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THE EMERGENCE OF SOCIAL NETWORK HIERARCHY USING CULTURAL ALGORITHMS

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In this paper we extend the cultural framework previously developed for the Village multi-agent simulation in Swarm to include the emergence of a hub network from two base networks. The first base network is kinship, over which generalized reciprocal exchange is defined, and the second is the economic network where agents carry out balanced reciprocal exchange. Agents, or households, are able to procure several resources. We use Cultural Algorithms as a framework for the emergence of social intelligence at both individual and cultural levels. Successful agents in both networks can promote themselves to be included in the hub network where they can develop exchange links to other hubs. The collective effect of the hub network is representative of the quality of life in the population and serves as an indicator for motives behind the mysterious emigration from the region. Knowledge represents the development and use of exchange relationships between agents. The presence of defectors in the hub network improved resilience of the social system while maintaining the population size at that observed where no defectors were present.

Keywords: Cultural Algorithms; Multi-Agent Simulation; Complex Hierarchical Networks.

1. Introduction

Archaeologists working in the Mesa Verde region of southwestern Colorado encounter one of the great mysteries of pre-Hispanic history. Thousands of habitations in the region attest to the presence of an ancient society of farmers referred to as the pre-Hispanic Pueblo Indians or ancient Anasazi.[1] Decades of survey and excavation in this region have developed a rich and detailed database on site location, size, and type, which can be coupled with a detailed knowledge of the current landscape and even estimates of its ancient productivity,[2] on which the work here is ultimately based. The archaeological mystery is why, after 700 years of successful occupation and adaptation to changing climates and populations levels, did these Pueblo Indians choose to abandon this region?

Many non-mutually-exclusive theories have been posed to answer this question. They include the Little Ice Age, arroyo cutting, disease, and warfare (see current overviews in Kantner[3] and Kohler.[4]) The most prominent-that the Great Drought of the late thirteenth century was sufficient to cause the abandonment was examined by Van West[2] and also by Kohler et al. in a multi-agent simulation model.[6] The model, which only considered the effects of reconstructed precipitation variability on production, failed to reproduce reductions in population as complete as those known to have occurred in the late 1200s. Hence it was suggested that other factors might play a role as well.

In follow-up work we [7,8,9] suggested that social and cultural factors contributed to the emigration decision. This position has some plausibility because excavations reveal many activities that appear to be organized at the level of, and for, the community. Kohler's initial agent-based model was then extended to weave a social network and embed cultural evolution in the modeled population so as to generate a more realistic scenario.

There has been increased interest in the study of large-scale networks in social, economic, business, and institutional systems and network dynamics in the wake of system changes. Within such large dynamic networks one of the key problems is that of navigability within the network. That is, how to insure that the next stop in a chain of requests is closer to the target node than the last. Maintaining knowledge about network navigability in the wake of change is one of the key sources of knowledge that individuals need to learn and update when necessary[10].

In terms of human networks the links between individuals can be strong or weak. In personal networks based upon kinship there are relatively few nodes (hub nodes) with many weak ties. However, multi-level networks can be built on top of strong tie networks that allow increasingly more flexibility in the exchange of information. In our model, we have a kinship network that is characterized by strong ties where individuals have few weak ones. We then superimpose multiple layers on top of the kin network, the economic network, and the hub network, that allow hub nodes increasing opportunities to funnel information through the network. A question of interest here is how many levels does a system need to have in order to have sufficient flexibility in the exchange of resources? And, how easy will it be for individuals to learn to navigate each of these networks in the wake of system change? This paper will investigate answers to these questions in terms of the Anazazi case.

Previously we allowed the population to exchange resources via generalized reciprocal exchange over a kinship network. The emergent network had small-world properties. In this paper we take the model of Sahlins [11] for balanced reciprocal exchange and implement that in the model along with the previous network. Our goal is to assess the relative impact of the two emergent networks with regard to their ability to improve system resilience in light of environmental changes.

The current model was developed in Swarm[12] with paleoproduction data for maize from A.D. 600 to 1300 and with requirements on agents to acquire protein by hunting deer, hares, rabbits, find sufficient firewood for use in cooking, and acquiring drinking water. The Palmer Drought Productivity Index (PDSI) paleoproductivity planes were used with future plans to test with other data planes. The additional resources increased the complexity of the system and consequently restricted the ability to run the model within reasonable time on a single machine. Pentium III dual processor PC's and Pentium IV 3.0GHz machines require several weeks to run the model for all the years. The hardware limitations were overcome by porting the model to a high-speed grid-computing distributed environment. Sixteen independent nodes with dual Xeon processors were configured to compute the model. The model was modified to execute on the grid by implementing a batch mode and enabling parallelization in the model to use the Swarm engine's parallel abilities.

In the first section of the present paper we introduce the cultural evolution model and the Cultural Algorithm (CA) framework used to embed social intelligence in the system. Next we provide an overview of the social network and the composition of the kinship, economic and hub networks. The exchange over these networks is then described. We define generalized reciprocal exchange as well as balanced reciprocal exchange that agents can participate in and learn to evolve better exchange choices. Historical, situational and normative knowledge is collected in the belief space that allows both individual and cultural learning about the exchange networks. In these experiments we require agents to use maize, deer, rabbits, hare, water and firewood, but we allow only maize to be exchanged. The experiments and results sections describe the effects of adding the hub network to the system, and then allowing exchange on the hub network, and then enabling defectors within the network. The trends generalized from these results are then described and show how social intelligence and learning is reflected in population and network volumes at the hub level.

2. Cultural Evolution

2.1. *Evolutionary Adaptation*

Holland developed a formal framework for any generic adaptive system.[13] His framework for adaptation concerns a system that is able to alter its structure and/or behavior based on the experience in some set of performance environments.[14] Adaptability is the capacity to function in an uncertain or unknown environment, and to use information to evolve and learn.[15] Adaptation can take place at three different levels: population, individual and component.[16] CAs were designed to allow the emergence of social intelligence at all three levels.

CAs consist of a social population and a belief space[14] as shown in figure 1.

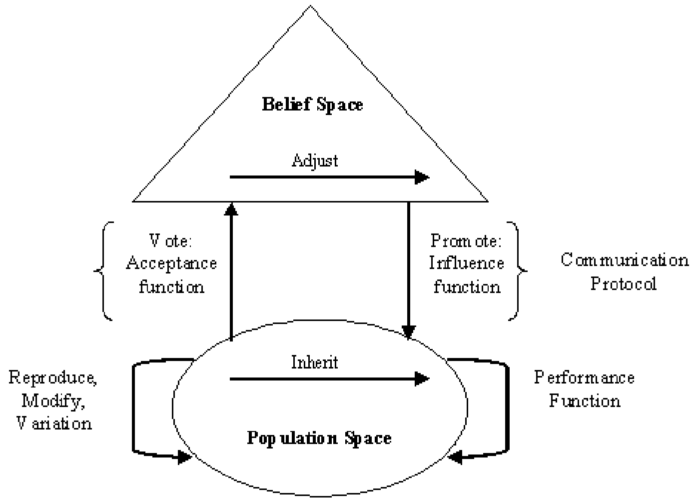

Fig. 1. Cultural Algorithm Framework According to Reynolds

Selected individuals from the population space contribute to the cultural knowledge by means of the acceptance function. The knowledge resides in the belief space where it is stored and manipulated based on individual experiences and their successes or failures. In turn, the knowledge controls the evolution of the population by means of an influence function. A CA thereby provides a framework in which to learn and communicate knowledge at both the cultural and individual levels.

2.2. *Knowledge Types*

There are at least five basic categories of cultural knowledge that are important in the belief space of any cultural evolution model: situational, normative, topographic, historical or temporal, and domain knowledge. These knowledge sources are derived from work in cognitive science and semiotics that describe the basic knowledge used by human decision-makers. In our CA all of these knowledge sources can be represented and learned. For example, in our current model we assume that agents can acquire knowledge about the distribution of agricultural land as well as wild plant and animal resources (topographic knowledge), the distribution of rainfall and water resources (historical or temporal knowledge), agricultural planting and harvesting techniques (domain knowledge), hunting technology, and fuel collection and use. Currently planting and harvesting techniques are held static. The amount of annual rainfall is also fixed based on tree-ring data that is used to estimate the production during each model year.

3. Social Networks

3.1. *Kinship Network*

The emergent networks in the model are composed of agents. Each agent is a nuclear family or household composed of a husband, a wife and their children. Household members live together in the same location, share their agricultural production, and are affected by the same environmental conditions. Children can grow up, marry, and move out to form their own households. Their connections to their parent households and siblings are maintained in our model. Similarly, the parents maintain ties to their children. When one of the parents in a household dies, the other can form a new household with an available single agent. The initial structure of the social network here supports the notions of parents, siblings, and grandparents on both sides of the family. The layout of the generalized reciprocal network (GRN) from the perspective of a household is described in table 1.

Table 1. Connected nodes identified by the kinship social network.

Link Type	Description
ParentHHTagA	a link to the parent from the mother's side
ParentHHTagB	a link to the parent from the father's side
ChildHHTag	one link to each child that moves away from this household and form its own household
RelativeHHTag	one link to each extended family member

The household (agent) rules for marriage and kinship dynamics were described in earlier work.[7] The social network is defined as the set of all kinship links. The first extension to the original model of Kohler et al.[6] introduced gender, marriage rules, and other localized enhancements to allow individuals to co-exist and reproduce. At the next level, the first base network, the kinship network, was introduced. This is a baseline network that links each individual household to its parents, siblings, children and other relatives. Over this network, generalized reciprocal exchange was implemented so as to enable the agents to mutually cooperate and exchange resources across the network to survive. In generalized reciprocal exchange[11] an agent can donate resources to another without expecting a specific payback. In other words, the assumption is that when the donator needs aid sometime in the future they will receive it from the other. A small-world social network emerged and the resultant agent populations were shown to be more resilient to environmental perturbations than those without the network.

Motivated by individual experience and population norms, an individual, by means of a CA, was able to learn to make more intelligent choices in cooperating over the kinship network. For instance, an agent can learn to make a better choice when it comes time to decide whom to ask for food when in need. Over time an individual can learn to select more cooperative kin, and indirectly, a population can identify known exemplars and establish its acceptable norms.

As a result, established individuals became good donors, and those in less productive locations may depend on the social network for survival through the redistribution of resources through the network. The existence of this network enabled us to define a "social move" for households that results over time in a clustering of households around productive lands, and the emergence of the hubs in a small-world social network. The locations of these simulated hubs were compared to community centers known archaeologically and a reasonably good fit was observed. This initial application of CAs gave us some confidence in their utility for this application.

3.2. *Economic Network*

In the next phase of development we implemented a second important baseline network: the economic network. For societies in this region, and for similar small-scale societies elsewhere, anthropologists and archaeologists have abundant evidence for the exchange of pots, stone and stone tools, and even maize within and between regions, on a scale that seems to surpass what would be expected from the kin-based exchanges we model in the GRN. This suggests the potential for economic-based exchange as another mechanism for redistributing resources among the agents. The version implemented here, where the receiver of a donation incurs a debt to be repaid in kind at a future date, is called balanced reciprocal exchange. Each household maintains a list of trading partners formed mainly from nearby agents that are independent from the kinship network. Individuals adopt a strategy to decide when and with whom to exchange. In this model, unlike the generalized reciprocal exchange model, individuals keep balances of the amounts owed and traded. The ability of agents to repay their debts reflects their reliability, generalized here as reputation. Households on productive lands, with stronger social ties, tend to develop good reputations; less reliable households tend to reside on less-productive lands and have weaker social ties. A CA is adopted again in the balanced reciprocal exchange network to guide the decisions that an agent and the culture make in selecting reputable trading partners.

3.3. *Hub Network*

A hub network is one that emergences from both the GRN and balanced reciprocal networks (BRN) (figure 2). The implementation of the two base networks allows the agents to elaborate their importance by promoting themselves to the next network: the hub network. The hub network consists of nodes of sufficient standing in both networks. In this paper we use the intersect, where a hub node must be prominent in both the GRN and BRN. An influential agent or node is one with many direct ties to other agents, such that the number of ties for an agent exceeds a minimum number or constant. In addition, the eligibility of a hub node for promotion is determined by its location within a probabilistic discrete Poisson distribution defined by its number of links to other hub nodes. Similarly, a hub node is able to demote itself and remove itself from the hub network if on re-evaluation it has lost its importance on either the GRN or BRN. Hubs have the ability to exchange between each other (under the ruleset we define as Co-op 6) and the ability to defect on their trades. A defector threshold, in terms of calculated Poisson distribution, is defined for a hub to trigger itself to defect.

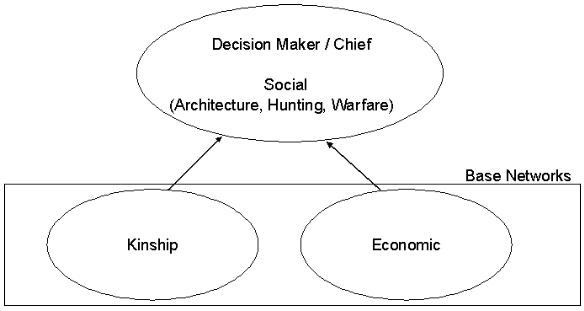

Fig. 2. Overall social network structure including the two base models and the evolving communal network.

4. Using The Social Networks To Support The Exchange of Resources

In this section we describe how the two networks, GRN and BRN, are integrated and how they evolve with the agent population. We begin with Generalized Reciprocal Exchange.

4.1. *Generalized Reciprocal Exchange*

The generalized reciprocal network (GRN) was introduced in previous work[7,8,9] using the kinship network. The GRN links agents with one another based on their kinship relations. The GRN serves to guide the flow of resources between relatives based upon the states of a giver and a receiver. One individual can request goods from a related individual without the donor expecting payback explicitly.

4.2. *Balanced Reciprocal Exchange*

The balanced reciprocal network (BRN) is an economic network that supports the exchange of goods between neighboring agents. In a balanced reciprocal transaction the giver expects an immediate payback of an equivalent amount or a deferred payback. The localization of the exchange between agents in the model is to enforce the physical constraints of travel distance limitations when an agent engages in exchange. This constraint is consistent with that implemented in the generalized reciprocal network. Each agent maintains a set of trading partners who are not

Table 2. Description of the different cooperation methods at the kinship level.

Cooperation Type	Description
0	No cooperation. No exchange of food between households.
1	When an agent requires food, it is allowed to select and request food from within its kinship network to survive.
2	When an agent has excess food, above a determined threshold amount, it is allowed to select an individual(s) from its kinship network and donate the excess.
3	Both methods 1 and 2 are enabled.
4	Full cooperation across the Kinship and Economic Network (Generalized and Reciprocal Exchange simultaneously)
5	Hub network emergence based on the INTERSECT of hubs from GRN and BRN networks, and accepted based on a Discrete Poisson distribution.
6	Hub Network developed in co-op 5, with addition of exchange with other hubs.

necessarily associated with the kinship network. A trading partner can be any agent within a given radius from the agent.

The overall agent strategy for exchange using both the GRN and the BRN is given below. The key idea is that exchange in the current model occurs when an individual needs resources. After updating their networks they first try to satisfy their own resource needs by calling in debts from their neighbors using the BRN. If they are not successful then they request aid from their relatives through the GRN. If they still are deficient in resources then they return to the economic network with new requests. Figure 3 illustrates the agent connectivity in the BRN. Table 2 lists the different cooperation strategies possible in the model to control the agent exchange abilities.

4.3. *Resources*

According to archeological data the Anasazi regularly cultivated maize (and beans and squash, which we do not model), and hunted deer, rabbits, and hares (and some other usually less-important animals that we also do not model). In addition they collected firewood for cooking and heating. Water is of course another requirement necessary for life. In the current model use of all these resources is enabled and tracked. In this paper, exchange is limited to maize on all networks.

4.4. *Integrating Base Networks to Facilitate Exchange*

Every step the agent performs the following actions specific to exchange:

(i) Update GRN
(ii) Update BRN
    (a) Remove dead partners [and non active/out of region/expired]

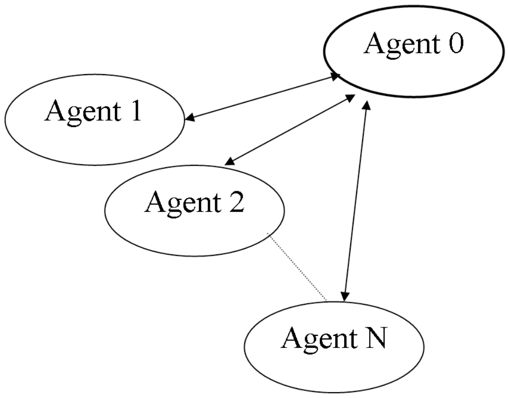

Fig. 3. Agent connectivity in the BRN. Agent 0 maintains its links with its exchange partners Agents 1 to N.

(b) Search each neighboring cell within a trade radius and get its settlers list and add new ones to the trade list

(iii) Update Hub Net
  (a) Self Promote/Demote to/from Hub Net based on current base status
  (b) Remove dead partners and search for new ones in range

(iv) Request payback of debt from BRN and Hub Net partners

(v) if HUNGRY/CRITICAL
  (a) Request food from GRN (no payback)

(vi) if HUNGRY/CRITICAL
  (a) Request food from BRN (with payback)

(vii) if HUNGRY/CRITICAL
  (a) Request food from Hub Net (with payback)

(viii) if CRITICAL
  (a) Agent is DEAD and removed

(ix) if PHILANTHROPIC/FULL
  (a) Donate surplus into GRN
  (b) Pay back debt owing into BRN
  (c) Pay back debt owing into Hub Net

5. Methods And Results

To understand the effect of balanced reciprocal exchange on the overall population and network resilience we set up a series of experiments to establish controls and comparison baselines. In previous work[8] we executed a sequence of experiments from co-op 0 to co-op 4 (table 2) and demonstrated that presence of both baseline networks permits the simulation to better match archeological estimates of agent population size. In the first round of experiments no cooperation between agents was enabled, and consequently the agent population died very early in the model. Next, with only the generalized reciprocal exchange enabled, the population again did not survive. In both these experimental setups the population was unable to survive suggesting the need for further cooperation.

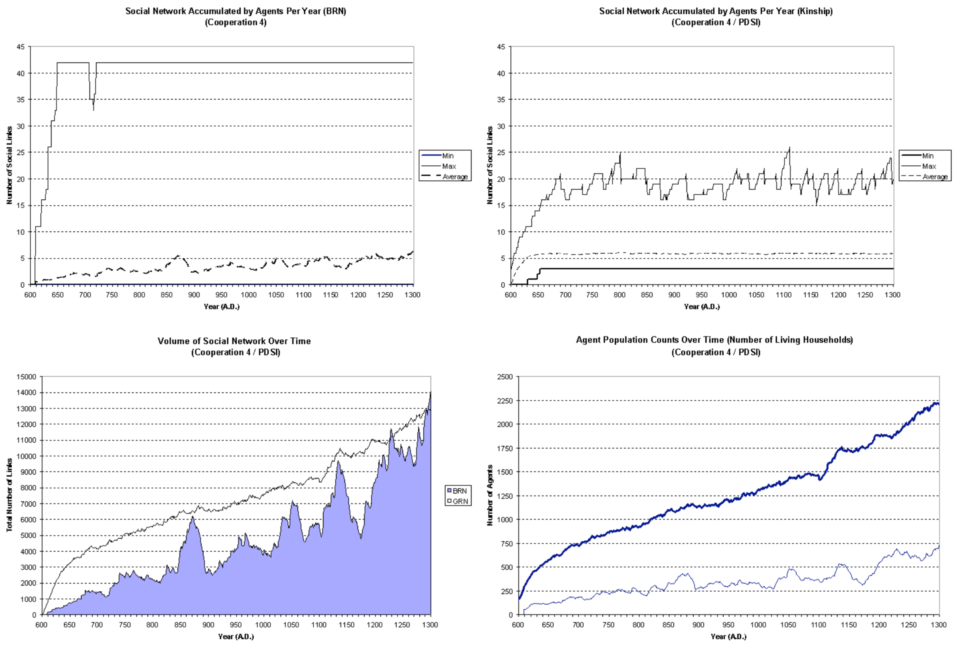

Fig. 4. Network characteristics with the presence of cooperation over the kin network (GRN) and the economic network (BRN).

In figures 4 and 5 we establish basic network characteristics in the presence of cooperation over both the kin and economic networks. Although the population counts remain steadily increasing, the economic network will become more resilient when defectors are present.

In the next phase of the experiments we extend the model to allow the emergence of the hub network.

The first step is to execute the model without exchange on the hub network. This allows us to measure the baseline effects of base social networks on the population (figure 6). Even though the hub network was not used for exchange the basic structure of the evolved network was shown to be consistent with that of the other

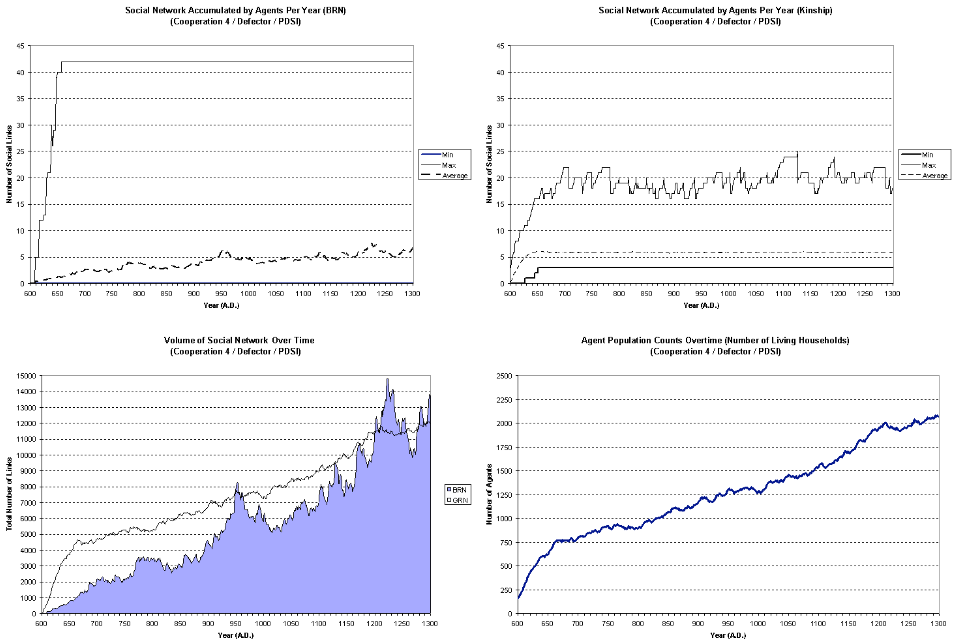

Fig. 5. Network characteristics with the presence of cooperation over the kin network (GRN) and the economic network (BRN) with the presence of defectors.

networks; that is, it also exhibited small-world characteristics.

In the absence of exchange on the Hub network we identify the network volumes of the baseline networks. Although the GRN volume is always higher than the BRN volume, the latter tends to increase as a proportion of all exchanges through time. Balanced reciprocal exchange enhances the kinship network, producing a slightly more complex structure. Also, this suggests that the network extends and complements the more limited range of the GRN. The volume of the generalized reciprocal network exceeds that of the balanced reciprocal network. This means that there are subsistence needs that are not met by the GRN on its own, and that over time the group learns to produce an economic network that gets better at fulfilling those needs.

In figure 7, exchange is introduced across the hub network to allow the hub agent to perform balanced exchange with other hubs. As a result, the volumes of the two base networks are smaller than that observed without the exchange in the hub network. Thus, adding the hub network reduces the pressure on the two base networks and allows them to be streamlined.

The BRN is the most responsive to changing production conditions (figures 6 and 7). The PDSI productivity reconstruction used here is mostly sensitive to changing precipitation. The Little Ice Age was from about A.D. 1300 to 1850;

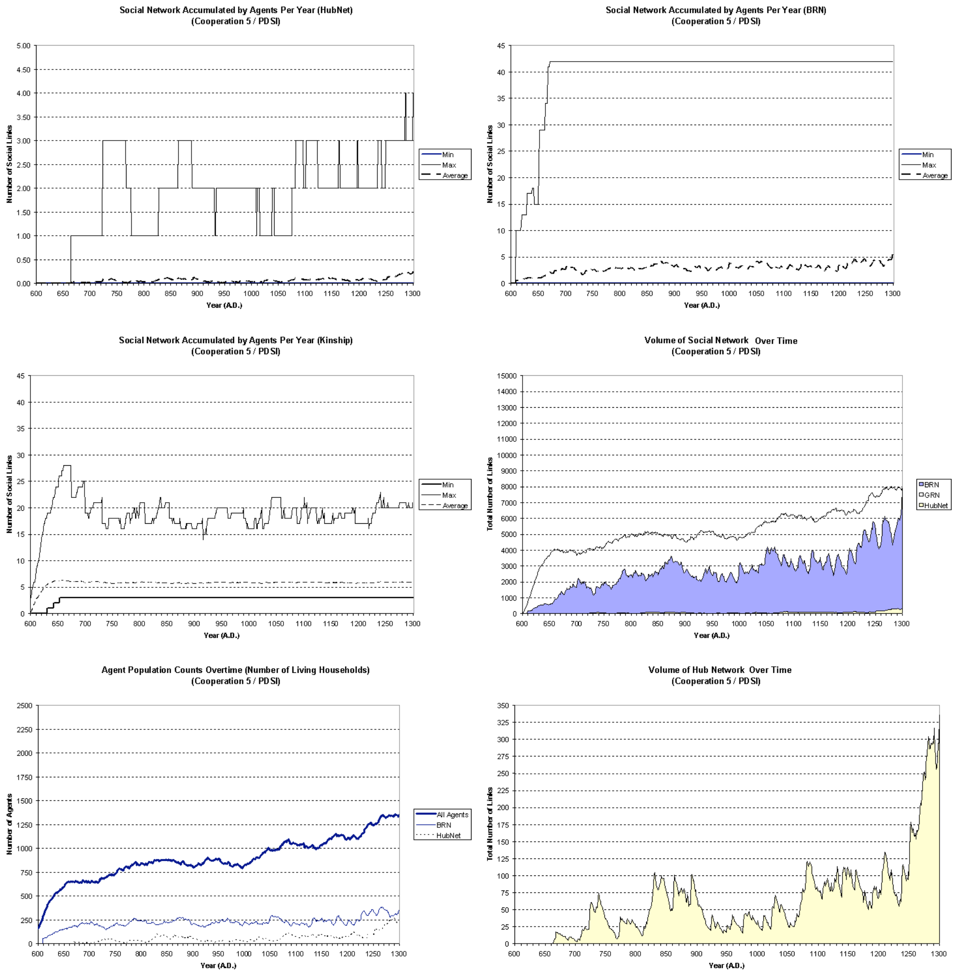

Fig. 6. Network characteristics with the presence of cooperation over the kin network (GRN) and the economic network (BRN) and the emerging Hub network.

it primarily affected temperature, not precipitation. Upward spikes in the BRN correspond to drought conditions, in which agents attempt to reduce their shortfalls through balanced reciprocity when their kin networks become insufficient to the task. Peaks in the volume of the hub network are slightly delayed relative to those in the BRN. Although hub network volume remains small relative to those of the other networks, it is nevertheless clear that the system comes to rely more heavily on this network towards the period of abandonment.

In figure 8 we show the network volumes that result when we introduce defectors into the hub network. A defecting agent is one that elects to request resources when needed, but strategically ignores repayment of debt or making donations to others.

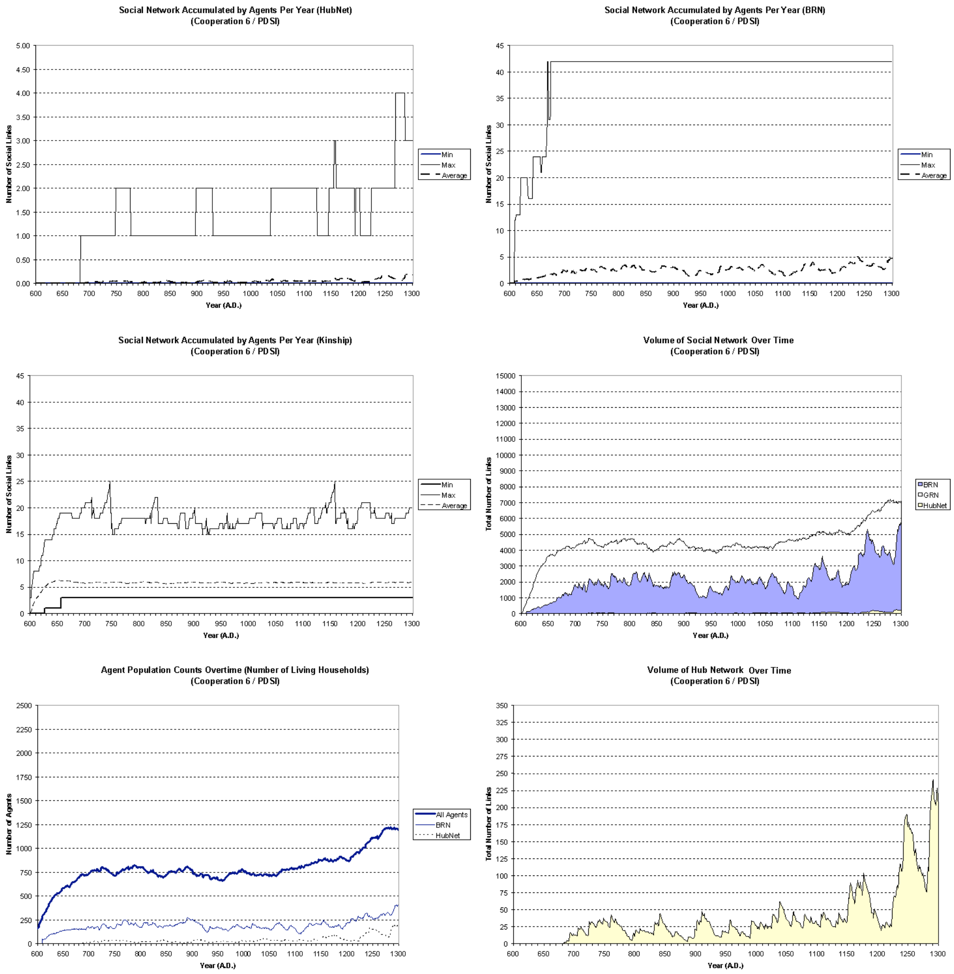

Fig. 7. Network characteristics with the presence of cooperation over the kin network (GRN) and the economic network (BRN) and the emerging Hub network including exchange across hubs.

A discrete Poisson distribution relative to the hub size is used to elect the probability that a hub agent should defect or not. Introduction of defectors into the hub network drastically increased the resilience of the network to environmental perturbations and increased its volume to nearly double that observed without defections. In conjunction with this observation, we note in table 3 the population sizes for some selected years across the simulation under all the tested conditions. This reveals that although defectors increased the overall volume and resilience, the population size maintained itself at about the same level as if no defectors present. Also, the introduction of the hub network did achieve a better control of population sizes as population density increased. The presence of defectors in the hub network presents

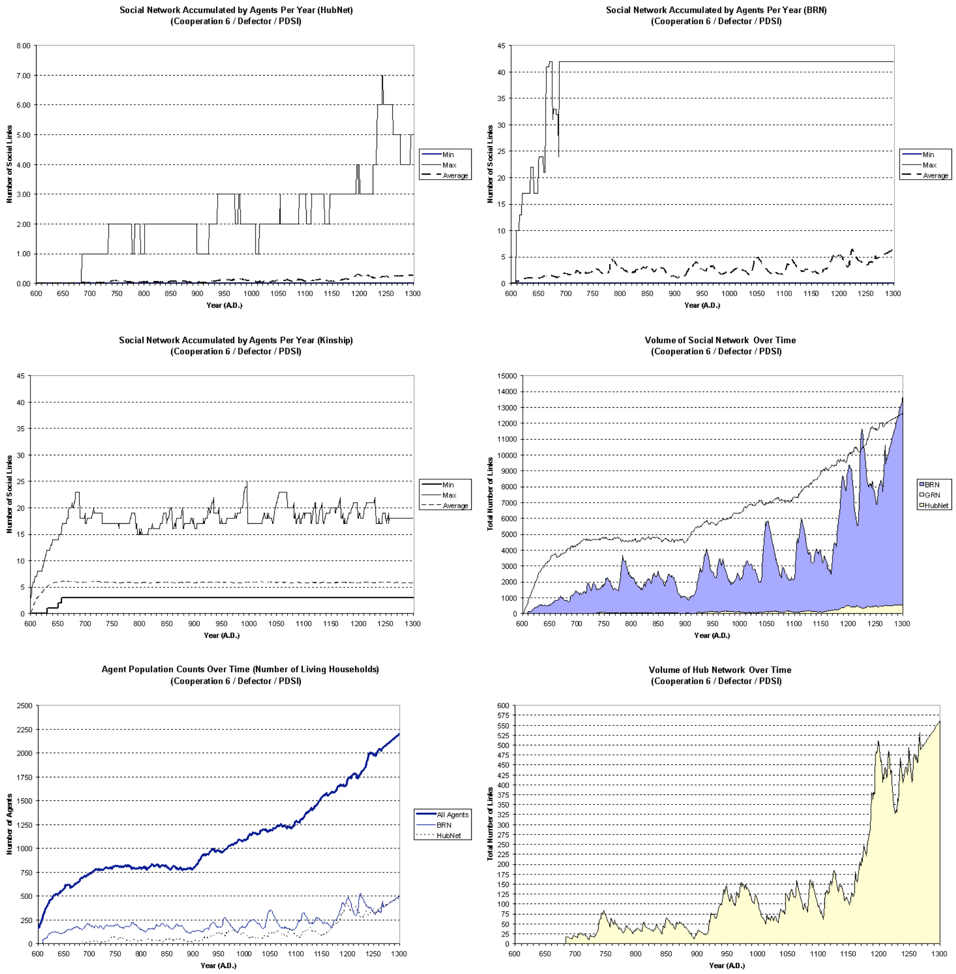

Fig. 8. Network characteristics with the presence of cooperation over the kin network (GRN) and the economic network (BRN) and the emerging Hub network including exchange across hubs with the presence of Defectors.

the hub agents with a better opportunity to survive since it provides them with a surplus that might be needed unexpectedly, while it weeds out the smaller-size hubs. This suggests that for agents to survive under stressful conditions they needed to aggregate in larger communities rather than live in small groups with few social links.

6. Conclusions And Future Work

Emergent properties observed in simulated populations of the Mesa Verde Village region reveal a pattern of social intelligence that individual households use to col-

Table 3. Agent population estimates during different periods.

Experiment Type	Agent Population Estimates		
(PDSI data planes)	A.D. 900	A.D. 1140	A.D. 1300
Co-op 0	0	0	0
Co-op 3	0	0	0
Co-op 4	1200	1750	2240
Co-op 4+Defect	900	1700	2100
Co-op 5	800	1100	1350
Co-op 6	750	850	1200
Co-op 6+Defect	750	700	1200

lectively adapt within a CA framework. In particular, the system is able to evolve and to use both a kinship network for generalized reciprocal exchange (GRN) and an economic network to support balanced reciprocal exchange (BRN). The system is not able to develop sufficient social complexity without the inclusion of both resource redistribution networks. Their structures suggest a complementary role for the two networks such that the economic network is adapted by the agents to extend the basic distribution of resources from just kin to non-kin as well. The addition of the hub-node network reduced the social complexity of the two networks from which it formed. However, the hub net was more susceptible to environmental perturbations than its predecessors. Adding the ability for agents in the hub net to defect improved the resilience of the system in the wake of environmental stress without a significant reduction in overall agent population. Through defection an agent can store up residual resources that allow it to survive unexpected environmental change.

In future work we will enable agent strategies to exchange all the resources available so that we can compare the networks for each of the resources to identify system fragility with respect to any given resource. This includes all the hunting and firewood collections. Furthermore the majority of agent actions here relate to risk reduction and risk avoidance activities. In future work, we will investigate the addition of agent actions that relate to risk taking. Such actions include alliance formation, raiding another group to gain land and other resources, and the wholesale movement of an agent or group of agents from one region to another.

Acknowledgments

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