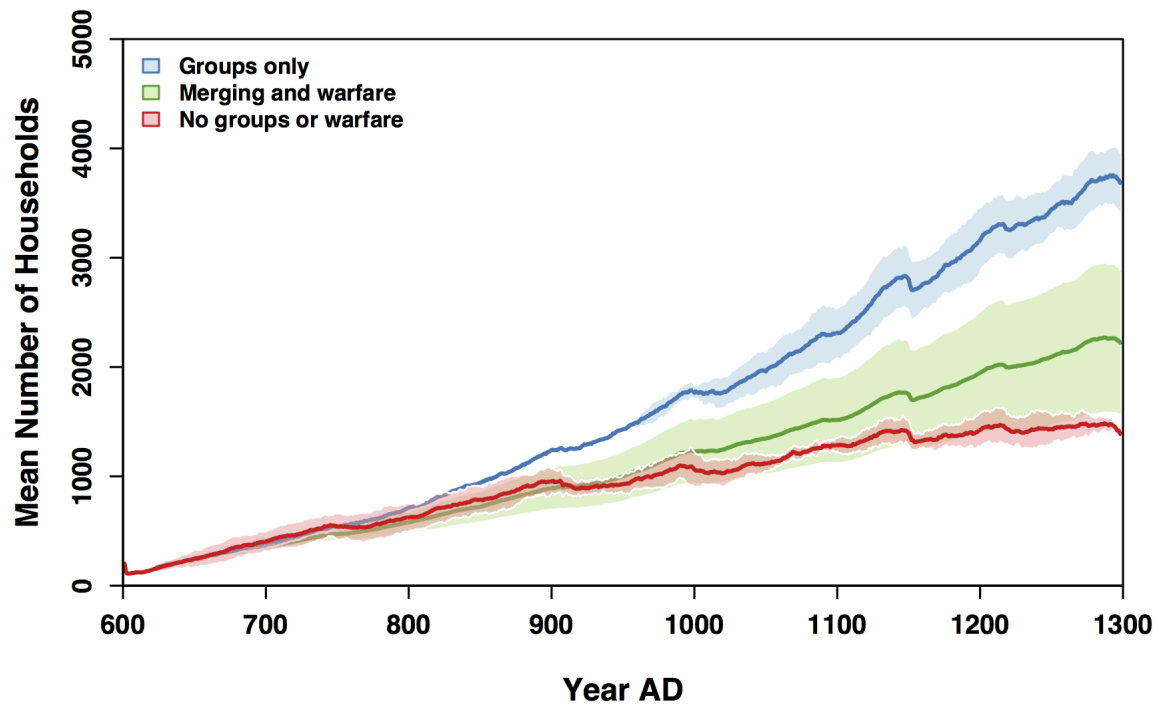


Figure 1. Mean number of households by run type through time. Shaded areas are one standard deviation from the mean.

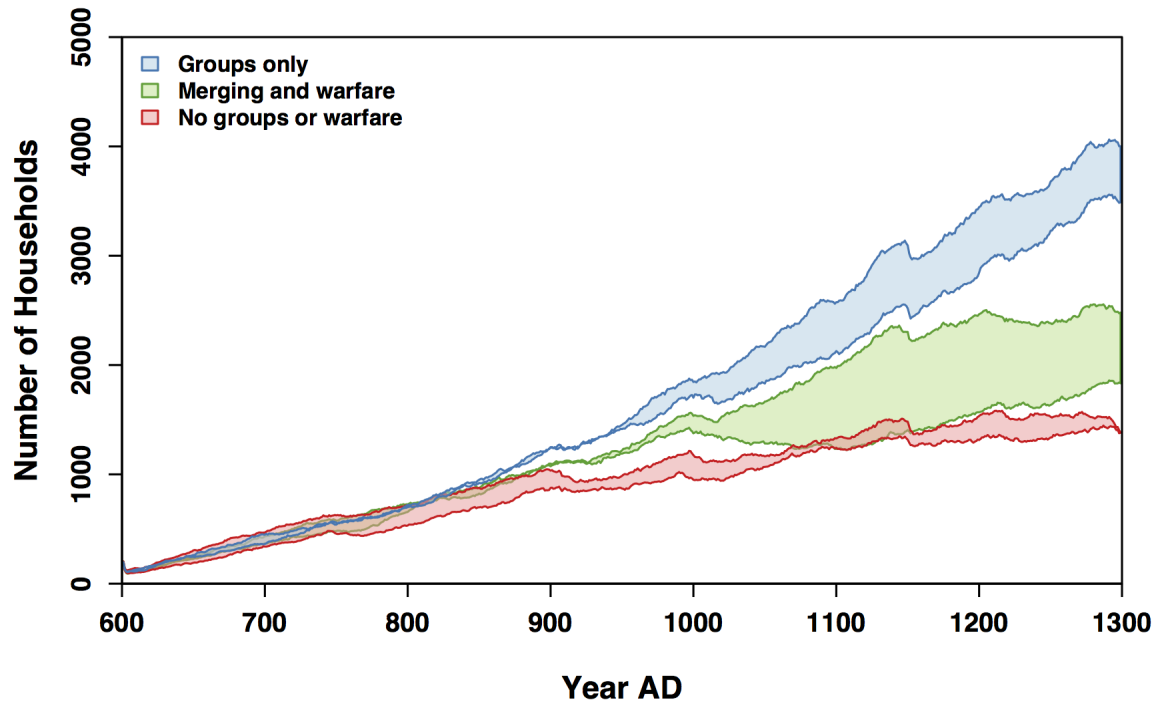


Figure 2. Path dependence in population size through time by run type. Each shaded area shows the difference in number of simulated households between two runs with identical parameters but different random number streams.

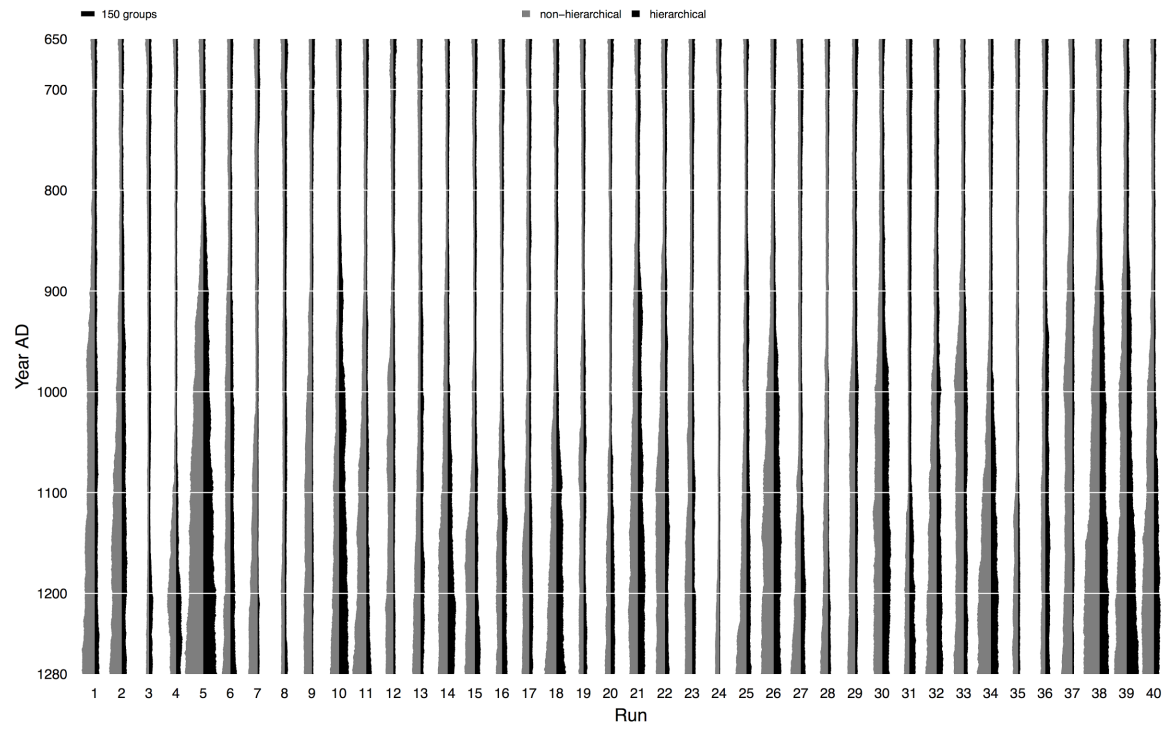


Figure 3. Number of hierarchical versus non-hierarchical groups through time, per run.

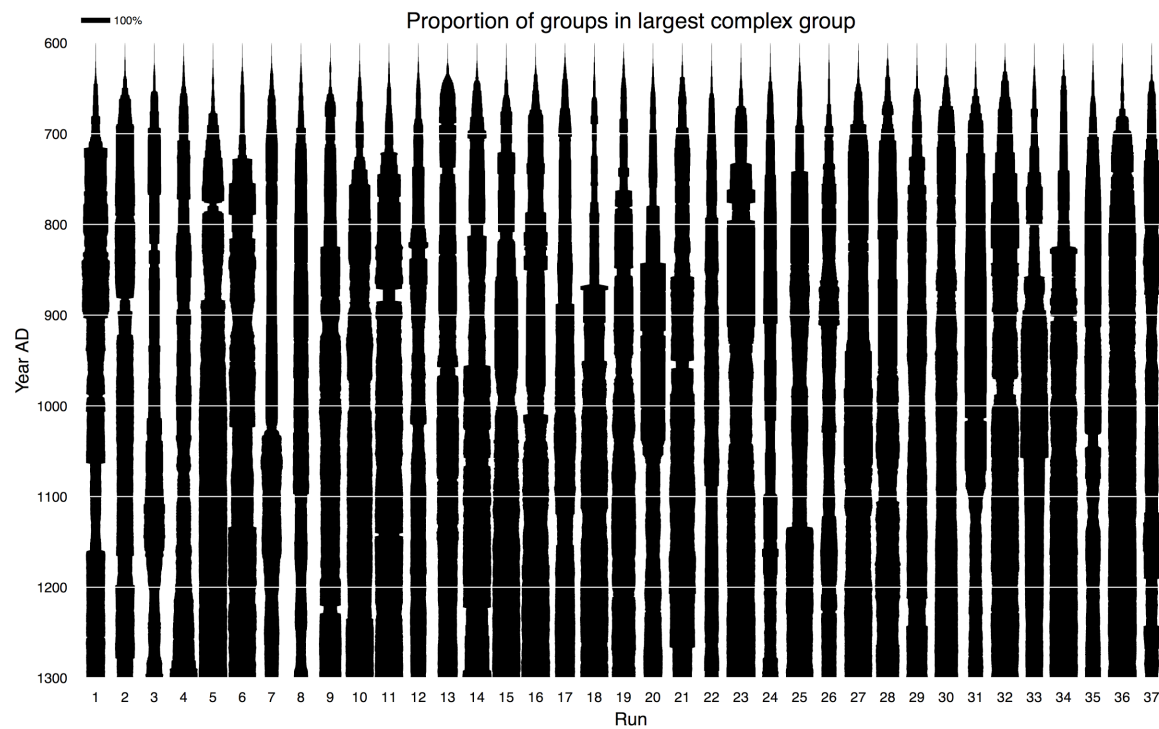


Figure 4. Percent of groups in the largest complex group. Wider bars indicate a greater percent in the largest group. In many runs, nearly 100 percent of groups are in the same complex group.

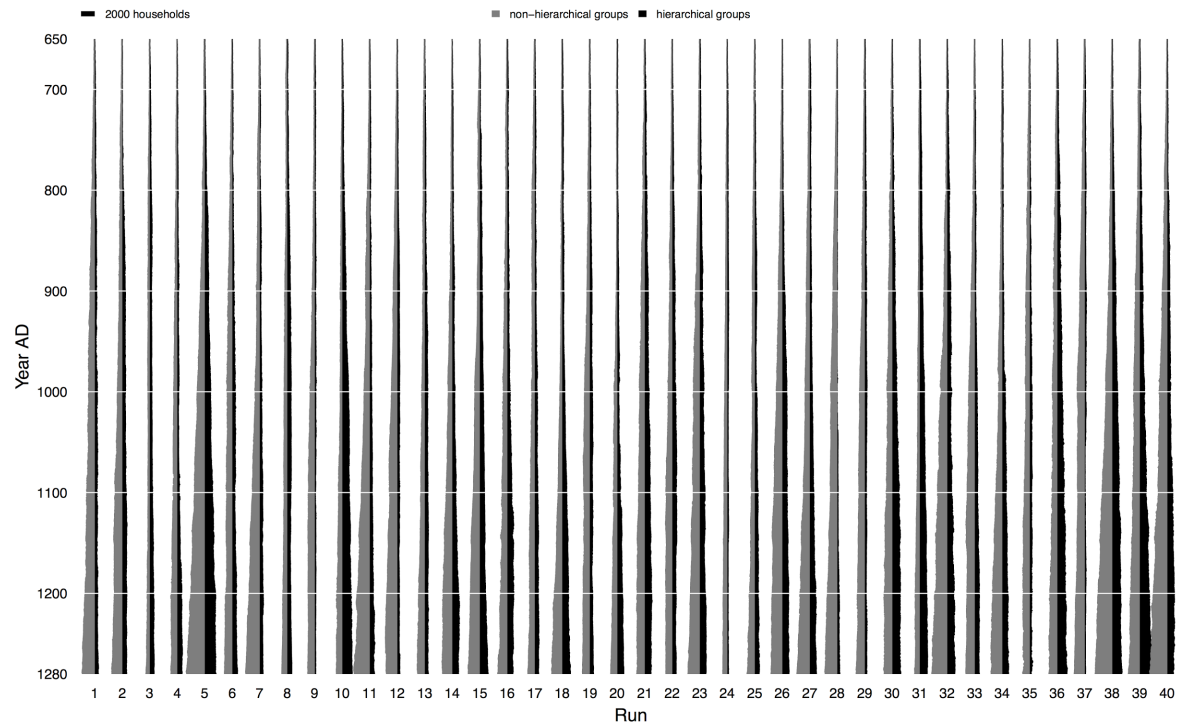


Figure 5. Number of households in hierarchical versus non-hierarchical groups through time, by run.

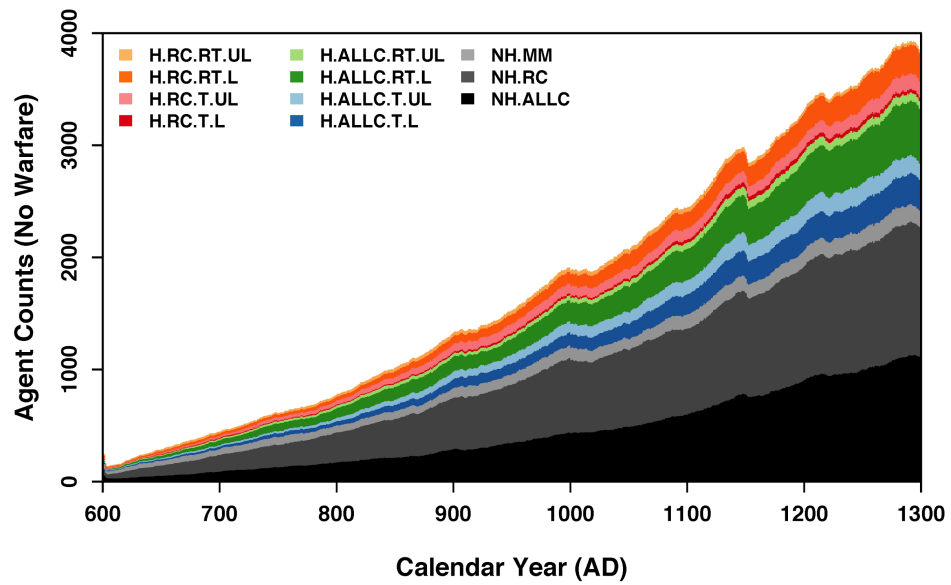
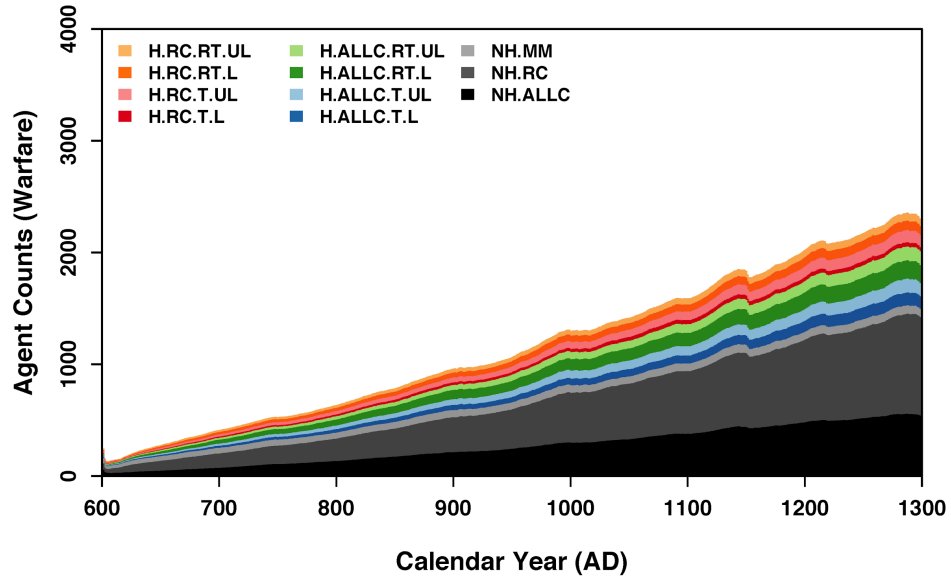


Figure 6. Average counts of agent types through time in runs with warfare and merging (top), and (bottom) with groups but without warfare or merging. See Table 1 and Kohler et al. (2012) for definition of agent types.

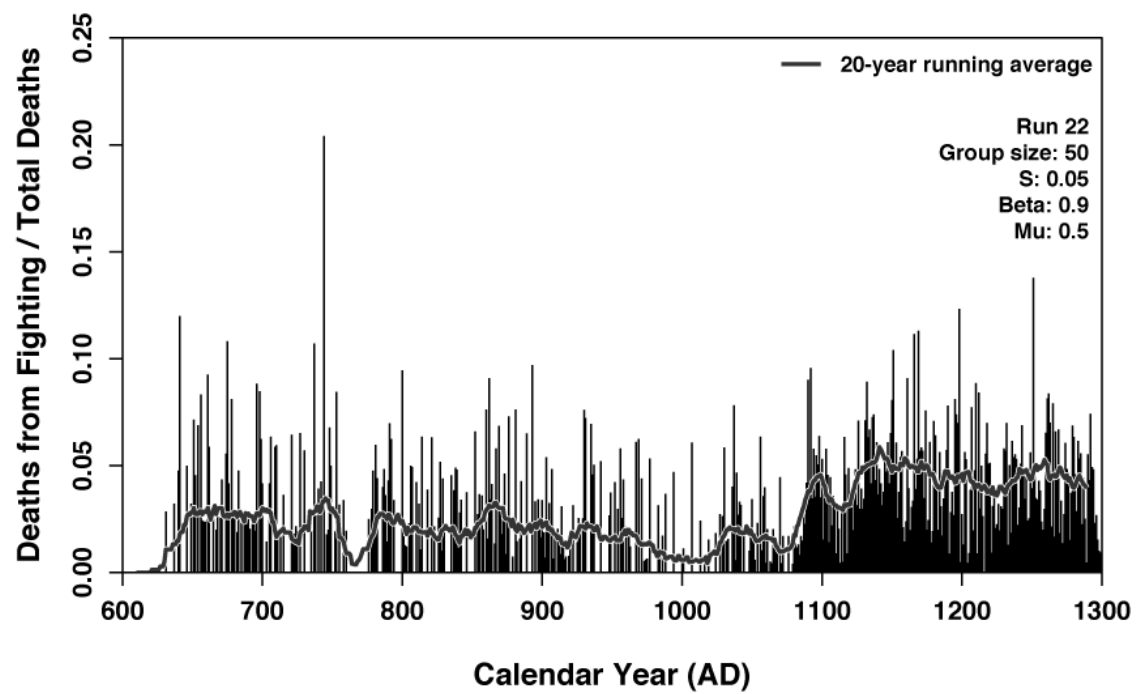


Figure 7. Deaths from conflict through time as a proportion of all deaths in Run 22.