Agent-Based Modelling of the Relationships among Kinship, Residence, and Exchange

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Abstract

In the North American Southwest, archaeological research has documented ceramic exchange networks in which spatially proximate households in consumer communities have greatly varying amounts of imported pottery. This paper uses agent-based modelling to gain insight into the processes responsible for these distributions. The agent-based model used here tracks kinship ties among agents representing individuals who give birth, marry, co-reside with spouses, and exchange things in a virtual landscape filled with small settlements of up to a few hundred individuals. Exchange of goods in the model flows through the kinship networks. The results suggest that the differential distribution of goods among spatially proximate households seen in the archaeological cases could result from a small-world network that forms as some individuals move to join spouses in far-off settlements, giving relatives in their home settlement preferential access to exchange goods originating in distant places.

Key Words: agent-based modeling, exchange, kinship networks

This paper describes an agent-based model designed to explore some aspects of the relationships among exchange systems, kinship networks, and settlement size. Since the 1970s, archaeologists have modeled exchange systems using either simple quantitative models or computer simulations. The literature on modeling exchange systems is too large to review here, but it is worth mentioning a few early influential examples of archaeological exchange models. These include Renfrew's (1975, 1977) arguments connecting the shape of fall-off curves over distances with highly abstracted "modes" of exchange (such as down-the-line or directional trade); Henry Wright and Melinda Zeder's (1977) computer simulation designed to explore the role of exchange of ritual items in "regulating" the production and exchange of subsistence goods; and Doran and Corcoran's (1985) simulation of production and exchange. Although the latter two examples are agent-based models, the agents are entire villages, and all of these early attempts model exchange at relatively large spatial and/or social scales, without considering the motivations of individuals or households.

A number of recent efforts have built on these earlier attempts by using agent-based modeling to explore various aspects of exchange systems. Among other things, these more recent models explore food sharing among households (Kobti 2012), specialization in resource procurement (Cockburn et al. 2013) the development of market systems (Watts and Ossa 2017), and the importance of small-world networks in distributing obsidian in the Near Eastern Neolithic (Ortega et al. 2014; Ibañez et al. 2015). All the cited models provide useful insights into the operation of prehistoric exchange systems, although none of them address the issues I explore below.

Archaeological and Ethnographic Background

Much of my own archaeological research has involved documenting ceramic exchange networks in the North American Southwest. In these networks, the abundance of imported pottery generally declines with distance from the source zone, but households in consumer communities often have greatly varying amounts of imported pottery despite being located in close proximity to each other (Allison 2000; Allison 2008).

Figure 1, for instance, graphs data from 68 ceramic assemblages that come from Ancestral Pueblo sites in the Moapa Valley of southern Nevada. These sites date between about A.D. 1050 and 1125 and are scattered along a small stream that creates a linear oasis in the Mohave Desert. Because the sites are small and dispersed, most of these assemblages represent the ceramic discard of single households, although a few assemblages combine materials associated with more than one house. Overall, about 29 percent of the pottery on these sites is one of two types (Moapa Gray Ware or Shivwits Plain) made in the forested uplands north of the Grand Canyon, 75-125 km to the east of the Moapa Valley (Allison 2000; Harry et al. 2013; Lyneis 1992; Sakai 2014). In individual assemblages, however, the percentage of imported pottery ranges from 2 to 69 percent. The wide range of assemblage sizes makes applying formal statistical tests difficult, but Figure 1 shows bands representing 90 percent and 99.9 percent confidence intervals around the mean value across the range of sample sizes represented. Overall, if the variation among the assemblages was due to sampling error alone, only 10 percent of the assemblages should plot outside the 90 percent confidence band, and (most likely) none would fall outside the 99.9 percent band. Clearly, the variation is not due to sampling error, but appears to reflect large differences in the amount of imported pottery obtained by different households living within short distances of each other.

Similar variation, beyond what could be explained by sampling error, is seen in the relative abundance of San Juan Red Ware on sites in southwestern Colorado dating from the late A.D. 700s or early 800s (Allison 2008). In that case, red ware pottery was made in a broad production zone located mostly in southeastern Utah, then exchanged eastward into southwestern Colorado. Near the modern town of Dolores, Colorado, about 50 km east of the production zone, ceramic assemblages dating to the late 700s or early 800s include an average of about nine percent San Juan Red Ware, but individual assemblages vary from less than two to more than thirteen percent. In contemporaneous sites twice as far (i.e., about 100 km) from the production zone, near the modern town of Durango, Colorado, the mean percentage of red ware is only about one percent, but individual assemblages vary from zero to more than four percent red ware. Also, neutron activation data shows that people living within walking distance of each other obtained San Juan Red Ware from different parts of the production zone (Allison 2010; Allison and Ferguson 2015).

In both of the cases described, settlements are relatively small. Moapa Gray Ware and Shivwits Plain producers and consumers lived in dispersed communities that included many small, single-household sites and a few larger settlements that housed small numbers of related households. The San Juan Red Ware exchange system involved some villages with populations in the hundreds, but also many smaller settlements that were part of dispersed communities.

Some archaeologists might interpret the variation in the relative abundance of non-local ceramics as reflecting differences in status and access to exchange, but there is little evidence for strong differences in prestige or wealth among the small-scale farmers represented in this case. Instead, I argue that the differential distribution of goods among spatially proximate households probably results from something like a small-world network (as argued by Ortega et al. 2014 and Ibañez et al. 2015), but one that links individuals, not entire settlements, across space.

Ethnographic data suggest that exchange in small-scale societies is strongly structured by kinship relations. Lederman (1986), for instance, describes the trade networks of 43 informants in a highland New Guinea village. On average, each informant had 59 trade partners, 55 of whom were relatives of various kinds. Only about 7 percent of the named trade partners were not kin.

Similar quantitative data on trade networks is rare in the ethnographic literature, but it is clear that kinship structures exchange transactions and the movement of goods in many societies. Among the Hopi, a Native American group that probably includes many descendants of the people involved in the archaeological exchange system described above, the link between kinship and exchange begins soon after birth when “the paternal grandmother and the other paternal female relatives arrive at the mother’s house to present their gifts. . . The naming ceremony initiates a whole series of economic ties between the paternal grandmother primarily, and secondarily the other paternal female relatives, and the grandchild, nephew, or niece, as the case may be....throughout life the individual is linked to those who assisted him to enter the world and named him a member of the group by ties that only death can cut...” (Beaglehole 1937:73). At marriage, “… specific personal relations are established by the transfer of gifts and the assumption of new economic obligations on the part of the two principals towards each other and towards the kinship groups to which each belongs” (Beaglehole 1937:75).

Ethnographic data also shows that, while conventions about post-marriage residence vary, people in many small-scale farming societies prefer to marry within their local community, in part because they often have access rights to land from the kin groups of both spouses, and need to live close enough to be able to work the land. But, as Rappaport (1968) notes, men cannot always marry locally: “full satisfaction of a preference for local women in unlikely among groups the size of the Tsembaga…Groups of such size are subject to imbalance in the numbers of persons of each sex…” On the other hand, “While unions between men and women of a single local origin confer certain advantages upon both parties and their natal agnatic groups, unions between people of different local origins confer others. Unions across the grain of the land serve to strengthen trading relationships …”

Modelling Goals

The agent-based model described below is an attempt to evaluate several linked hypotheses about the relationship between kinship networks and exchange. First, that the variation seen in the archaeological examples in the abundance of trade ware pottery is due to a small number of people having better long distance connections across the landscape, giving them easier access to pottery made in distant locations. Second is the idea that these differences can arise simply through variation in kin networks and post-marriage residence, in the absence of pronounced differences in status or wealth. A third idea, though initially more a question than a hypothesis has to do with the effect of increasing settlement size. Do larger settlements lead to larger differences in access to trade goods? Or do larger-sized villages smooth out the demographic variables enough that village endogamy becomes universal and everybody’s kin and trade networks are restricted to their home village?

How the Model Works

The model is implemented in NetLogo 6.0, a high-level programming language designed for agent-based modelling (Wilensky 1999; Wilensky and Rand 2015). The model is available for download at <https://github.com/jallison7/kintrade-model>. The choice of NetLogo as a platform involves a trade-off between ease of use and performance. Many procedures commonly used in agent-based modelling are built in to NetLogo as primitive operations, which greatly facilitates coding of the model, and NetLogo’s graphical interface makes it easy to visualize some aspects of the model’s performance. These positive features also have a downside, however, as they can cause the model to run slowly . As currently configured, the model takes less than a minute to run when the population is small, but the number of operations increases exponentially with population size, and some of the analyses reported below took hours to run. This is probably due in large part to the extensive use of agent filtering statements (when agents search for eligible spouses, for example), which are easy to code in Netlogo but often run slowly (Railsback et al. 2017). Further extensions of the model may require recoding it with attention to improving its processing speed.

The model simulates exchange of ceramic vessels among individuals organized into villages and linked by kinship ties. Specifically, the analyses reported here all use eight simulated villages arranged in a line (although the model code allows the number of villages to vary). This creates a much simpler settlement landscape than exists in the real-life exchange systems, which include a variety of settlement sizes and communities that are more dispersed than the villages created by the model. In NetLogo's graphical interface, the villages are evenly spaced on the x axis and represented as circular areas 30 patches in diameter. Both the spacing of the villages and the representation as circles are display conventions with no affect on the model outcome.

Each run of the model begins with a setup procedure that locates the villages and populates each village with agents representing men and women. A variable called village-size sets the mean size of each village, although the actual number of individuals created varies randomly, following a Poisson distributuion. Each individual created has an equal probability of being male or female. Across a large enough number of iterations of the model, simulated villages are, on average equal in size to the village-size parameter, and the procedure creates equal numbers of male and female agents. But in any single case, the size and sex ratios of villages vary. As Table 1 shows, in ten tests of the procedure with the village-size parameter set to 100, the total initial population size for the eight simulated villages varies from 757 to 834, but the average across the ten tests (799.6) rounds to 800, exactly what it should be. The sex ratio (males/females) in the same tests varies from .85 to 1.11, or from about 46 % male to about 53 % male.

Initial population sizes and sex ratios for individual villages vary even more (Table 2). Similar variation in settlement size and sex ratio is common in real-world situations, and it is important to the way the model creates simulated networks of kinship relations.

The individuals created during setup are randomly assigned ages, with every age from 1 to 45 being equally probable. When created the individuals have no kin ties, and the first generation of agents never have parents, siblings, or affinal relatives. They do marry, however. Once all the initial individuals are created, females above the age of 16 search for suitable males to marry. Suitable is defined as over the age of 16, not already married, and within 10 years of the age of the female seeking a spouse. Females first look for suitable spouses within their own village; if none of the males within their village are suitable, they then look for a spouse elsewhere. A variable called max-marriage-radius controls how far from their current village women will go to find a spouse. The model as currently implemented is strictly matrilocal. If a suitable spouse is found in another village, the male moves to the village of his spouse. Because of the variation in population size and sex ratio, and the rules controlling who can marry whom, not every individual is able to marry.

Once the initial generation of individuals have been created, the model begins to run. Each "tick" in NetLogo is conceptually a year, in which all individuals age, some marry, some have children, and some die. In each year of the simulation, unmarried females over the age of sixteen search for suitable spouses as in the initial setup procedure. The birth rate is controlled by a variable called birth-probability, which is the probability that a married female between the ages of sixteen and forty will have a child in any particular year. Children under the age of sixteen never die in the model, so the "birth probability" is better understood as the probability of having a child that will survive to at least age sixteen. A variable called death-probability, representing the probability of death in a given year, controls the death rate for individual agents between the age of 16 and 60. The death rate is constant in the model from age 16 through age 60, but individuals over the age of 60 always die.

Both the birth probability and death probability are variable in the model, although the analyses reported here all use .17 for the birth probability. That means a female who lives to age 40 will have, on average, four children who live to at least age 16. The death probability is also fixed, in these analyses at .05, meaning five percent of individuals over the age of 16 die each year. These values are probably not entirely realistic but were chosen through experimentation that showed simulated populations are approximately stable with those values; in most runs of the model with these settings, the total population decreases slightly, but not enough to threaten the viability of any village. These values create a population structure that seems somewhat reasonable, although it probably skews too young to be realistic.

The top half of Figure 2 shows the age structure of the population after 100 ticks for one run of the model with the initial village size set to 100. In this run of the model, approximately half the population (401 out of a total population of 814) is age 16 or younger, while only nine individuals (about one percent of the population) are 55 or older. The bottom half shows the age structure, up to age 60, for modern populations of Agta foragers who live in the Philippines (Headland et al. 2007). The overall life expectancy of the Agta population is only 23 years, largely due to extremely high infant and child mortality rates. Compared with the population structure produced by the model, the modern Agta population shows fewer children and adolescents (about 35 percent of the population age 16 or under), a much more robust representation of adults between 30 and 55, and more individuals over the age of 55 (five percent between 55 and 60, with additional individuals over the age of 60 not shown in the histogram). Because the model assumes no infant or childhood mortality, compensating with relatively low fertility rates (Agta women average seven births per woman compared to about four in the model), it will probably never precisely replicate the population structure of the Agta or any other comparable group. Still, this comparison suggests the model could be improved through adjustments to the birth and death rates that increase the number of adults surviving after the age of 30. A simple reduction in the death probability would accomplish this, but, without compensating adjustments in the birth probability, it would lead to population increases rather than the approximately stable population achieved with the setttings used here.

Each run of the model has a one hundred year initialization period, during which several generations of individuals are born, marry, and die. The model tracks a network of kinship relations for each individual’s through links to their parents, children, siblings, spouses, and first-order affinal relations (i.e., their spouse’s parents and siblings). These individual kin networks vary in two important ways. First, because birth, death, marriage, and reproduction all vary randomly, some individuals have larger networks than others. Second, males move when they marry out of their birth village, but remain linked to parents, siblings, and other relatives in their home village. This means that some individuals have relatively expansive kin networks, with links to kin several villages away from where they reside. Other individuals have kin networks that are restricted to their birth village.

After the 100 year initialization period, the model begins to simulate the production and exchange of pottery. Production and exchange continue for 50 years, during which agents continue to be born, marry, and die, and the details of individual kin networks continue to change. Women in Villages 1 and 2, the first two villages at the left side of the NetLogo graphics window, are the potters. A variable called annual-production controls the rate of output of each potter. In each year, individuals ask for pottery from members of their kin networks who live either in the same village or in villages “upstream” in the simulated linear exchange network. This means pots can move around among individuals within a village, or move to the right from villages located further to the left, and therefore closer where the pottery is produced, but they never move back to the left. Males and females both take part in the exchange, but only adults over the age of sixteen participate. Whether an exchange actually takes place is controlled by a variable called exchange-threshold. If an agent receiving a request to exchange owns more pots than the exchange threshold, then they pass one on to the agent making the request.

Among agents residing in the same village, the order with which the agents seek exchange transactions is random, as is the order with which they select members of their network to ask. But the exchange proceeds one village at a time, beginning with the villages at the left side of the system and moving progressively to the right. Agents continue to request pots until they have exhausted their kin network, or have received a number of pots equal to a variable called annual-demand, which is fixed at five in the analyses reported here.

Results

The analyses reported here are preliminary, representing a first attempt to explore the implications of the model. Even though the model is relatively simple, there are many variables, and it is easy to generate voluminous output. The model allows ten parameters to be controlled using sliders on the NetLogo interface, although, as noted above, most of these were fixed in the analyses reported here in order to keep the results simple enough to interpret. These potentially variable parameters that were not in fact allowed to vary are the number of villages (nvillages = 8); birth-probability (0.17); death-probability (0.05); the length (in NetLogo ticks, conceptually years) of the initialization period before starting the exchange (start-exchange = 100); the length of the period during which the model simulates pottery production and exchange (exchange-length = 50); and the maximum number of pots an agent will receive in a single year (annual-demand = 5).

Parameters that were varied include the average starting population of villages (village-size = 100, 200, 300, 400, 500, and 1000); how many villages away females would seek spouses (max-marriage-radius = 2, 4, or 6 villages away); the number of vessels each potter would make in a single year (annual-production = 5 or 10); and how many vessels an agent had to possess before they were willing to complete a requested trade transaction (exchange-threshold = 2, 5, or 10).

For each of the six village sizes, there were 18 different combinations of the other variables, for a total of 108 different configurations of the model. Each of these configurations was run 200 times, for a total of 21,600 runs of the model. At the smaller initial village sizes the model runs relatively quickly, and computing power is not much of an issue. Larger initial village sizes increase the number of virtual individuals, kinship links, pots produced, and transactions, and require more computing resources. On a desktop computer with a 3.4 GHz Intel i7-6700 processor and 32 GB of RAM, one run of the model with the initial village size set to 100 (i.e., a total population of approximately 800) takes about 4 seconds. A five-fold increase in the initial village size to 500 (and total population to approximately 4,000) increases the run time to about 90 seconds. Completing the 3,600 runs with the population size doubled again (to approximately 8,000 total) required leaving the computer running for more than two days.

Analysing the voluminous output is challenging, but a few trends are clear. One result of interest is how the different parameters affect the model's ability to move pots through the system. Here, production rate made surprisingly little difference. With annual-production set at 5, a mean of 329 vessels made it to Village 8 across all runs of the simulation. Doubling the production rate to 10 doubles the number of vessels in the system (approximately, because the number of vessels produced is subject to random fluctuations in population size in the producing villages), but the mean number of vessels that made it to Village 8 only increased to 341.

The exchange threshold has a larger effect, as might be expected. When the exchange-threshold variable is set at 2, a mean of 475 vessels make it to the end of the system. As the threshold is increased to 5, meaning agents are less likely to meet requests to exchange, the mean number of vessels making it to Village 8 drops to 301, and when the threshold is 10, it drops to 229.

But the max-marriage-radius variable, which controls how many villages away agents will go to find a spouse, has the largest effect on the number of vessels moving through the system. When marriages are constrained to no more than two villages away, only 15 pots, on average, reach Village 8. Increasing the possible marriage distance to four villages away results in a mean of 244 pots reaching the end of the system, and if people can go six villages away to marry, then, on average, 747 pots are exchanged to the far end of the system. As Figure 3 shows, this pattern probably results from the way marriages to spouses in distant villages create long-distance kinship links that reduce the number of transactions required to move pots across the system. Longer-distance marriages and the resulting changes in post-marriage residence effectively shorten the distance from the producing villages to the most distant village in the simulation for some agents.

Village size also has a strong effect. In terms of raw numbers, larger village sizes lead to larger total populations, more ceramic producers and more pots produced, and ultimately more pots make it to Village 8 (Figure 4). With village-size set to 100, on average 172 pots arrive in Village 8, while setting village-size to 1,000 allows a mean of 484 pots per run in the end village. But it may be more important to note that, when scaled to the population size, smaller settlement sizes actually work better (Figure 5). More pots per person (2.7, on average) arrive in Village 8 when village-size is 100 than when village size is 1000 (0.5, on average). In other words, it actually becomes more difficult for Village 8 residents to acquire pots when the population is larger even though the total number of pots in the village greater.

A similar effect happens with the number of long distance links created, and is probably the reason why pots become more difficult to acquire with larger population sizes. A larger population leads to more links overall, and more outside agent's home villages, but when the number of links is scaled to population size (Figure 6), it is clear that larger settlement sizes make it less likely that a given individual will have kinship links outside their home village. Presumably this is due to the demographic smoothing of larger population sizes that make it more likely that individuals will realize the preference for marrying within their home village.

Other patterns of interest require detailed examination of disaggregated data and examination of individual runs of the simulation. These include the structure of the networks formed and the variation in outcomes for individual agents. I will focus here on comparison of two runs which differed in only the setting of the village-size variable, which was 100 in one run and 500 in the other. Max-marriage-radius is set to 6, exchange-threshold to 10, and annual-production to 10. Limited additional analysis suggests that the differences seen in these two runs are at least broadly representative of patterns that would be seen with a larger sample of runs, but much work remains to be done.

Figure 7 shows the number of pots owned by Village 8 residents at the end of each of the runs. In both cases, most of the agents have no pots. In both cases, the distribution is highly skewed and one or two individuals possess a large number of vessels. With village-size at 500, one agent has 20 pots and another has 14. But the distribution is much more skewed with village-size at 100. One agent has 38 vessels; the next most successful traders are three individuals with nine pots each. This variation in outcomes is broadly similar to the variation seen in the archaeological examples briefly described above. Importantly, the success of the most successful individuals in Village 8 are not due to their centrality in the network; the three most successful all have average numbers of links (Figure 8). Two of them, however, benefit from very distant kinship links. Most notably, the individual with 38 pots in the village-size = 100 run was a male born in Village 2 who married into Village 8 (Figure 9); the direct link to a producing village provided a major advantage over other Village 8 residents.

Conclusion

The model reported here is a simple attempt to understand the processes underlying the archaeological distribution of trade ware pottery in some specific cases. Like most models, this one is oversimplified in many ways. Yet it is complex enough that I have only begun to explore the behavior of the model under different condition. Still, the results here suggest several important conclusions.

First, if most exchange is among kin (which ethnographies suggest is commonly the case in small-scale societies) then random variation in the size and specifics of kin networks can lead to large differences in outcomes. Some of the differences may be due to small-world networks forming as some individuals move to join spouses in relatively distant villages. These differences in outcomes emerge from actions of many individuals following simple rules of kinship, marriage and residence, with exchange channeled along kinship lines. Individuals may compete to succeed in trade networks, but some individuals will be more successful than others even without such competition. Finally, as settlement size grows, a higher proportion of marriages are endogamous, and fewer people have kin connections to distant villages. This may be a factor in the development of market systems or other forms of trade networks in which kinship is less important than in the small-scale societies on which I base my model.

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Table 1. Variation in population size and sex ratio after the initial setup procedure in ten test runs with the village-size variable set to 100.

Run	females	males	total	sex ratio (males/females)
1	441	374	815	0.85
2	390	397	787	1.02
3	396	361	757	0.91
4	378	407	785	1.08
5	407	417	824	1.02
6	422	412	834	0.98
7	418	365	783	0.87
8	387	428	815	1.11
9	404	388	792	0.96
10	423	381	804	0.90
Total	4066	3930	7996	0.97

Table 2. Variation in population size and sex ratio among the eight villages for the first run shown in Table 1.

Village	Females	Males	Total	sex ratio (males/females)
1	63	40	103	0.63
2	57	51	108	0.89
3	44	40	84	0.91
4	67	54	121	0.81
5	47	45	92	0.96
6	50	47	97	0.94
7	66	56	122	0.85
8	47	41	88	0.87
Total	441	374	815	0.85

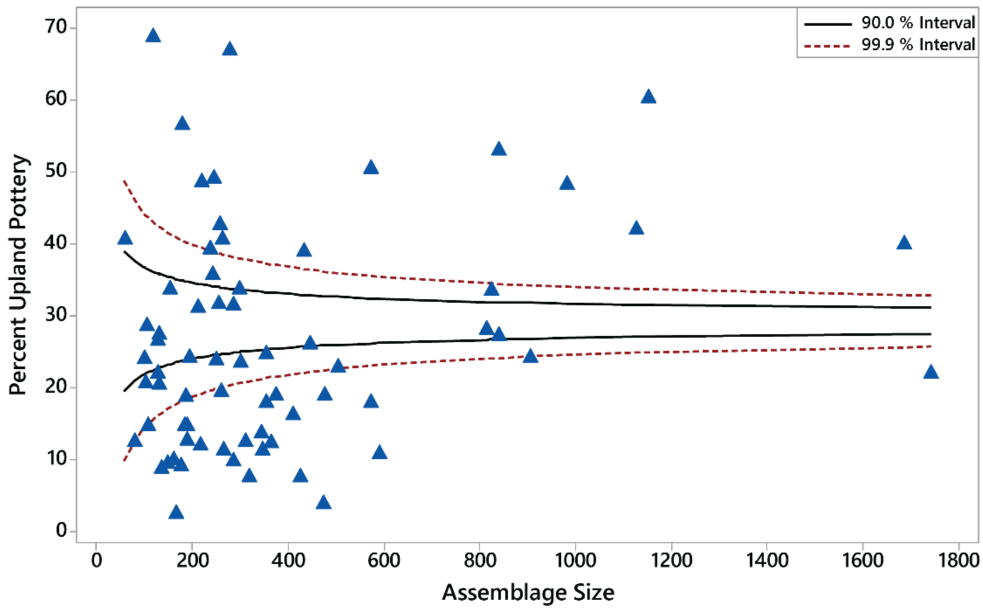

Figure 1. Scatter plot of ceramic data from 68 ceramic assemblages in the Moapa Valley, Nevada. The plot shows assemblage size versus percent of ceramics imported from upland production areas 75-125 km to the east.

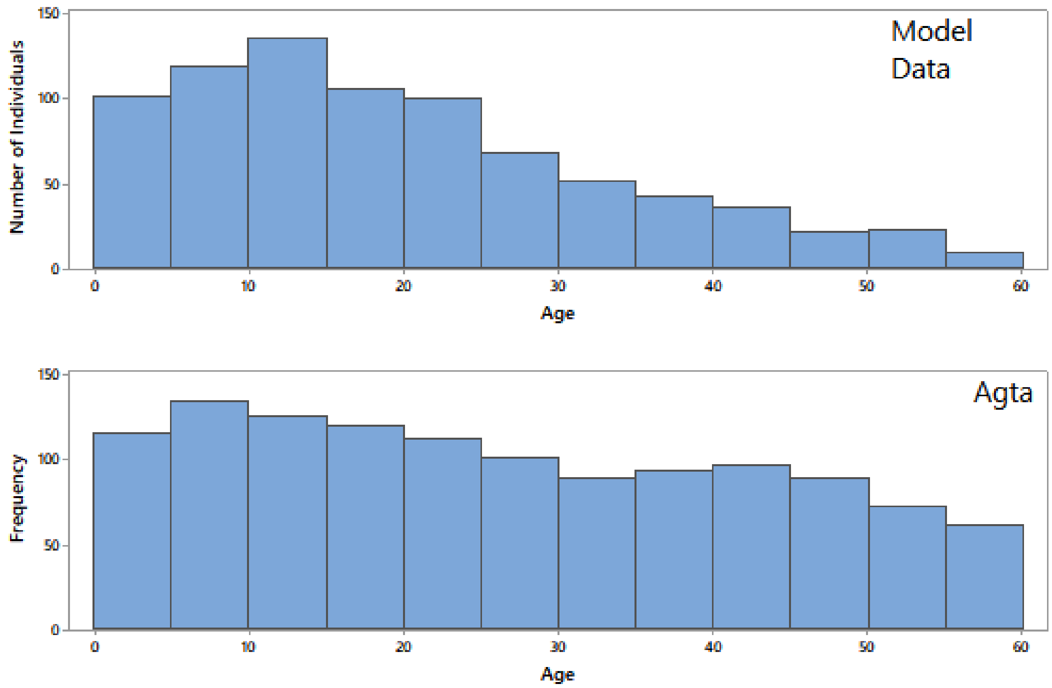

Figure 2. Comparison of the population structure resulting from one run of the model with the observed structure of a modern population from a small-scale society of Agta foragers from the Philippines. The model produces a population that skews younger than the observed population.

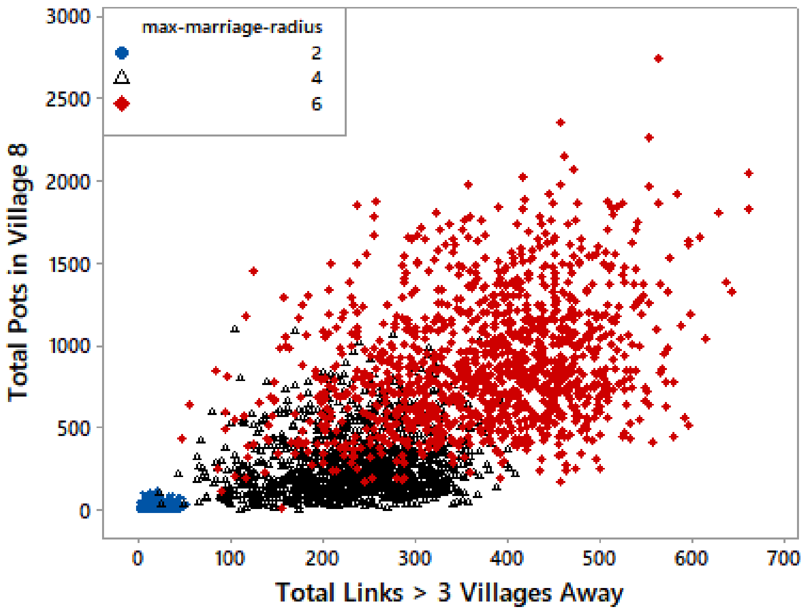

Figure 3. Scatter plot showing the effect of the max-marriage-radius variable on the number of kinship links created to individuals residing at least three villages away and on the number of pots acquired by Village 8 residents in one run of the simulation. These results are from 3,600 runs of the model with the village-size variable set to 500.

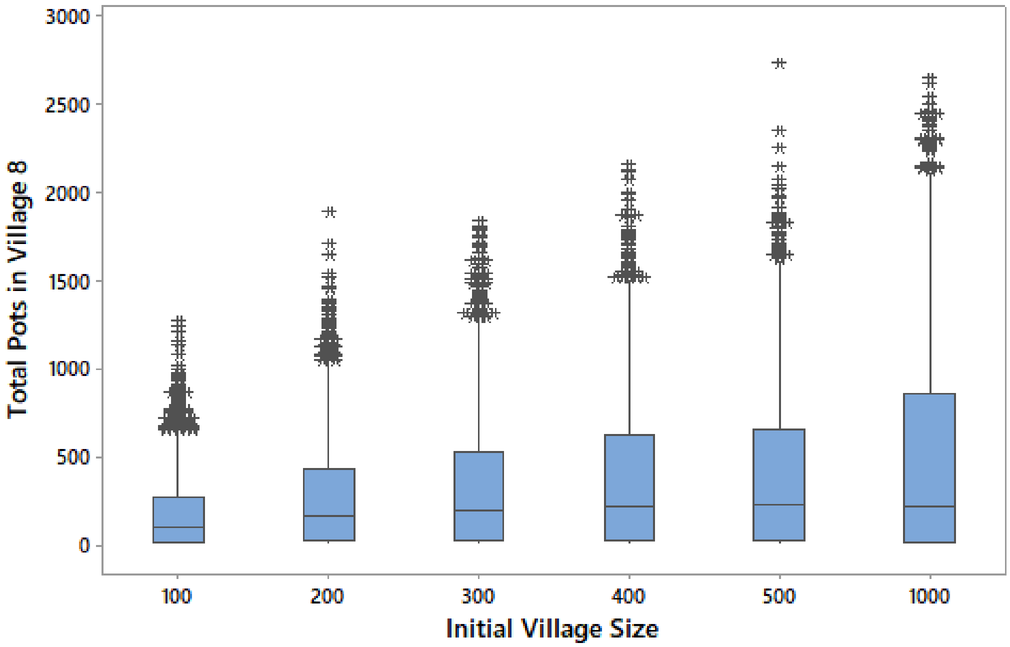

Figure 4. Boxplots showing the effect of the village-size variable on the number of vessels that reach Village 8 across all runs of the simulation.

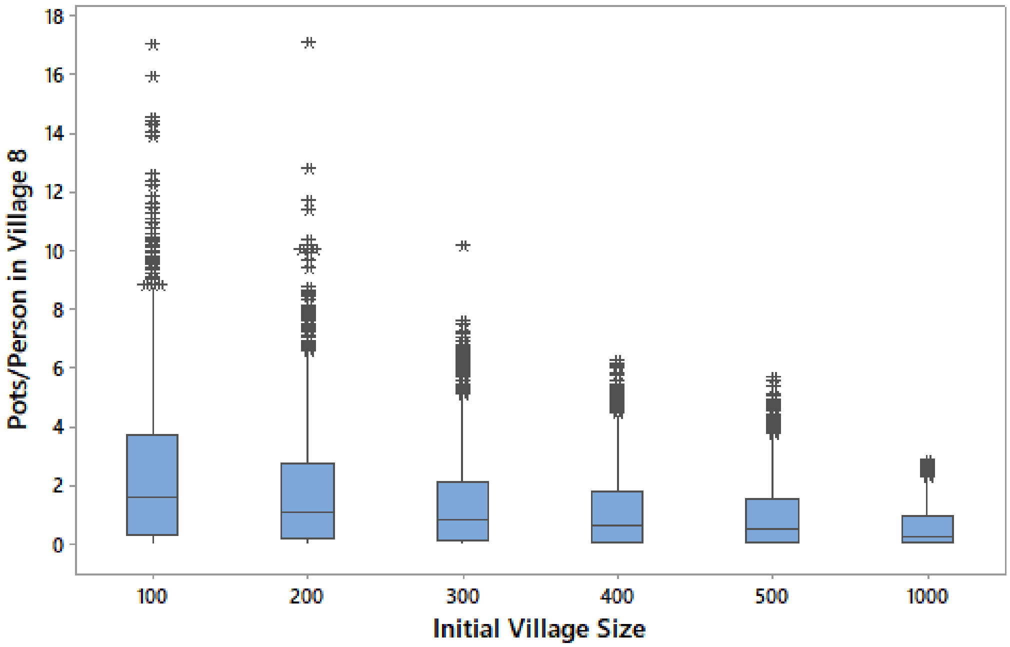

Figure 5. Boxplots showing the effect of the village-size variable on the number of vessels *per person* that reach Village 8 across all runs of the simulation.

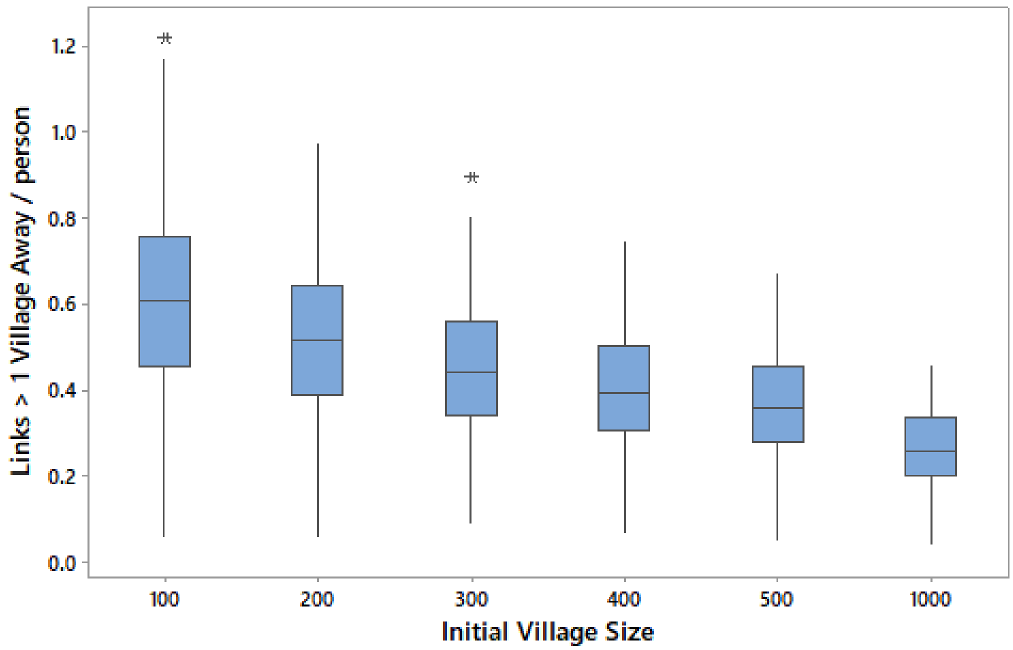

Figure 6. Boxplots showing the effect of the village-size variable on the number of kinship links created per person that are with individuals residing more than one village away.

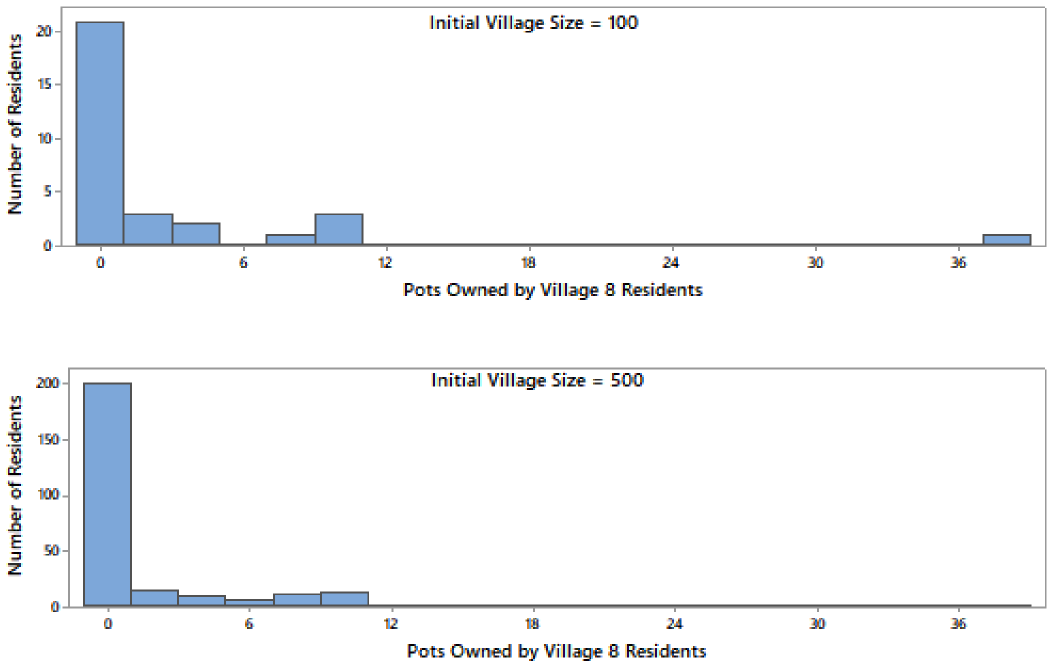

Figure 7. Number of pots owned by individual Village 8 residents at the end of two runs of the simulation with different initial village sizes. Note the difference in the y-axis scale that makes it impossible to see bars representing single individuals with 14 and 20 pots in the lower histogram.

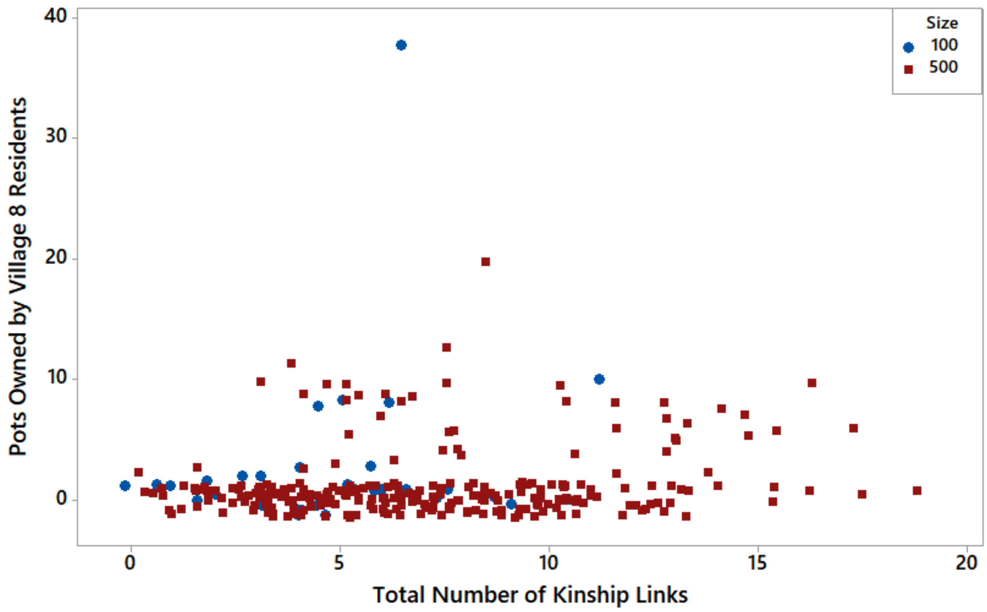

Figure 8. Scatterplot of the number of pots owned by Village 8 residents by the number of kinship links at the end of two runs of the simulation with different initial village sizes. Note that the individuals with 38, 20, and 14 pots all have average-sized kinship networks.

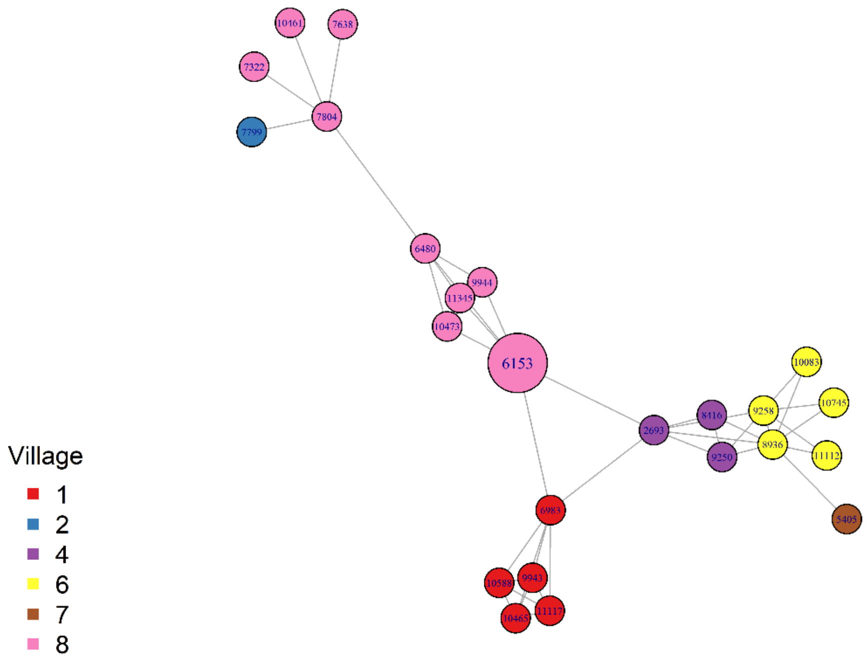

Figure 9. Network graph of the kinship links of Agent 6153, the Village 8 resident with 38 pots. The graph shows the network up to three links away from Agent 6153. Note the direct connection back to Village 1, one of the producing villages. The direct link results from the fact that Agent 6153 married into Village 8, but was born in Village 1 and still has close relatives there.