ELSEVIER

Social Networks 21 (1999) 311–337

SOCIAL NETWORKS

www.elsevier.com/locate/socnet

Spatial arrangement of social and economic networks among villages in Nang Rong District, Thailand

Katherine Faust [a,*], Barbara Entwisle [b], Ronald R. Rindfuss [b], Stephen J. Walsh [c], Yothin Sawangdee [d]

[a] Department of Sociology, University of South Carolina, Columbia, SC, USA
[b] Department of Sociology and Carolina Population Center, University of North Carolina, Chapel Hill, NC, USA
[c] Department of Geography, University of North Carolina, Chapel Hill, NC, USA
[d] Institute for Population and Social Research, Mahidol University, Salaya, Thailand

Abstract

This paper examines the spatial arrangement of social and economic networks among villages in Nang Rong district, Thailand. We use spatial information from a geographic information system (GIS) for the district to help interpret the patterns of movement of agricultural equipment (large tractors) between villages, of people into villages for temporary labor, and of people to village temples and to elementary and secondary schools within the district. Once social networks have been incorporated into the GIS they can be mapped in relation to geographic features of the district, such as topography, landcover, and locations of roads, rivers, and villages. Not only does geographic information about village locations allow us to properly orient the graphs of these networks, but the resulting visual displays reveal strikingly different spatial arrangements for the five networks. Networks of shared temples and elementary schools link small sets of villages in close geographic proximity whereas tractor hiring, labor movement, and secondary school networks bring together larger sets of villages and span longer distances. Information on landcover from satellite digital data provides insights into the patterns of network ties throughout the district and shows a clear relationship between tractor hiring networks and type of agricultural activity in the district. The spatial analytic capabilities of the GIS also allow us to assess the impact of the administratively defined district boundary on our measured relations and to evaluate whether rivers and perennial streams create barriers to network ties between villages.

* Corresponding author: Tel: +1-803-777-6848; fax: +1-803-777-5251; e-mail: faust@garnet.cla.sc.edu

0378-8733/99/$ - see front matter
PII: S0378-8733(99)00014-3

1. Social networks and spatial networks

How do networks of social and economic engagements link communities into larger regional-level systems? How are spatial proximity, features of topography, and land use related to economic and social networks between communities? This paper addresses these questions by looking at the spatial organization of social and economic linkages among villages in Nang Rong district, Thailand. We incorporate networks of five kinds of ties — sharing temples, elementary and secondary schools, labor movement, and tractor hiring — into an existing geographic information system (GIS) for the district to examine variation in spatial patterning of social networks and the relationship between these networks and such geographic constructs as proximity and land use. Doing so provides insight into how spatial aspects of land use are associated with patterns in networks of social and economic relationships among villages. Also, representing social networks spatially makes potential data error more visible, providing a valuable tool in checking data quality, and makes spatial pattern and distribution more obvious as a possible indication of landscape form and function.

The proper spatial location of network actors aids network visualization. Well-designed sociograms draw attention to important features of networks (Klovdahl, 1981; Freeman, 1996, 1997; McGrath et al., 1997) and proper geographic locations for nodes can provide additional insights into spatial aspects of network patterns. Interactions between people and between communities are influenced by opportunities and barriers to contact. The frequency of travel and visiting across locations depends on proximity, accessibility, and the characteristics of available travel routes. Some of these opportunities and barriers are spatial or geographic, yet social network analyses have seldom studied either spatial configurations of relations or how geographic features might shape social networks. In fact, most social network data sets do not contain information about the geographic locations of actors. Even analyses of networks in which actors have spatial locations (such as networks of economic and political transactions between nations or alliances between communities) do not incorporate geographic locations and accompanying spatial information into network models.

Over the past several decades a handful of studies have looked at regional-level networks among communities where nodes for communities can be spatially referenced. These studies have incorporated spatial information into their *representations* of networks but have paid little attention to spatial aspects of networks in their models. River routes of trade between villages have been used to study how Moscow's centrality in this network affected its rise as an influential city within the region (Pitts, 1965, 1978). Intervillage networks have also been used by Halpike (1970) to study patterns of alliance formation between Konso, Ethiopia towns, by Crump (1980) to compare the communications infrastructures between villages in Zinacantan and Chamula, Mexico, and by Barkey and Van Rossem (1997) to study contentious legal actions between Ottomon Empire towns. Morris et al. (1996) use networks of social interactions and visiting patterns between villages in Uganda as part of their analysis of the social and spatial basis for the spread of HIV. Networks within towns have been used by Hammond (1972) and Doreian (1987; 1988) to study the spatial arrangement of Mayan ceremonial plazas. On a larger scale, Hage and Harary (1991; 1996) use network models to study regional exchange systems among islands in Oceania.

Although these examples represent networks using sociograms in which points can be spatially referenced (nodes for villages are in appropriate geographical locations; ceremonial plazas are placed properly within the villages; positions of islands in Oceania correspond to the map of the area) subsequent analyses of these networks employ only the abstract graph — that is, they study graph theoretic properties based on linkages between nodes — but do not incorporate geographic distance or other properties of the landscape, topography, or spatial relationships (topology) among points. Nor do they investigate how locations of points, proximity, travel costs, landscape, topography, land use, spatial density or other geographic features are associated with characteristics of the social networks.

In contrast to the lack of attention to spatial features in social network research, social geographers have long employed graph theoretic ideas and *spatial network* models to represent and analyze flows between locations (Haggett and Chorley, 1969; Evans et al., 1995; Walsh et al., 1997). Nodes represent locations (cities, communities, etc.) and edges represent flows between points, such as roadways, rivers, or air traffic. Geographers then use graph theoretic concepts to model flows between locations and to calculate optimal locations for services such as fire stations or hospitals. However, with the exception of movements of people or commodities (e.g., commuter traffic flows from suburbs to cities), geographers have only minimally incorporated *social* networks or information on explicitly *social* transactions between occupants of different locations into their spatial models. Nor have geographers employed the wealth of social network analytic concepts and models.

Geographers have been concerned with the spatial patterning of social networks, organizations, and institutions particularly as those patterns relate to environmental factors and landscapes. Much of this work has been fostered by cultural ecologists and political ecologists in geography who have relied on qualitative ethnographic analyses, case study sampling, and intensive field ethnographies to study social systems and their influences on environmental systems (e.g., Denevan, 1989; Forsyth, 1996; Bebbington, 1997). For instance, Bebbington (1997) analyzed the spatio-temporal relationships between agricultural intensification and local social–spatial network developments associated with cooperative water management strategies, institution building for market development, and other social capital development initiatives in the Andean Highlands.

Geographers have also recognized the opportunity to integrate these field-oriented ethnographic studies with quantitative studies that account for broader-scale processes in both the political and the biophysical environments. Geographers have called for ‘‘hybrid research approaches’’ in order to link investigations of global change processes to sustainable development studies (Batterbury et al., 1997). Such approaches incorporate quantitative and qualitative research methodologies through the study of land use/cover change, which represents the most fruitful opportunity for the political ecologists and global change scientists to integrate quantitative and ethnographic research approaches (Turner, 1997). Gould (1996) argues that physical geography and human geography have always brought the spatio-temporal perspective to analyses of process.

Although both social network analysis and social geography employ graphs and graph theoretic concepts to analyze relations between units, the two traditions have proceeded as relatively separate enterprises. On one hand, social network studies seldom have actors with known geographic locations. On the other hand, although geographers employ graphs to represent flows between locations, for the most part they do not incorporate social transactions or social networks into their analyses. Recent advances in GIS's, with extensive capabilities for storing and analyzing spatial data, provide a means for joining social networks with spatial information and geographic models. Our intent in this paper is to begin to bridge these somewhat separate traditions by incorporating social network information into a GIS, thus spatially referencing the social transactions between actors in the network — in our case, villages in a district in Thailand. This will allow us to use the wealth of spatial information and spatial analysis capabilities available in the GIS to help understand network patterns. We can then model spatial aspects of social and economic networks between villages and relate these networks to information about spatial proximity, topography, land use and other spatial properties. Spatially locating and viewing social network data also allow for an assessment of the quality of the social network data in a manner that would not be available without the utility of the GIS. To our knowledge this is the first example incorporating a rich social network data set with a fully developed GIS.

2. Setting and data

2.1. Setting

Nang Rong, our research site, is located in Northeast Thailand (Fig. 1). Approximately the size of an eastern US county, the district includes three administrative centers and approximately 300 agricultural villages. Villages range in size from 19 to 475 households, averaging just under 100, according to 1994 survey data. Typically, they consist of a compact cluster of household residences surrounded by agricultural fields and forests of varying densities and type. The climate is very hot and is characterized by a pronounced dry and wet period — monsoonal rains are the primary source of moisture for agriculture and personal consumption. Social life takes place outside in shaded areas, in front of and underneath the dwelling units (which often are raised up on stilts). There is little privacy. Culturally and linguistically the region is diverse, reflecting the origins of original settlers. A few villages date back several hundred years to when the district was part of Cambodia, but primary waves of recent settlement occurred at the turn of the century and then again after the second world war. Villagers may speak Korat Thai (a dialect of the national language), Khmer, Lao, and/or Suai. In contrast to this cultural and linguistic diversity, the region is religiously homogeneous. Villagers are primarily Buddhist, and local temples are an important focus of religious and social activity.

Nang Rong is a relatively poor district. Most villagers are farmers, growing rice and upland crops such as cassava, sugar cane, kenaf, and corn. Soil quality is generally poor. Most agriculture is rain-fed, dependent on the timing and amount of the annual monsoon. Rice typically is grown in a patchwork of small paddies located in low lying

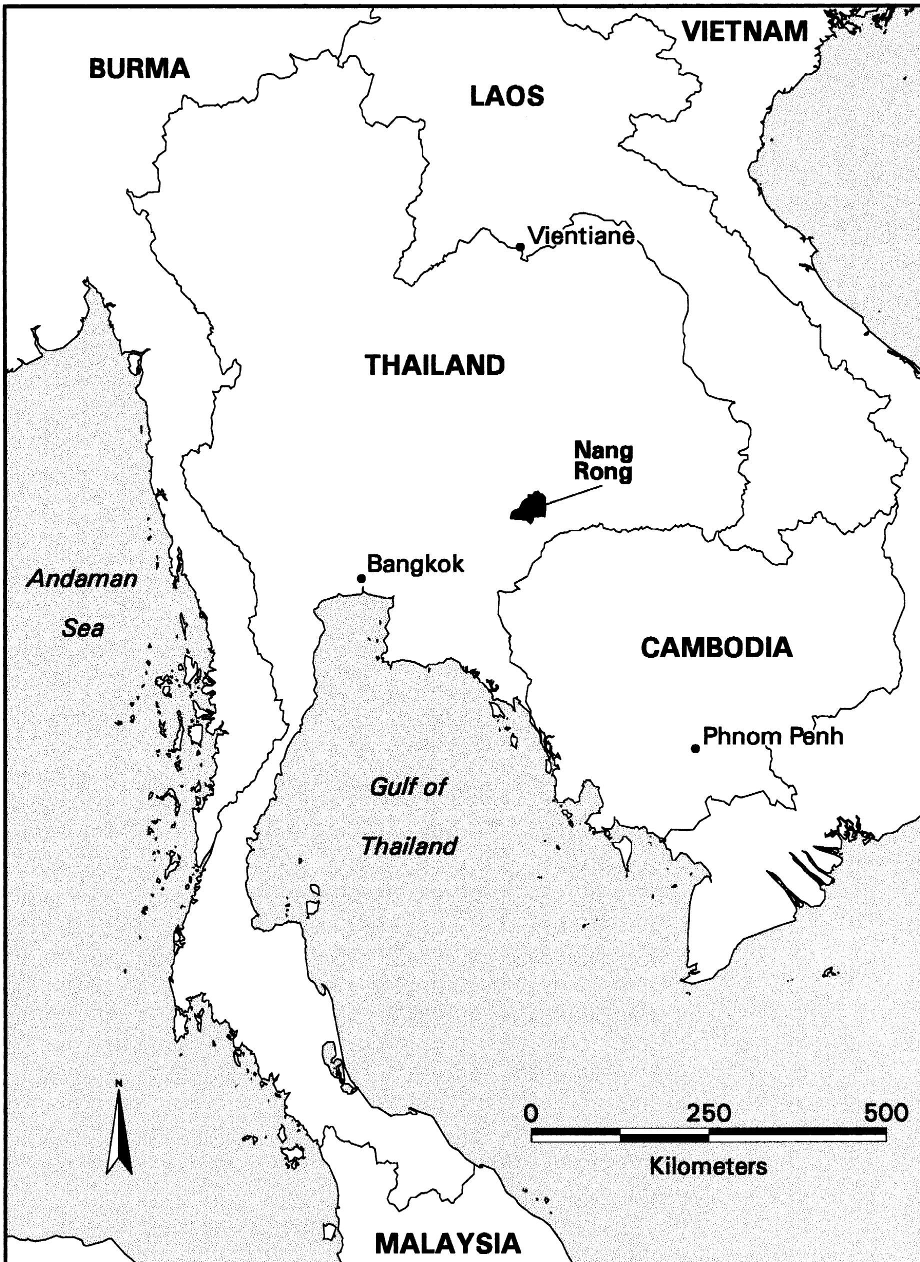

Fig. 1. Location of Nang Rong study area.

areas of the district. ‘‘Walking tractors’’ (roughly similar to rototillers in the US) are used to prepare the ground for planting at the beginning of the season, and mechanized mills are used to separate the edible portion of the grain from its husk, but otherwise rice cultivation in Nang Rong involves intensive handwork to plant, transplant, weed, and harvest the crop. In contrast, upland crop production is more mechanized. Large tractors are used to prepare the fields for planting and sometimes also for harvest. Cassava, exported to Europe as a supplement for cattle feed, is the most important upland crop. Given the expense, and the poverty of the district, most cassava farmers rent rather than own one of these tractors. Extensive deforestation has occurred in Nang Rong since World War II, associated with the expansion of agriculture. By 1993, forest covered only 17% of the district (Evans, 1998).

The landscape of the study area responds to a number of environmental and population gradients. From the biophysical perspective, variability in the fertility of the soil, elevation and slope of the terrain, and geomorphic parameters related to topography, particularly the terrace structure likely influence human behavior within this agricultural landscape as a consequence of landuse/landcover patterns and their areal distribution. From a social perspective, the position of the villages, demographic characteristics of the village and district, topology of villages to the land, and the three-dimensional variability of resource endowments and site suitability likely further influence social interactions as a by-product of geographic site and situation.

2.2. Geographic information system for Nang Rong

A GIS is an automated system for the capture, storage, retrieval, analysis, and display of spatial data (Clarke, 1990: 11). It generally consists of a relational data base linking the geographic portion of feature elements to their attributes and the integration of hardware, software, and geospatial information for conducting various types of spatial analysis, generating variables, displaying results, and creating maps. The construction of a GIS data base requires an investment of time and resources that makes sense especially when a given case or study area will be the focus of intensive research activity over a long period. A GIS data base was initially constructed for Nang Rong, Thailand to support research on (1) land use and population change (Rindfuss et al., 1996; Entwisle et al., 1997b; Evans, 1998; Walsh et al., 1999) and (2) family planning accessibility and its consequences for contraceptive choice (Entwisle et al., 1997a). Social networks represented as linkages between spatially referenced points, such as villages, are easily incorporated into a GIS data base.

Many capabilities of GIS are relevant to our examination of social networks in spatial context. First, the GIS serves as a key tool for integrating and analyzing data from diverse sources. The social network data come from a village survey. Village locations were obtained from maps and corrected using readings taken with global positioning system (GPS) devices in the field. Landcover classifications (i.e., rice, upland crops, forest, water) were derived from remote imagery (satellite data). The flexibility of the GIS is important to interrelating such different kinds of data. The social network and village location data are spatially discrete, whereas the landcover classifications are spatially continuous. Furthermore, the insights derivable from and about social networks are amplified in relation to the other data. Through the cumulation of demographic, social, economic, and environmental information over several projects based there, Nang

Rong, Thailand has become a ‘‘laboratory’’ for the study of social and landuse/landcover change.

Second, visual display through maps is the key to describing the spatial orientation of village networks in Nang Rong. The central results of this paper are presented through maps (Figs. 3–9, below). However, presenting graphs of relations using correct locations for villages raises important problems for preserving the confidentiality of the village survey data. If we were to present the social networks overlaid on a map of the entire district of Nang Rong with correct village locations and district boundaries indicated on the map, responses to village survey questions could be traced to specific villages and specific respondents within the villages. Being able to trace responses to specific villages conflicts with the need to maintain confidentiality based on assurances given to respondents as well as the basic foundation of contemporary social science. There are several ways to guard against a breach of confidentiality. One approach is to alter the map in some way, e.g., by transposing and reorienting it. We considered this approach, but it can create problems when social network data are related to other kinds of data having a strong spatial orientation. In Nang Rong, rivers flow south to north; topographic elevations trend from south to north; and the monsoon moves from west to east. Patterns of land use reflect this. Instead, to maintain the confidentiality of responses while preserving spatial information about villages and spatial relationships between villages, we present graphs for subregions of the district without specifying their exact locations within the district. We selected two subregions (labeled A and B in Figs. 3–9) that differ in their predominant agricultural activity, as indicated by the landcover classifications around the villages.

We should note that this conflict between explicit geographic presentation, as well as analysis, and the need to maintain confidentiality is an issue with which the social network and geographic communities will need to grapple. To see the point more clearly, imagine we had individuals instead of villages and that the network generator were sexual behavior rather than sharing a temple. The resulting social network maps would make it very public who was sleeping with whom.

Third, the spatial analytic capabilities of the GIS are used to measure distances between villages, the distance from each village to the district boundary, to characterize the kind of land cover/use in the area surrounding each village, and to locate rivers, perennial streams and bridges between villages. With the POINTDISTANCE command in ARC/INFO, a GIS software package, we estimate Euclidean (‘‘as the crow flies’’) distances from each village to all of the others. We can then calculate the average Euclidean distance traversed by ties between villages on different social network relations. We also use these estimates to consider error in the social network data. For example, descriptive village names are sometimes repeated in Nang Rong (e.g., three different villages are named Khok (a low hill) Pluang (a once-prevalent type of tree)). It is possible that coding errors were made in recording social network ties involving villages with shared names. We use intervillage distances to help shed some light on this issue. In a similar manner, the distance from each village to the nearest district boundary was calculated. Since the district of Nang Rong is an administrative unit, using the district boundary to specify our population of study villages may misrepresent the actual social network boundary. We anticipate that villages in close proximity to the district boundary will have more ties to villages outside Nang Rong district than will villages far from the district boundary. This may misrepresent network properties calculated for networks bounded by the district border. Finally, the spatial analytic capabilities of the GIS were used to characterize the land cover/use surrounding each village. Using the landcover classifications (i.e., rice, upland crops, forest, water) derived from satellite data, we calculated percent of land in upland agriculture and the percent of land in rice cultivation within a 1.5-km buffer around each village (Evans, 1998) [1]. Upland agriculture (notably cassava cultivation) requires greater use of tractors than does rice cultivation. Thus, we expect that these landcover measures will be related to the level of activity in the tractor hiring network. Villages with a large percent of their surrounding land in upland agriculture should be central in the tractor hiring network, whereas villages with a high percent in rice should not be central in this network. Since landcover is related to agricultural activities, landcover classifications may also be related to the movement of temporary labor into villages. The spatial analytic capabilities of the GIS permit us to systematically test relationships between spatial properties and social network features.

2.3. *Village survey and network data*

Information about villages and social networks of ties between villages come from a survey of all 310 villages within Nang Rong District. The data were collected during group interviews with village headmen and other village leaders in spring 1994 [2] and covered a wide range of topics including economic activities, agriculture, water resources, transportation and communication, electricity, social institutions, and health care. As part of the interview, selected questions were asked about relationships between villages. We focus on five relations for the purposes of this paper: hiring tractors, movement of temporary labor, sharing temples, elementary schools, and secondary schools. Before presenting the questions that served as generators, we give a brief description of each relation. Tractor hiring in Nang Rong refers to a temporary economic arrangement involving large, relatively expensive tractors. Few villagers have the financial resources needed to purchase such a tractor. If they plant cassava or sugar cane, villagers must hire someone's large tractor or plow with less efficient methods. Because of the expense, those owning a large tractor try to realize a return on their investment by hiring it out when not using it to plow their own fields. Tractor hiring signifies an economic relation, but the movement of tractors through the district connotes information exchange as well. The drivers chat with farmers as they go from village to village, spreading information and gossip from one to the next. We expect that tractor drivers serve as an important conduit for agricultural news, especially regarding price shifts and land management practices. Prices for cassava were fairly steady

[1] The percent in upland agriculture was calculated as 100 − (percent in rice + percent in forest).

[2] With questions of a factual nature, group interviews can provide higher quality data than individual interviews. Even if one person tends to dominate the responses, others are there to check and verify the accuracy of the answers given. To further improve the quality of the community or village data, all interviews occurred with at least two interviewers present.

through the early 1990s, but those for rice fluctuated sharply within and between years. Land management practices may include land preparation practices, date of planting, seed varieties, and site characteristics and yield relationships.

Agricultural activity within the district is seasonal, and the demand for labor fluctuates throughout the year. As a consequence, at times of low labor demand in a village, people may travel to other villages for temporary labor. At times of high labor demand, villagers may hire additional laborers from outside the village. The movement of people between villages for temporary labor is an economic link between villages, but also is an opportunity for social interaction between villagers from different locations.

Buddhist temples (wats) are places of worship, but in addition serve as gathering places. Based on conversations with headmen from a range of villages in Nang Rong, we have found that temples often symbolize a common history shared by the member villages. For example, the village built by the original settlers as well as offshoot villages are likely to share a temple. The temple is an important focus of activity on a variety of religiously important days (key moments in the lunar cycle, Songkran, and the beginning and end of Buddhist Lent). Thai Buddhist services tend to be less formal than typically is the case in Western religions, and the talk may cover a variety of topics including secular ones. In addition, village fairs are frequently held at the temples. For all of these reasons, the temples can be understood as a place where information is exchanged as well as a place of religious observance.

Whereas temples often grow out of a common history, the sharing of schools is more of an outgrowth of administrative action. Schools nonetheless serve as an important incubator of social ties. In Thailand, a shared school experience lays the foundation for lifelong friendships. Knowing which villages share a school thus provides important information about the potential for close friendships across village boundaries. Nang Rong children typically complete an elementary school education — now 6 years — but relatively few proceed beyond this. Those who do will attend one of the secondary schools in the district. In addition to further strengthening close ties between classmates, secondary schools may provide a context where migration groups might form. In rural Thailand, children will migrate for employment (farm and non-farm) as early as age 12 or 13.

The specific (translated) questions pertaining to the tractor hiring, temple and school networks are as follows.

Tractor hiring: asked of villages in which villagers hire a large tractor from another village.

‘‘From which village do villagers hire a tractor?’’

Labor movement: asked of villages that occasionally have to hire groups of laborers from other villages.

‘‘From which villages do these groups of laborers often come?’’

Sharing temples: asked of villages with a temple.

‘‘Does this temple belong to other villages or not? If yes, which villages?’’

Elementary schools: asked of villages that did not have an elementary school in the village.

‘‘Where do the children in this village go to study elementary school?’’

Secondary schools: asked of villages that did not have a secondary school in the village.

‘‘Where do the children in this village go to study secondary school?’’

The elementary and secondary school relations show the movement of students from the responding village to other villages in the district. In contrast, the tractor hiring, labor movement, and temple relations show the movement of people or equipment *into* the responding villages. In analyses reported below, these latter three relations are reoriented so that directed arrows show the movement of tractors or people to the villages. We imported the five relations as data layers into the existing GIS for Nang Rong district. Each relation was represented as a collection of ordered pairs of villages, where the ordered pairs indicated the presence of directed ties between villages.

During the village survey, interviewers had a list of all the villages in Nang Rong against which they could check and code the responses of the village leaders. Ties with villages in neighboring districts or provinces outside Nang Rong district were also noted. The list of villages was organized by subdistrict, the administrative units of which districts are composed. We have already mentioned duplicate village names. Villages sharing the same name are generally located in different subdistricts. There are 19 instances in which two villages have the same name, eight instances in which three villages share a name, and four instances in which four, five, six, or seven villages have the same name (involving a total of 84 from the 310 villages). Responses to the village network questions often were coded after the interview was complete. Duplicate names could have posed a problem. Interviewers might not know which of a pair or triplet of villages was intended, or may have been unaware of or forgotten that a given village name might refer to more than one village. We discuss this potential for error in more detail below.

Although the data on tractor hiring, labor movement, temples, and schools were collected at the level of the village, and questions were framed in terms of relationships between villages, we also see these relations as indicative of social and economic relations (or potential relations) between people and households. People hire and use tractors in their agricultural work; people travel between villages for temporary labor; people attend temples with people from other villages; children go to school with children from other villages. Thus these ties between villages represent actual, or at least potential, contacts, communications, and transactions between people from the various villages. As such, they relate to the potential flows of information and resources both between people and between the villages were people reside. Since villages have known geographic locations within the district, we can study the spatial aspects of these social and economic networks.

3. Analysis of the village networks

Descriptive statistics on network density, centralization, and subgroups allow comparisons among the tractor hiring, labor movement, temple sharing, elementary school, and secondary school networks. Table 1 presents descriptive statistics on these network features. The four relations are quite similar in density, ranging from 0.0017 to 0.0043. This corresponds to average in- and outdegrees of less than 1.0 for all but one of the relations. In contrast, the four relations are quite different in centralization and in subgroup structures. Centralization of indegrees, as measured by the variance of indegrees, is highest for the secondary school relation and relatively low for the other four relations. High indegree centralization for secondary schools is to be expected since secondary schools are located in 17 of the 310 villages and these schools draw students from many other villages. Outdegree variance is highest for the tractor hiring and labor movement relations and relatively low for the other three relations. This indicates that a few villages supply tractors to many other villages and that villages differ greatly in the extent to which they send laborers to other villages.

The relations also differ in their subgroup structures and in the prevalence of isolates. Over one-half of the villages are not involved in tractor hiring (184 of 310 villages are isolates), whereas the vast majority of villages either send or receive elementary school students and share temples. There are temples in 111 villages and elementary schools in 96 villages. Paralleling these observations, we see that the relations differ in their subgroup structures. The temple sharing and elementary school relations contain many

Table 1
Description of village networks

	Hiring tractors	Sharing temples	Elementary schools	Secondary schools	Labor movement
Density	0.0017	0.0024	0.0025	0.0025	0.0043
Indegree					
min–max	0–5	0–7	0–8	0–49	0–7
variance	0.84	1.77	1.90	16.30	2.58
Outdegree					
min–max	0–17	0–3	0–3	0–2	0–15
variance	3.38	0.44	0.38	0.38	4.29
Mean in- and outdegree	0.51	0.74	0.76	0.78	1.34
Number of isolates	184	47	20	82	64
Number of components[a]	9	59	59	9	5
Size of components[a]					
min–max	2–87	2–14	2–19	2–144	2–229
mean	14.00	4.46	4.92	25.33	49.2
Number of ties outsideNang Rong District					
min–max	0–3	0–1	0–2	0–3	0–5
mean	0.381	0.010	0.055	1.029	0.206
Percent with no ties outside district	73.9	99.0	94.8	12.6	87.4

[a] Excluding isolates.

small components (maximal weakly connected subgraphs) whereas the tractor sharing, labor movement, and secondary school relations have few components, some of which are quite large.

These results suggest different arrangements of the five relations, but the spatial aspects of these networks cannot be seen in graphs where village locations are arbitrary. Fig. 2 presents a graph of the tractor hiring relation without using information about proper locations for the villages (isolates have been omitted from this figure). This graph was constructed using KRACKPLOT (Krackhardt et al., 1994). We first analyzed a combined relation consisting of the union of the ties on the four individual relations

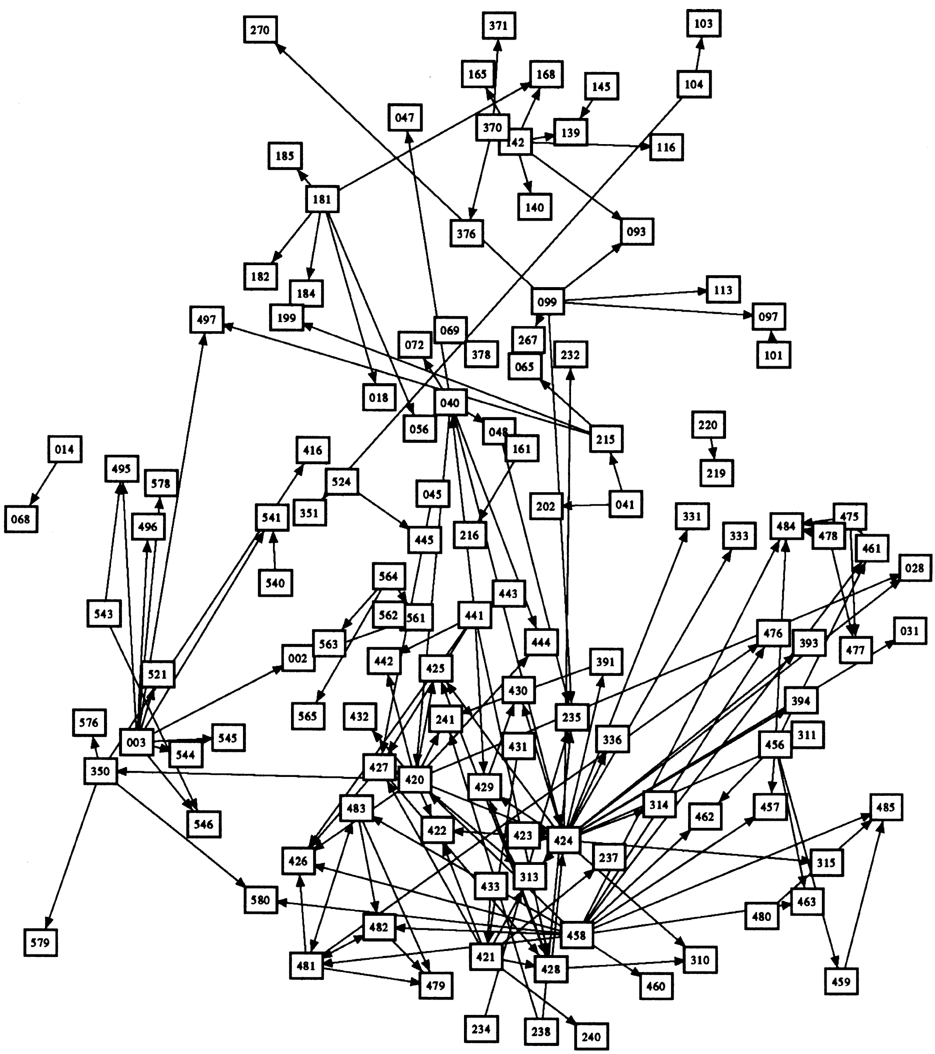

Fig. 2. Tractor hiring network without spatially referenced village locations.

(tractors, temples, elementary schools, and secondary schools). The point locations in Fig. 2 are the result of adjusting the configuration from QMDS, attempting to place adjacent points near each other and to reduce the number of crossing lines for all four relations simultaneously. One notable feature of this graph is the relatively dense concentration of tractor hiring ties between villages in the lower portion of the figure. However, without proper village locations and other spatially referenced information we cannot tell whether tractor hiring is related to geographic proximity of villages or to other geographic features such as landuse or topography.

It is far more informative to incorporate the social networks into a GIS which includes village locations. We can then map the networks using proper village locations and see how network properties such as subgroups and centralization are related to geographic and topographic characteristics of the district.

4. Social networks in the GIS

In this section we combine the social network data with information and analytical capabilities from the GIS. We first display the five networks using proper village locations. We then use the spatial analytic capabilities of the GIS to calculate Euclidean distances between villages in order to look at the distances traversed by different relations. We also use information about landcover classification from satellite images to help interpret spatial patterning of the relations. We then assess how the administratively defined district boundary impacts our measured relations and how rivers and perennial streams may pose barriers to network ties.

Figs. 3–7 show the tractor hiring, temple sharing, elementary and secondary school, and labor movement relations for two subregions within Nang Rong district. We present

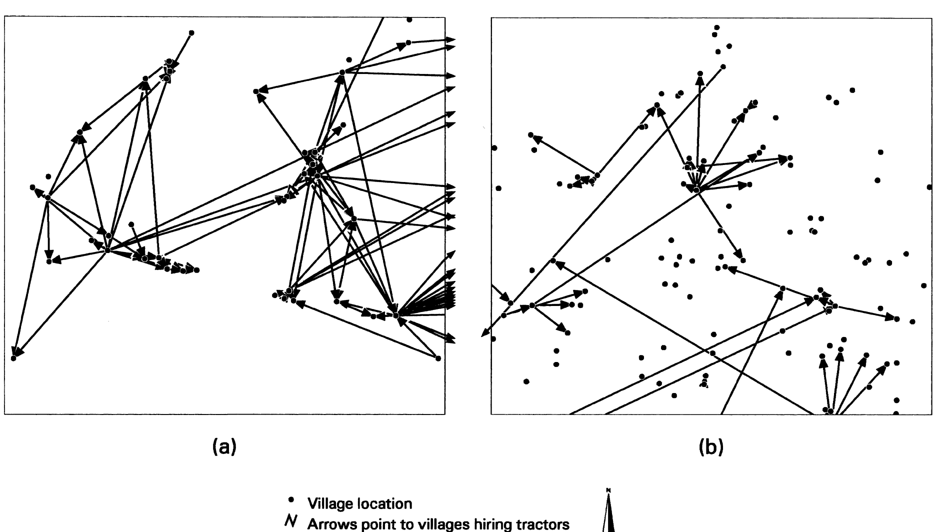

Fig. 3. Tractor hiring network in two regions of Nang Rong.

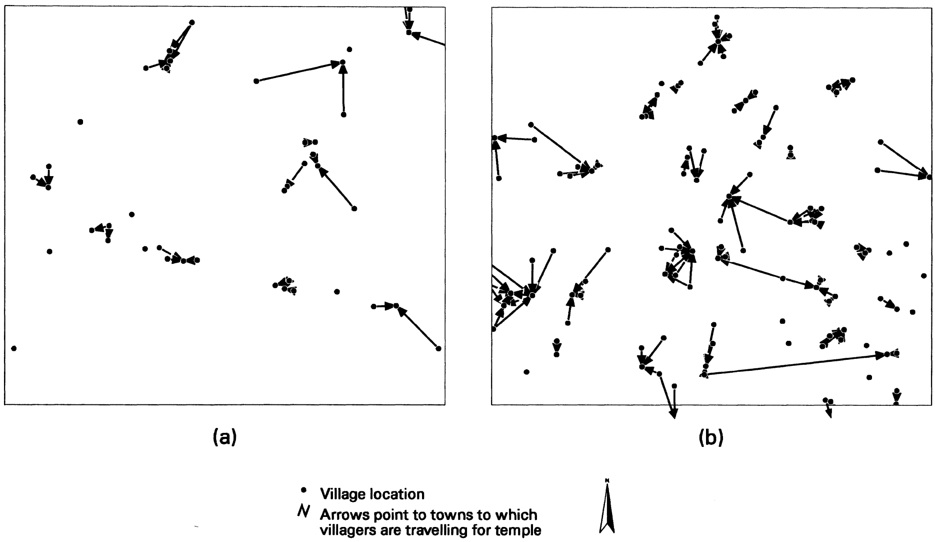

Fig. 4. Temple sharing network in two regions of Nang Rong.

networks for these two subregions rather than for the entire district so as to preserve confidentiality of response. When social survey data are used to generate pictures of ties between villages, the mapped social network can reveal specific responses given in survey interviews. The shift from a region to subregions changes the scale of the analysis, however, and may change what we see as a result. We have chosen these two

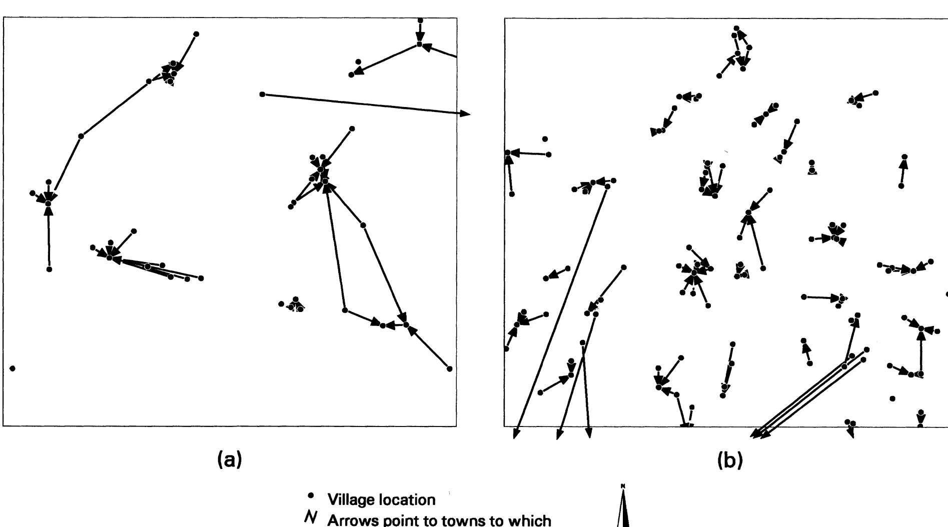

Fig. 5. Elementary school network in two regions of Nang Rong.

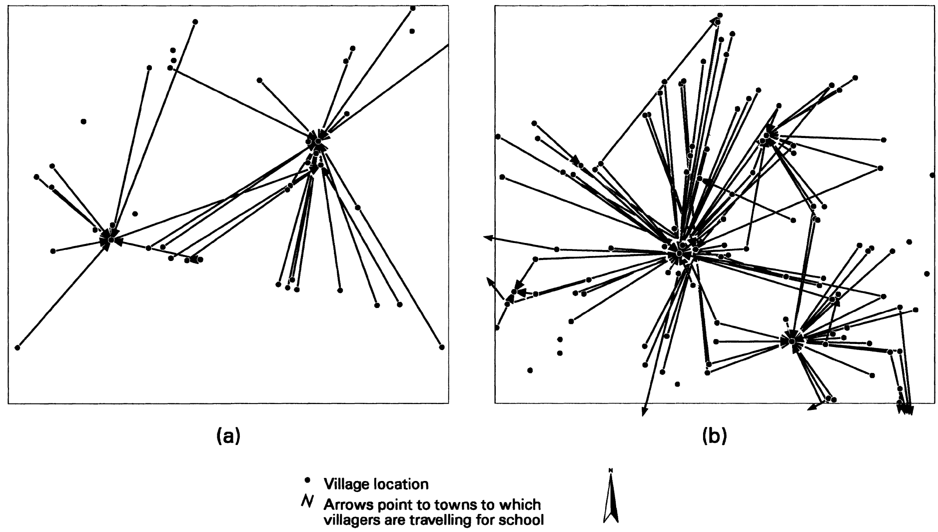

Fig. 6. Secondary school network in two regions of Nang Rong.

subregions to illustrate the main patterns emerging from a district-wide analysis. Another implication of the shift to subregions is the possibility of network ties to villages outside of the subregion. We indicate such ties with arrows whose heads extend beyond the (artificially imposed) boundaries of the subregion.

Consider the spatial patterning of the five relations. Sharing of temples and elementary schools are fairly evenly distributed throughout the district. This is shown in Figs. 4

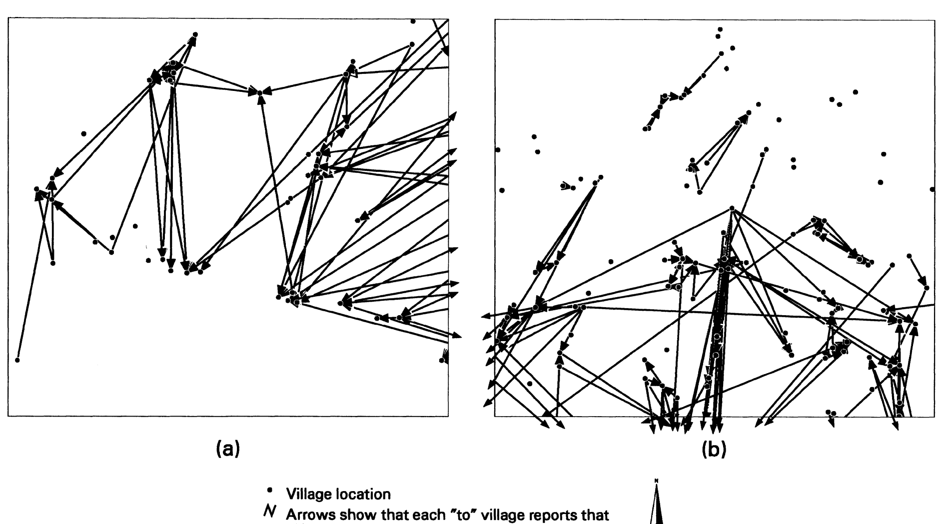

Fig. 7. Labor movement network in two regions of Nang Rong.

and 5. There are numerous small subsets of villages sharing temples, consistent with the presence of many small components in this network. The elementary school network is similar in pattern to the temple network with small components spread homogeneously throughout the area. For both the temple sharing and elementary school networks the distances traversed by the lines are relatively short. On average, temple sharing ties link villages within the district that are 1.48 km apart and elementary school ties link villages 2.11 km apart. [3] Thus, we see that villagers attend temples and elementary schools in close proximity to their home village. Although the temple and elementary school networks are similar in their spatial patterning, the correlation between the two is quite low (matrix correlation = 0.084). Temple and elementary school networks provide a context for close ties between residents of different villages, but their origins differ in important ways. The sharing of temples often grows out of a common past, while sharing of elementary schools is the result of administrative action.

In contrast to the temple and elementary school networks, the secondary school network has a few villages with secondary schools that attract students from many other villages. This shows up as star-like patterns in Fig. 6 and is consistent with high indegree centralization on this relation. The lines in the secondary school network are longer than in the temple sharing and elementary school networks (5.26 km on average), showing that students travel greater distances to secondary school than to temples or elementary schools. This type of patterning is exactly what one would expect. All children are required to attend elementary schools, but not secondary schools. Thus there are primary schools near all villages, but only a few secondary schools in the district. As the educational system moves towards promoting higher attainment for all students, more secondary schools will be built and the network pattern connecting villages will change.

Similar to the secondary school network, the tractor hiring and labor movement networks also links villages across relatively long distances (4.77 km on average for tractors and 5.28 km for labor), as shown in Figs. 3 and 7. The presence of a small number of villages as suppliers of tractors, as suggested by the high variance in the outdegrees on this relation, is also visible in this graph. Unlike the labor movement, temple, elementary school, and secondary school networks, however, spatial variability is pronounced in the tractor-hiring network. Consider the comparison between subregions A and B of Figs. 3–7. For the temple, elementary school, and secondary school networks, the level of activity is a little bit higher in subregion B than in subregion A, but this is due to pattern of settlement. More villages dot the landscape in subregion B than A, and this accounts for the difference. For tractor hiring, it is the reverse comparison. The level of activity, and thus the density of the network, is higher in subregion A than in subregion B.

How can we understand this spatial variation in the level of activity in the tractor hiring network? Insight into the difference between the two subregions can be gained by overlaying the tractor hiring network on landcover classifications derived from 1993 Landsat Thematic Mapper satellite data (see Evans, 1998 and Entwisle et al., 1998 for a

[3] The mean distance between all pairs of villages within Nang Rong district is 19.41 km.

description of how this was done). The ability to construct such an overlay is one of the advantages of incorporating social network data into a GIS. We distinguish between four types of landcover: rice (red); upland agriculture, mainly cassava (yellow-brown); forest (green); and water (blue). Fig. 8 shows the tractor hiring network superimposed on these landcover classifications.

The two subregions of the district clearly differ in landcover. Subregion A is characterized by upland agriculture, predominantly cassava but also including sugar cane. There is some rice cultivation in subregion A, but it is limited. The overlay of the tractor network on the landcover classification suggests a correspondence between large tractor use and upland agriculture. Heavy tractors can be used to prepare the land for planting, given the size and layout of the fields. In contrast, hiring of large tractors is less common in subregion B, where rice cultivation dominates. Rice is grown in small paddies — many less than a hectare in size — surrounded by low dikes or bunds. Tillers pulled by water buffalo or small walk-behind tractors (similar to rototillers used in gardens in the US), rather than large tractors, are used to prepare the land. The relationship between crop type and the kind of agricultural equipment used, along with the uneven distribution of crops throughout Nang Rong district, underlies the variation in density of flows of agricultural equipment between villages.

More systematic understanding of the relationship between landcover classification and the social networks can be gained by exploiting the spatial analytic capabilities of the GIS to characterize the landcover in the area surrounding each village. For each village, a 1.5-km buffer around the village was defined. Within each buffer the percent

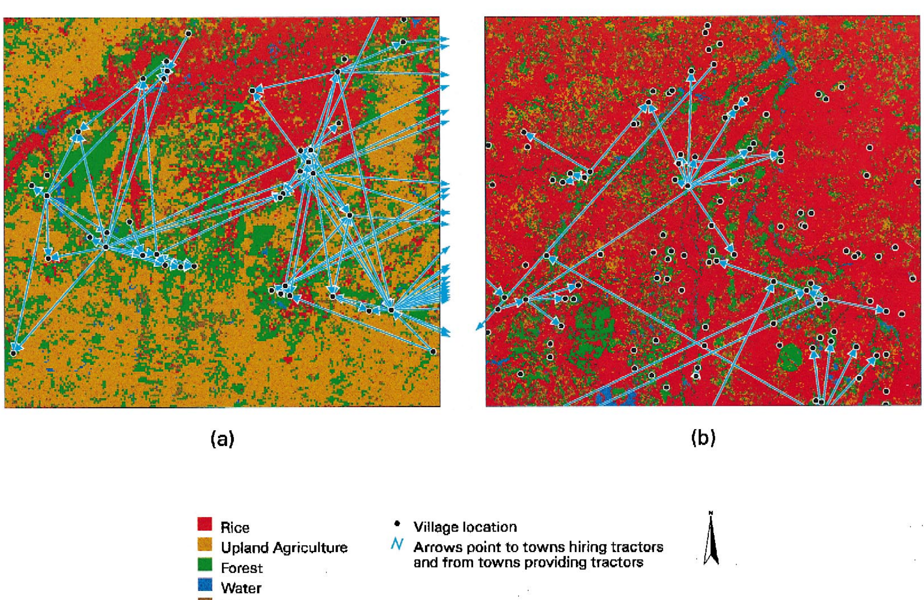

Fig. 8. Tractor hiring network overlaid on land use classification in two regions of Nang Rong.

of land in rice and the percent in forest was calculated. Upland agriculture makes up the remainder. (Percent in upland agriculture was calculated as 100 − (% rice + % forest)). For the 310 villages, the percent of land classified as upland agriculture ranges from 2.28% to 73.23% with a mean of 18.58%. The percent of land in rice ranges from 2.23% to 88.77% with a mean of 61.65%.

How is landcover related to village centrality in the various networks? Table 2 presents correlations between the landcover variables and indegree and outdegree centralities for the five relations. Of the five relations, only centrality in the tractor hiring relation is related to landcover. Villages with greater amounts of land in upland agriculture are more likely to both send and receive tractors. Villages with greater amounts of land in rice are less likely to both send and receive tractors. These findings are consistent with our previous observations of tractor activity as related to land use classification (Fig. 8). It is not surprising that centrality in the elementary school, secondary school, and temple networks is unrelated to land use classification. School locations are administratively determined. Attendance at temples is likely determined by accessibility, proximity, and a common history.

The relationship between landcover and tractor hiring ties helps us understand how spatial aspects of land usage are associated with patterns in networks of economic transactions between villages. Because these data are from a single time point, however, our understanding of the association between land use and density of tractors is simply correlational. We cannot discern whether prior presence of tractors in subregion A facilitated cassava cultivation in that area, or whether requirements of cassava cultivation brought an influx of tractors to that region. We do know that cassava, as a crop, was first introduced to Chonburi and Rayong Provinces, which lie to the southwest of Buriram Province, where Nang Rong district is located. Both Chonburi and Rayong

Table 2
Correlation between landcover classification and village indegree and outdegree centrality

	Percent of 1.5 km buffer planted in	
	Upland agriculture	Rice
Outdegree		
Hiring tractors	0.3469**	−0.3524**
Sharing temples	−0.0905	0.0781
Elementary schools	0.0627	−0.0782
Secondary schools	−0.0788	0.0687
Labor movement	−0.0955	0.0697
Indegree		
Hiring tractors	0.4607**	−0.4823**
Sharing temples	−0.0736	0.0181
Elementary schools	−0.0089	−0.0104
Secondary schools	−0.0287	−0.0326
Labor movement	0.0155	−0.0456

** $p < 0.01$.

Provinces are places where young men and women migrated for work during the dry season in Nang Rong. It may be that the seasonal migrants were influential in bringing both large tractors and cassava to Nang Rong simultaneously. We also note that the area currently under cassava cultivation was the last in Nang Rong to be settled and the last to be deforested. It may be that the large tractors played a role in this process in ways that had not occurred in the rest of the district.

We can also use the spatial analytic capabilities of the GIS to examine how our the boundary of our network impacts measurement of network properties. The boundary of our network is the administratively determined border of Nang Rong district. This administrative unit may or may not coincide with a boundary of social interactions between villages. We can use spatial information to examine how village location within the district is related to network properties. Specifically, we look at how the distance from a village to the district border is related to village ties beyond the district to other districts and provinces.

For each village, the distance from the village to the nearest district border was calculated. Villages range from 0.12 km to 14.74 km from the nearest district border, with a mean of 5.64 km. Since the village survey recorded ties to villages outside Nang Rong district, we can look at how proximity to the district border is related to the extent of ties outside the district.

The extent to which ties extend outside Nang Rong district varies across the relations. Only three of the villages with temples (1% of all villages) share the temple with villages outside Nang Rong district. Sixteen villages (5.1%) send some students to elementary school outside the district, but 271 (87.4%) send some students to secondary school outside the district. Eighty-one villages (26.1%) hire tractors from outside the district, and 39 (14.4%) have temporary laborers come from outside the district. Consequently, limiting our population of villages within the district differentially impacts the different networks.

Table 3 presents correlations between the distance to the district border and the number of ties outside the district for the five relations. Results show that villages close to the district border are more likely to send students to secondary school outside the district and are more likely to have temporary laborers come from outside the district. However, contrary to expectations, villages that are close to the border are *less* likely to

Table 3
Correlation between number of ties outside the district and distance from the village to the district boundary

Relation	Ties outside the district
Hiring tractors	0.1597**
Sharing temples	0.0742
Elementary schools	0.0620
Secondary schools	−0.1411*
Labor movement	−0.1206*

* $p < 0.05$.
** $p < 0.01$.

hire tractors from outside the district. This unexpected result could be due in part to the spatial distribution of tractors already within the district (i.e., close to the border), but certainly deserves further investigation.

Finally, we use the spatial analytic capabilities of the GIS to examine the impact of hydrologic barriers (permanent rivers and perennial streams) on the likelihood of ties between villages. We expect that such barriers will decrease the likelihood of ties. However, the impact of a waterway between a pair of villages should be lessened if there is a bridge available.

In our analysis of distances between villages, presented above, the social network ties between pairs of villages were mapped through straight-line vectors connecting village centroids. These indicate the directionality and ''Euclidean'' distance between the linked villages. Euclidean distance assumes an isotropic surface in which travel occurs on a frictionless plain and where impedances associated with the location and type of roads are set to zero. Therefore, the movement between villages is unconstrained by the position and type of roads and/or relative or absolute barriers. Entwisle et al. (1997a), however, showed that road location and type that connected villages in Nang Rong district were important predictors of contraceptive choice, and Walsh et al. (1997) showed that the geographic nature of local transportation networks was important in defining hospital service areas and in routing patients to health care facilities considering supply, demand, impedance, and spatial interactions represented within location/allocation models.

To study barriers to interactions between villages, we use the GIS to examine the geographic pattern of villages that are (a) positioned within 3-km Euclidean distances of each other, (b) linked through the existing road network, (c) constrained through the presence of an intervening hydrographic feature (i.e., permanent river and perennial stream), and (d) connected by a bridge over the river or stream implied by the presence of all-weather roads crossing the water features. Operationally, the GIS was used to identify all village pairs that occurred within a 3-km Euclidean distance of each other. The hydrographic layer in the spatial database was then used to search for any permanent rivers and perennial streams that were located between the defined village pairs. Finally, the road networks (i.e., paved all-weather, loose-surface all-weather, dirt fair-weather, and foot-paths) were examined to define the presence of bridges crossing the permanent rivers and perennial streams indicated by the location of all-weather roads occurring within 150% of the Euclidean distance between village pairs. In this way, permanent rivers and perennial streams were regarded as relative barriers to village ties that could be negated through the presence of a bridge, implied through the class of road (i.e., all-weather) that crossed the water course.

Of the 310 villages, 1045 pairs were located within 3 km of each other. Of that total, 195 village pairs had a permanent river or perennial stream located between them, and 74 pairs had a paved or gravel all-weather road crossing the river or stream, thereby, indicating the presence of a bridge.

Fig. 9 shows the distribution of the village pairs bisected by existing water courses and connected through an all-weather road extending over the river and streams. This pattern of bridge connections between villages is associated with the high density of villages occurring along the rivers and streams, and is consistent with the emphasis

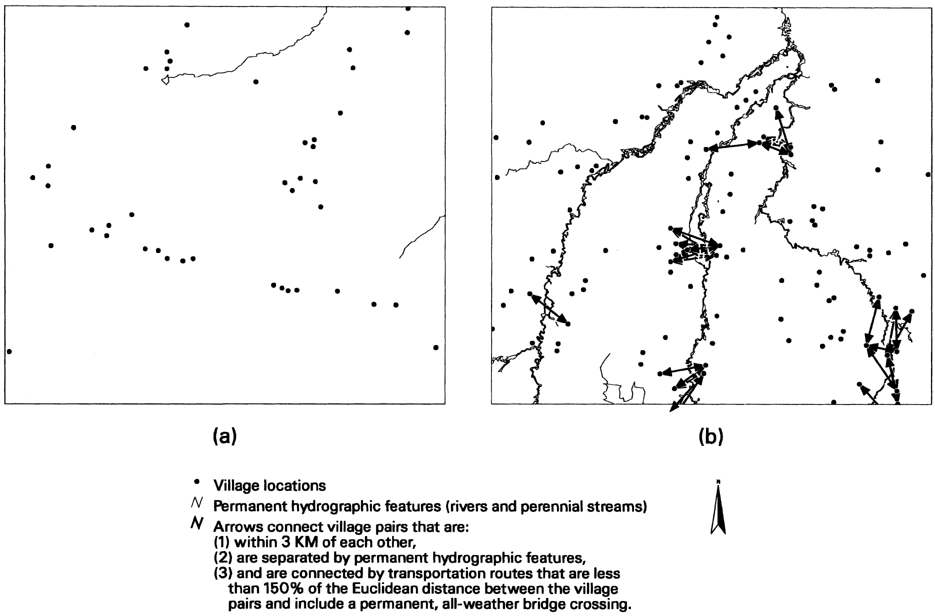

Fig. 9. Bridge connections between villages in two regions of Nang Rong.

within the district on the cultivation of rice, and the water requirements for rice cultivation in lowland environments.

Table 4 shows the distribution of ties on the five relations for villages that are within 3 km of each other. The pairs of villages are presented in three conditions: pairs with no river between them, pairs with a river and also a bridge, and pairs with a river but no bridge. Results show that for all relations, ties between proximate villages are less likely if a river is present than if it is absent, even when a bridge is available. A bridge between two villages separated by a river slightly increases the likelihood of a tie as compared with villages separated by a river but no bridge. The impact of a river is especially notable for elementary schools and sharing temples. A tie between a pair of villages is four times as likely for elementary schools and 10 times as likely for sharing temples if there is no river separating them than if there is a river with a bridge between them.

In this analysis, the GIS was used to support a set of spatial queries that included the application of a distance threshold (a 3-km spatial buffer around villages), movement along a road network subsequently constrained by road type (paved and gravel all weather roads), and the implementation of a relative barrier to village ties (a permanent river and perennial stream) traversed by the implied presence of a bridge. Tools within the GIS were used to partition space, link villages through a transportation network, and bias elements of the road network to reflect actual impediments to movement between villages as a consequence of flooding associated with monsoonal rains. These results were used to characterize the spatial conditions between pairs of villages (rivers and

Table 4
Impact of rivers and bridges on the presence ($x_{ij}=1$) or absence ($x_{ij}=0$) of ties between villages within 3 km of each other

		Hiring tractors[a]			Sharing temples[b]			Elementary school[c]			Secondary school[d]			Labor movement[a]		
River	Bridge	$x_{ij}=0$	$x_{ij}=1$	%	$x_{ij}=0$	$x_{ij}=1$	%	$x_{ij}=0$	$x_{ij}=1$	%	$x_{ij}=0$	$x_{ij}=1$	%	$x_{ij}=0$	$x_{ij}=1$	%
No	–	1625	75	4.4	392	203	34.1	996	202	16.9	1553	65	4.0	1535	165	9.7
Yes	Yes	146	2	1.4	59	2	3.3	91	4	4.2	123	4	3.1	141	7	4.7
Yes	No	241	1	0.4	65	1	1.5	158	3	1.9	234	0	0.0	235	7	2.9

[a] 2090 ordered pairs of villages.
[b] Ties to villages with temple, 722 ordered pairs of villages.
[c] Ties from villages without an elementary school, 1454 ordered pairs of villages.
[d] Ties from villages without a secondary school, 1979 ordered pairs of villages.

perennial streams traversed by a bridge or not) and then were tabulated with the social network data (presence or absence of a tie on each relation).

5. Insights from spatially referenced social networks

Incorporating social networks into a GIS provides both descriptive and analytic advantages. Most simply, a GIS with spatial locations for points allows us to properly orient graphs of social networks. Once networks are oriented, regional-level network patterns become visible in a way not apparent when point locations are arbitrary. In our example, differences in spatial patterning of the tractor hiring, labor movement, temple, elementary, and secondary school networks are striking in the properly oriented graphs. The contrast between temple sharing and elementary school networks, which have many small components with linkages between village spanning fairly short distances, and the tractor hiring, labor movement, and secondary school relations, which have fewer large components with linkages spanning much longer distances, can easily be seen in the spatially referenced networks. Intervillage distances calculated in the GIS verified these observations based on visual displays. These differences among the networks suggest that networks of social relations bring together villages in fairly close proximity and in small subsets spread homogeneously throughout the district, whereas economic ties link villages across longer distances and in larger groupings. These patterns also show how these relations operate in different ways to integrate villages in regional-level patterns.

Displaying networks for properly located villages also aids in diagnosing possible data quality problems. We suspect errors when lines between villages seem to violate an otherwise orderly pattern. For example, the temple and elementary school networks are generally local, but there are some instances of villages more than 10 km apart apparently linked through a shared temple or elementary school. These ties could be based on kinship relationships or prior residences of villagers, but we also wondered about the possibility of data coding error. Earlier, we mentioned the problem of duplicate village names in Nang Rong, and it is possible that the ‘‘long lines’’ involve some of these villages. Two pairs of villages more than 10 km apart apparently share a temple, and seven pairs of villages more than 10 km apart apparently share an elementary school, according to the survey data. For temple sharing, for both pairs, one of the villages involved in the pair has a name duplicated somewhere else in the data set. For elementary schools, this is true for four of the seven pairs of distant villages. Thus, it seems quite possible that duplicate names lie behind coding error. The presence of such suspect ties would not be apparent in a graph with arbitrary village locations.

Another kind of data problem can be seen in spatial patterning of isolates in a network. In the secondary school network there is a concentration of isolates in the middle of the district (not shown here). The absence of arrows to and from villages in this region appears to show that these villages do not send children to secondary school. This led us to consider more carefully how data on schools were collected. In the community questionnaire villagers were asked to name other *villages* to which children went for secondary school. The question format and recording of responses inadvertently omitted the secondary school located in the district *town*, located roughly in the center of the district. It is the spatial aspects of these network patterns that led us to suspect data problems.

Beyond simply orienting the graphs, information in the GIS about features of topography, land use, and hydrography provides a rich spatial background upon which to interpret and understand patterns in social networks. In our example, overlaying the tractor hiring network on the landcover classification provides insight into the relatively dense network of tractor hiring in a cassava growing region of the district, as contrasted with the relatively sparse tractor network in a predominantly rice growing region. This suggests that if we had data over time that was geographically grounded, it might provide a fertile source of hypotheses about the emergence of different types of networks and how they change their shape over time.

More powerful advantages arise from the spatial analytic capabilities in a GIS, which can be used to quantify spatial properties of an area, such as degree of land fragmentation, spatial density, travel time between locations, and so on. These spatial variables can then be used in conjunction with network variables to systematically examine relationships between network properties and geographic features. In our analysis, the GIS was used to calculate landcover variables, percent rice and percent upland agriculture, as spatial characteristics of villages. The relationship between landcover classification and centrality in the tractor network verified our observation from the overlay of the spatially referenced tractor network on the landcover map. In addition, using the analytic capabilities of the GIS we found that village proximity to the district border was related to greater movement of temporary labor into the village from outside the district and greater likelihood of sending students to secondary school outside the district. Finally, we used the GIS to determine locations of rivers and perennial streams between villages and to locate bridges crossing these waterways. We found that a river or perennial stream reduces the likelihood of a tie between villages that are in close proximity, even when a bridge is present. This effect is especially pronounced for sharing temples and elementary schools.

Future possibilities for using GIS's in conjunction with social networks are abundant. As an example, a nearest-neighbor analysis might be used to assess the cumulative distance between connected villages sharing tractors within various regions of the district or in comparison to other mapped relations such as sharing of temples. Quantitative measures of dispersion, proximity or spatial connectedness, for example, can be computed. Also the derived spatial pattern of social networks can be explained relative to social and spatial processes. Existing geographic concepts associated with space, for example Central Place Theory, might be used to explain spatial patterns of feature use across social units. The identification of regional centers, hinterlands, service areas of temples and/or schools might be useful concepts to explore patterns in social networks. These spatial properties can then be related statistically to features of social networks. Thus, in the future we will be able to investigate such questions as: Is social network centrality of a village related to its geographic centrality, or to other features of its geographic location? How are geographic distance and travel time related to the likelihood that different kinds of network linkages are present between villages? Is there spatial patterning to the distribution of cohesive subgroups within a network and how is this patterning is related to topographic features of the region? All of these are potential future directions for the spatial analysis of social networks.

6. Conclusion

This paper takes the innovative step of integrating networks of social and economic ties between villages into a GIS. Both forms of data — network ties between villages and spatial information on topography, land use, etc. — are incorporated into a single system. The data structure of a GIS uses information about spatially referenced points, properties of these points, and linkages between the points. This data structure can readily accommodate social networks when points are spatially referenced, which in turn provides a basis for new insights. In our example, graphs with spatially referenced villages reveal quite different spatial patterns for networks of tractor hiring, temple sharing, elementary schools, and secondary schools. These spatial patterns suggest that economic networks (for example, tractor hiring) link villages into fairly large subgroups spanning long geographic distances. In contrast, networks based on other activities (for example, sharing temples or elementary schools) bring together small subsets of villages in close geographic proximity. In addition, information about variation in land use throughout the district helps us understand spatial differences in network density for the tractor hiring network. In our example, the GIS for Nang Rong district already contained information about village locations and other attributes of villages (such as their size and population density) along with topography and land use for the district. Information about network ties between villages was easily added to this GIS. But, of course, the opposite path is also an option. A GIS could be built to assist in the analysis of geographically referenced social network data. Increasingly, public use spatial data layers are available in digital form, although as we have mentioned, confidentiality concerns may arise in some applications.

Acknowledgements

The work reported in this paper is part of a larger set of interrelated projects. Funding support for the entire set of projects includes grants from the National Institute of Child Health and Human Development (RO1-HD33570 and RO1-HD25482), the National Science Foundation (SBR 93-10366), the EVALUATION Project (USAID Contract #DPE-3060-C-00-1054), and the MacArthur Foundation (95-31576A-POP). The larger set of projects involves various collaborations between investigators at the University of North Carolina and investigators at the Institute for Population and Social Research (IPSR), Mahidol University, including Aphichat Chamratrithirong, Chanya Sethaput, Kanchana Tangchonlatip, Aree Champaklai, Thirapong Santiphop, Wathinee Booncha-laski, Yupin Vorasiriamorn, and Kriengsak Rojnkureesatien. Expert programming and spatial analysis assistance was provided by Tom Evans, Rick O'Hara, Phil Page, John Vogler, Alan Snavely, Erika Stone, and Bill Welsh. Karin Willert helped with analysis of the social network data. John Vogler developed the programs to implement the study of the spatial linkages between villages and the influence of rivers, streams, and road types on village ties and generated the maps presented in this manuscript. Phil Page consulted in the programming design. Sara Curran provided assistance at numerous points in the various Nang Rong projects and Peter Bearman provided assistance in designing the social network components of the questionnaires.

References

Barkey, K., Van Rossem, R., 1997. Networks of contention: villages and regional structure in the seventeenth-century Ottoman empire. American Journal of Sociology 102 (5), 1345–1382.

Batterbury, S., Forsyth, T., Thompson, K., 1997. Environmental transformation in developing countries: Hybrid research and democratic policy. The Geographical Journal 163 (2), 126–133.

Bebbington, A., 1997. Social capital and rural intensification: local organizations and islands of sustainability in the rural Andes. The Geographical Journal 163 (2), 189–198.

Clarke, K., 1990. Analytical and Computer Cartography. Prentice-Hall, Englewood Cliffs, NJ.

Crump, T., 1980. Trees and stars: graph theory in southern Mexico. In: Mitchell, J.C. (Ed.), Numerical Techniques in Social Anthropology. Institute for the Study of Human Issues, Philadelphia, pp. 163–190.

Denevan, W.M., 1989. The Geography of Fragile Lands in Latin America. In Fragile Lands of Latin America. In: Browder, J.O. (Ed.), Westview Press, 11–24.

Doreian, P., 1987. Measuring regular equivalence in symmetric structures. Social Networks 9 (2), 89–107.

Doreian, P., 1988. Equivalence in a social network. Journal of Mathematical Sociology 13 (3), 243–282.

Entwisle, B., Rindfuss, R.R., Walsh, S.J., Evans, T.P., Curran, S.R., 1997a. Geographic information systems, spatial network analysis, and contraceptive choice. Demography 34, 171–188.

Entwisle, B., Walsh, S.J., Rindfuss, R.R., 1997b. Population Growth and the Extensification of Agriculture in Nang Rong, Thailand. Paper presented at the annual meetings of the Population Association of America, Washington, DC.

Entwisle, B., Rindfuss, R.R., Walsh, S.J., Evans, T.P., 1998. Satellite Data and Social Demographic Research. Paper presented at the annual meetings of the Population Association of America, Chicago.

Evans, T.P., 1998. Integration of Community-Level Social and Environmental Data: Spatial Modeling of Community Boundaries in Northeast Thailand. PhD dissertation. University of North Carolina at Chapel Hill.

Evans, T.P., Walsh, S.J., Entwisle, B., Rindfuss, R.R., 1995. Testing model parameters of transportation network analysis in rural Thailand. Proceedings, LIS/GIS '95. Nashville, TN, 2, pp. 994–1005.

Forsyth, T., 1996. Science, myth, and knowledge: testing Himalayan environmental degradation in Thailand. Geoforum. 27 (3), 375–392.

Freeman, L.C., 1996. Visualizing Networks manuscript. carnap.ss.uci.edu/vis.html

Freeman, L.C., 1997. Using Available Graph Theoretic or Molecular Modeling Programs in Social Network Analysis manuscript. tarski.ss.uci.edu/new.html

Gould, P., 1996. Space, time and the human being. (Geography: state of the art: I. The environment dimension). International Social Science Journal 48 (4), 49–61.

Hage, P., Harary, F., 1991. Exchange in Oceania: A Graph Theoretic Analysis. Clarendon Press, Oxford.

Hage, P., Harary, F., 1996. Island Networks: Communication, Kinship and Classification Structures in Oceania. Cambridge, NY.

Haggett, P., Chorley, R.J., 1969. Network Analysis in Geography. Edward Arnold, London.

Halpike, C.R., 1970. The principles of alliance formation between Konso towns. Man 5 (2), 258–280.

Hammond, N.D.C., 1972. Locational models and the site of Lubaantún: a classic Maya centre. In: David, L.C. (Ed.), Models in Archaeology. Methuen and Co., London, pp. 757–800.

Klovdahl, A.S., 1981. A note on images of networks. Social Networks 3, 197–214.

Krackhardt, D., Blythe, J., McGrath, C., 1994. KrackPlot 3.0: An improved network drawing program. Connections 17 (2), 53–55.

McGrath, C., Blythe, J., Krackhardt, D., 1997. The effect of spatial arrangement on judgements and errors in interpreting graphs. Social Networks 19, 223–242.

Morris, M., Handcock, M., Wawer, M., Gray, R., 1996. Using mobility networks to establish treatment and control clusters in a randomized community trial. Paper presented at the Classification Society of North America, Amherst, MA.

Pitts, F.R., 1965. A graph theoretic approach to historical geography. The Professional Geographer 17 (5), 15–20.

Pitts, F.R., 1978. The medieval river trade network of Russia revisited. Social Networks 1, 285–292.

Rindfuss, R.R., Walsh, S.J., Entwistle, B., 1996. Land Use, Competition, and Migration. Paper presented at the annual meeting of the Population Association of America, New Orleans.

Turner, B.L. II, 1997. The sustainability principle in global agendas: Implications for understanding land-use/cover change. The Geographical Journal 163 (2), 133–141.

Walsh, S.J., Page, P.H., Gesler, W.M., 1997. Normative models of healthcare planning: Network-based simulations within a geographic information system environment. Health Services Research 32 (2), 243–260.

Walsh, S.J., Welsh, W.F., Evans, T.P., Entwisle, B., Rindfuss, R.R., 1999. Scale dependence of social and biophysical factors in northeast Thailand. Photogrammetric Engineering and Remote Sensing 65 (1), 97–105.