The structure of sexual networks and the spread of HIV in Sub-Saharan Africa: evidence from Likoma island (Malawi)

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It is widely believed that the HIV epidemic in Sub-Saharan Africa (SSA) is driven by transmission during unprotected heterosexual intercourse. In particular, infection with HIV in SSA is thought to be fueled by repeated contacts with sex workers or other highly sexually active group, and subsequently diffused to the general population through links of marriage or other stable types of partnerships. Such a theoretical model of sexual mixing has informed many policy simulations of interventions to stem the spread of the disease (see Oster 2005). However, empirical evidence for this diffusion process (i.e. from a group of highly active individuals to a low activity "periphery") is somewhat scarce as epidemiological studies have generally reported weaker than expected relations between measures of such sexual behavior and risk/prevalence of HIV infection. At the individual level, differences in the rate of sexual partner acquisition only marginally predict an increased risk of infection for both prevalent (e.g. Gregson et al. 2002) and incident cases (e.g. Quigley et al. 2000). Similarly, at the population level, several comparative studies of the factors of HIV infection have found that differences in the prevalence of risky behaviors (high rate of partner change, contacts with sex workers etc.) could not explain the "uneven spread" of HIV across regions of SSA (Boerma et al. 2003). These discrepancies between indicators of sexual activity and prevalence/risk of HIV have been primarily attributed to two factors: reporting bias and differential mortality of HIV-infected individuals. Recently, they have also generated a heated debate over the relative importance of non-sexual modes of HIV transmission (e.g. unsafe medical injections) in fostering the HIV epidemic in SSA (e.g. Gisselquist et al. 2002).

In this paper, on the other hand, we examine empirically the population-level structure of sexual networks and explore the role it may play in fostering explaining the observed discrepancies. Indeed, the relationship between sexual behaviors and epidemic outcomes depends not only on the number or type of partners someone has, but also on the behaviors of these partners, of partners' partners, and the emerging network of interconnections. Numerous models in mathematical epidemiology have shown the striking non-linear implications of such connectivity patterns for infection dynamics and disease control (e.g. Kretzschmar and Morris 1995, Newman 2002). Early in the epidemic, Caldwell has also suggested that variations in the general organization of sexuality might be responsible for large differentials in prevalence between Western and Eastern Africa (Caldwell et al. 1989, Orubuloye et al. 1992). Despite this theoretical significance however, we have very little idea of what such networks actually look like in Sub-Saharan Africa. This is likely due to the fact that virtually all the existing data on sexual behaviors in Africa comes from individual-centered surveys. And even though a few recent studies have tried to deduce global network properties from such local designs (e.g. Schneeberger et al. 2003, Liljeros et al. 2001), statistical work has shown that such inferences are quite hazardous (e.g. Jones and Handcock 2003, Handcock and Jones 2004).

We thus use a unique dataset that combines complete population data on the networks of romantic and sexual relationships of roughly 1000 individuals living in seven villages of Likoma, an island in the northern region of Lake Malawi, with biomarkers of HIV infection for all members of these networks. We believe the data resulting from this project are one of the very few – if not the first - sociocentric dataset on sexual networks in SSA. This innovative study design will allow us to "map" the person-to-person spread of HIV and investigate empirically the relations between connectivity patterns and disease diffusion. In this paper, we 1) describe the context of our study, 2) describe in some detail the process of data collection, 3) provide detailed images and measurement for the structural characteristics of largely complete sexual networks through which HIV spreads, 4) discuss how the most commonly used epidemiological models of HIV spread in SSA conform to the empirical structures we observe. While such images and measurements of network structures are available in different contexts (e.g. Bearman et al. 2004), they are lacking for African populations with generalized HIV epidemics.

Context: Likoma island

The study takes place in Likoma district, in the northern region of Malawi. This district is made of two small islands, Likoma and Chizumulu, which are located deep into Mozambican waters, some 70 kms from the shores of Malawi. Despite the proximity of Mozambique, these islands remained Malawian after former "president-for-life" and independence hero Kamuzu Banda fought hard to retain them (In Likoma, the legend even proudly says that Kamuzu cared so much about the islands that he gave the Mozambican government some very profitable tea estates in the south of Malawi in order to secure property of the two islands). The population of the two islands barely exceeds 10000 people and is comprised mostly of the Nyanja and Tonga ethnic groups. More specifically, the inhabitants of Chizumulu are largely Tongas, the same ethnic group that is found in the closest coastal city, Nkhata Bay. On the other hand, there is only one small Tonga settlement on Likoma island, in a somewhat secluded village (Mbungo). Most people there refer to themselves as "Nyanjas", i.e. literally "people from the lake". Their language is a mixture of Chichewa (the official language of Malawi), Tonga and even Portuguese due to the proximity of Mozambique. Furthermore, Likoma being the siege of the administrative district, it regularly hosts civil servants from the northern region of Malawi who belong to other tribes (tumbukas) so that other languages end up being spoken on the island. Below we highlight a few points which we believe are relevant to the formation of sexual networks in Likoma.

Likoma island has the shape of a rectangle of dimensions 4kms * 6kms. It is made of 12 villages of 600-700 habitants each, and of a trading centre located roughly in the middle of the island. The overall level of economic development of Likoma is quite low, even though the island has been the object of several governmental favors in recent years (electrification campaign, distribution of maize…). Transportation to the island is scarce as only one boat (a steamer!) travels between Likoma and the mainland of Malawi. It often takes more than 10 hours to cross the 70 kms between Nkhata Bay (the closest port) and the island. Planes do come to Likoma but are almost exclusively used by tourists who visit the very fancy lodge located at the southern tip of the island. As a result, Likoma is not a place of passage, and islanders are seldom exposed to visitors from the mainland of Malawi. In fact, the rare "outsiders" who stay for some time in Likoma are civil servants affected to the island, groups of soldiers sent to the army camp located in the southern side of the island, or students of the government secondary located at the northernmost tip of the island. Transportation to Mozambique is more readily available, as small dhow ferries and canoes cross the few kilometers between Likoma and the small town of Cobue several times a day. This region of

Mozambique, however, is very much a "dead angle" as it is far removed from the major cities of the Indian Ocean (Nampula, Maputo) or even from the regional capital of Lichinga (figure 1). Only a few thousands of people live on the shore that stretches on the Mozambican side of Lake Malawi from Cobue to Mtengula ("Augusto Cardoso") and the area lacks most basic amenities and services. Habitants from Likoma thus only travel there to fetch firewood, which is scarce on the island, sell fish and maybe do some small farming on plots of lands they own. Despite the distance and travel time, inhabitants of Likoma are thus attracted to and depend on the larger cities of northern Malawi, where they often spend a weekend or longer periods of time.

Figure 1: Map of Lake Malawi around Likoma

Fishing is the main economic activity in Likoma. It is exclusively reserved to males and most men usually spend long hours on the lake (and thus away from home) on any given day. Fish is generally sold in Likoma or in Mozambique, unless someone has made a big catch. In which case, people would travel to the mainland (possibly even to the capital city, Lilongwe) to sell the fish there and generate a considerable profit. It is important to note that, whereas fishing itself is reserved to males, selling fish at the market is predominantly a female activity. This gendered division of labor keeps spouses away from each other for most of the day and sometime the night, as moonlight fishing is widely practiced. As a result as well, a large proportion of women travel regularly to the mainland of Malawi to sell fish.

During march and april, the waters of Lake Malawi get agitated around Likoma, and many fishermen travel southward, to the quieter waters of Mbenji, in Salima district, where they can pursue their activity and generally make big profits. Some fishermen in Likoma have used the income generated this way to diversify their activities and start doing some small-scale business, build general stores or resthouses. However, in general, employment opportunities are very scarce on the island outside of fishing: they are limited to some punctual small jobs ("*Ganyu*"). For example, some men may be hired for

half a day by the food distribution agency to offload maize from the boat, or by the ministry of equipment to clear a road… Employment prospects for women are even more limited, and most of them spend their day doing household chores. A minority of women are involved in some small-scale business activities, either baking and selling African cakes, or traveling to Nkhata Bay every weekend or so to buy basic commodities such as soap or sugar and later sell them at the trading centre in Likoma.

Outside of fishing, remittances from relatives having migrated to the mainland of Malawi, Mozambique and especially Zambia, South Africa and the UK are the only other major source of income for the island. Indeed, a few men who have migrated to these latter places have been very successful and are currently taking care of entire villages. Migration outside of Likoma is thus highly valued as an income generating strategy. Both young men and young women are encouraged to seek opportunities outside of the island: for young men, it means pursuing some business activities in the cities of Malawi or abroad, or possibly pursuing higher education there; for most women, on the other hand, marrying someone from the mainland appears as the only way out of Likoma.

Education is widespread in Likoma as missionaries established primary schools very early in the century. Older habitants of the island often boast that in the 50's and 60's everybody on the island could speak English. These days, almost everyone attends the first grades of primary school. However, many drop out after a few years of schooling: the quick cash generated by fishing lures boys away from the school benches whereas pregnancies tend to put a sudden end to many girls' school careers. As a result, only few locals attend the prestigious government secondary school located at the northernmost tip of the island. Those who do attend the school often quickly leave Likoma in search of employment or higher education after they receive their diploma. They are also very attractive as potential partners for the girls of the island…

Marriage in Likoma is not as universal an institution as in other regions of Malawi. Out-of-wedlock pregnancies are numerous, and it is common to find women in their 20's who have had 3 children with 3 different fathers… As a consequence of sex-selective migration (and possibly differential mortality), sex ratios are highly skewed in favor of females, and many women face a very tight market on the island. However, a good number of them also argue that they are not even looking for a spouse in Likoma as they would rather marry someone that would take them away from the island and to the northern cities of Nkhata Bay, Karonga or Mzuzu (see map in fig. 1). These preferences appear to "balance" the marriage market or possibly even "segment" it: there are both men and women who remain unmarried late in their 30's. The island is thus home to quite a few 30 or 40 years old bachelors who spend their day drinking local beer at

one of the many "Gebuza" (Mozambican beer) places on the island, and mostly choose to engage in short-term sexual partnerships. Unwed women in their 30's, on the other hand, may choose to look for a spouse in Mozambique, although this is an option that women do not value as inhabitants of this country are perceived as extremely poor and have to rely on farming for subsistence, which the islanders consider tiresome… Polygamous unions also may prove attractive; however formal polygamy is said to be on the decline in Likoma as payments for spouses have steadily increased over the past years and few men from Likoma can now afford several wives. Finally, divorce is common in Likoma, but is not as prevalent as in other places of Malawi (Reniers, 2003).

HIV is well present on the island: recent ANC surveillance data suggests that roughly 20% of the district population might be affected by the virus. The high frequency of funerals (almost two a day) and the ages at which people die would tend to corroborate this assessment. As a result, the Malawian ministry of health has recently started the distribution of ARVs on the island (December 2005). According to the Likoma district hospital, more than 20 people are currently enrolled in this program. However, unlike what has been found in mainland Malawi and in most Sub-Saharan Africa, knowledge about the disease and protective measures does not appear to be universal in Likoma. Indeed, when we conducted VCT there (see below), many health workers reported having to inform inhabitants about the modes of transmission of the virus, the incubation period or the links between HIV and AIDS. Condoms are available at the hospital, but nurses report that their stock is not exactly in high demand. Maybe because of its location in the middle of Lake Malawi, Likoma is a little "out of reach" for NGOs and other awareness campaigns, and the lack of radio or TV reception further limit exposure to prevention messages. Witchcraft is also extremely widespread on the island (each village has 2 or 3 competing *sing'angas,* traditional witch doctors), and most premature deaths are attributed to occult forces rather than to past risky behavior, preventing people to learn about the disease (see Watkins 2005 for a detailed analysis of learning in social networks about HIV).

Despite this lack of detailed knowledge, though, habitants of Likoma are aware of the virus and are quick to blame two types of people for its spread: the Mozambicans and the soldiers who live at the army camp located at the southwestern end of the island. Indeed, some rumors in Likoma say that the government of Mozambique "exiles" all HIV positive individuals to the northeast of the country, close to Likoma and far away from the population centers of the Indian Ocean (Maputo). As a result, Mozambicans are said to be in terrible health and are believed to crowd the wards of the district hospital in Likoma. These beliefs certainly contribute to the lower prestige of Mozambicans on the partnership market. Soldiers on the other hand come from the mainland of Malawi, are generally well-paid and thus have a lot of appeal for the local girls

especially those who do not have the opportunity to travel out of Likoma all that often. However, they are only stationed on the island for one month, and rarely leave with a spouse or a promise to marry but rather entertain short-term partnerships. Older women often complain that these soldiers leave many unwanted pregnancies as well as diseases on the island when they depart Likoma after their mission is over.

Data

Data for this paper come from a study of complete sexual networks that was conducted in seven villages (among 18) of Likoma island during the fall and winter of 2005/2006. There are several components to this study, which are all aimed at identifying sexual partnerships within the populations and ascertain how HIV might spread along the paths they create.

Household listing: Prior to the beginning of the survey, we conducted a complete enumeration of all the households in both Likoma and Chizumulu. During this census, we asked in particular about the names, potential nicknames, and ages of all residents of a household. We also took the GPS coordinates of the houses we visited, as well as the coordinates of various "landmarks" in each village: for example, the borehole, the village center, the primary school… This information provided the basis for the identification of sexual partnerships (see below). In total, we listed more than 1800 households in the two islands, 1300 of which in Likoma and roughly 500 in Chizumulu. The average size of a household was around 5 members, and we also found that more than half the population of these two islands was under 15 years old.

Sampling scheme: The 7 villages we surveyed were selected as follows: 3 villages were selected in the northern part of Likoma, 3 in the southern part, and the seventh village is the place where the ferry to the mainland usually docks, close to the trading centre. It is also the place where the army camp is located, and where most government workers or other "outsiders" reside. This sampling scheme was purposive as activities and social life seems to have different orientations in the northern and southern parts of Likoma. In villages closer to Mozambique (south), settlement is scattered, men spend virtually all their time on the lake, fishing, and during the months of march and april they massively travel to the mainland to continue fishing there. In the northern part of the island, on the other hand, settlement is much more compact, and village life is much more intense. Many refer to these places as the "true Likoma" or the "heart of Likoma" (in

particular, this is where the traditional chief comes from). In addition, the 3 villages we chose in the northern part of the island are homes to 5 or 6 big families, who have sent a large number of their members to the mainland or abroad and therefore receive remittances regularly. As a result, men in these villages do not have to rely on fishing as exclusively as in the other side of the island: they are at home (or at the beer place) a lot more frequently than their counterparts from the southern side of the island. We thus wanted to investigate whether such different village contexts generated different patterns of sexual networking and eventually different prevalence of disease.

Network survey – identification of sexual partnerships: In these villages, we attempted to interview *all inhabitants aged 18-35*. First, respondents were asked a series of questions about their background (education, religion…) as well as about their social activities and relations. In particular, respondents were asked in detail about their marital and birth histories. Then, respondents were asked about their sexual relationships during an audio-CASI interview. ACASI has been shown to reduce interviewer or social desirability bias in responses in the US context and has been used to collect data on sexual networks by the National Longitudinal Study of Adolescent Health, "Add Health" (see Bearman et al. 2004). This protocol for the collection of sexual partnership data effectively guarantees the confidentiality of the network information reported, and has been approved by the institutional review boards of the University of Pennsylvania and the Malawi College of Medicine.

More specifically, the computer-assisted interview proceeded as follows: first, respondents were asked whether they had been involved in a sexual partnership at some point during the past 3 years (Chichewa word: Chibwenzi). If this was the case, they were then asked to mention the full name, the first name and an initial or the nickname of this partner to the machine (they were equipped with recording headsets prior to the start of the interview). Respondents who did not report that they had a sexual relationship over the past 3 years were then asked if they had been involved in a relationship with someone who was just a friend, or maybe someone who was a relative or an employer, or was just a one-night stand. This probing sequence follows the interviewing strategy of Mensch et al. (2003) and based on a quick eyeballing of the data, seems to have been quite successful at eliciting partnerships: a large number of respondents who initially denied having had sexual relations eventually reported one or several such partnerships.

After providing the name of this partner, respondents were asked a short series of questions about the relationships, e.g. starting date, place of meeting etc, condom use during the relationship, frequency of

intercourse… More importantly for the purpose of constructing network data, respondents were asked where their partner was currently residing and where he/she was residing at the time of the relationship if the relationship is over: in their own village, elsewhere in Likoma, in Chizumulu, in Mozambique or in Mainland Malawi. If their partner resides in Likoma, respondents were then asked to provide a few additional details about his/her residence: in which village is this person staying, and where specifically in this village this person was staying. For example, from such reporting we would know that a respondent has been involved in a relationship wit John Banda who lives in Ulisa village close to the groceries… Respondents were then asked to repeat these steps for up to 5 partners. Through this process, and using the lists of household members as well as the GPS data collected during the initial census, we were able to assemble data on partnerships between inhabitants of the 7 sampled villages considered here, as well as between habitants of the sampled villages and people living in Likoma but outside the sample area. We use these partnerships to generate a detailed picture of the networks of sexual relations within which inhabitants of Likoma are embedded.

It is important to note that in some instances, the information provided during these computer interviews was not sufficient to accurately identify a sexual partner. For example, someone would just report having been involved in a relation with "Maria" who is in her 20's, lives in Khuyu village near the power plant and does some small business. After looking up the census lists, we found that 2 or 3 women fit that description… We did not attempt to gather further information on these types of relations, and as a result they are not included in the pictures we present below. Our analyses are thus conservative and the networks we present may actually be denser than what they appear. However, we were able to identify accurately more than 85% of the partnerships reported to have taken place within Likoma.

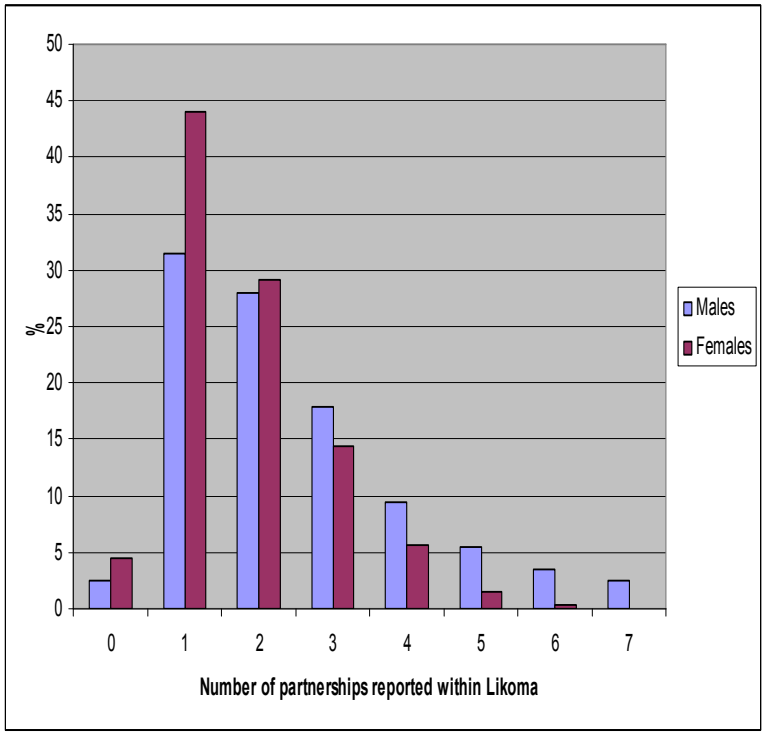
HIV Testing: After completion of the network survey, each respondent was given the opportunity to get tested for HIV. The devices used for testing were 2 rapid tests assays: Determine and Unigold, and each respondent was administered the two tests in parallel (this conforms to the WHO protocols for rapid testing). Participation in this biomarker collection was significantly lower than for the network survey as only 75% of the respondents originally interviewed accepted to get tested. Furthermore, it appears that refusal was selective as many men had already left for the mainland to go fishing by the time we started to conduct VCT on the island. Despite this, observed prevalence in the sampled villages was 10.3%. The biomarker data has not been merged with the survey data yet so we do not discuss these results further in this paper.

Preliminary Results

We now turn to some (very) preliminary results from the network survey. First of all, we describe the connectivity distribution within the villages of Likoma we surveyed, as well as between these villages the mainlands of Malawi or Mozambique. We describe mixing patterns at the local level and investigate potential differences in preferred types of partners between men and women. Then we turn to the distribution of components sizes that emerges from the local choices and preferences described above, as well as to other graph-theoretic measures of the structure we observe in Likoma. Finally, we try to assess whether the observed structures conform to some widely used models of sexual mixing described above, such as *preferential attachment*, and what they may imply for the spread of sexually transmitted diseases.

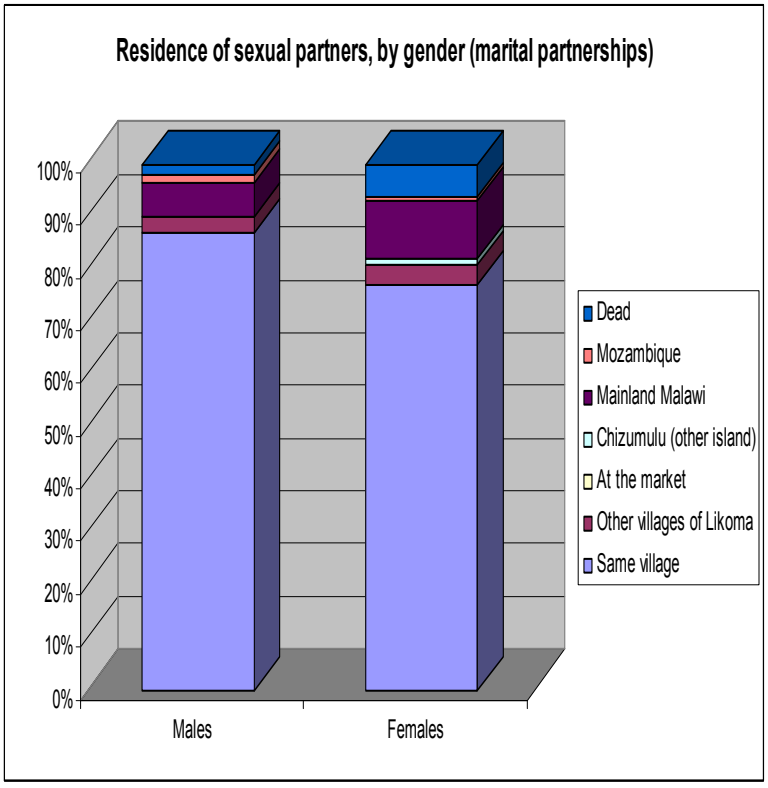
Degree distributions

During the survey, respondents reported having been involved in an average of 3 relationships over the last 3 years (including marital relationships). We found some differences between the reporting of males and females: male respondents reported an average of 3.3 relations, 2.6 of which were said to have taken place in Likoma, whereas female respondents reported 2.7 relationships, 1.9 of which took place within Likoma. The diagram in figure 1 presents the distribution of the number of partnerships reported to have taken place within Likoma (i.e. "out-degree"



distribution) and highlights these gender differences. In particular, the spread of those distributions appears significantly different as more men report relatively high number of partnerships (5+), whereas for women most answers fall in the modal categories (1 or 2 partners). A small proportion of the respondents also reports not having engaged in a relationship on the island over the last 3 years: almost 5% of the women we interviewed reported either no relations at all, or only relations on the mainland of Malawi. These may include women who recently moved to Likoma, or who display strong preferences for partners from outside of the island. Finally, it is important to note that, as a result of our study design and instruments, these distributions are truncated. We therefore make no attempt to try and identify the specific nature of the underlying degree distribution, and in particular we do not attempt to see if it is "scale-free" or not. Instead we focus on investigating the distribution of partnerships within the island population, and try to characterize the network structure that emerges from it.

Partner preferences



We now turn to the preferences respondents display with regards to the partners they choose. An aspect of sexual networking that has been identified as important by the epidemiological literature on HIV in SSA is the role of partnerships with people from outside the local communities: relationships with strangers, commercial sex workers, bar girls or people from town are deemed to be the main avenues through which HIV enters and spreads into villages and rural communities (the so-called "risky behaviors").

Our data allows us to ascertain the geographical origin of partners, and it is presented in figures 4 and 5 below. Marital partners are largely found within in the same village as most spouses in Likoma co-reside. However, due to

divorce and polygamy, some spouses or former spouses may be found in other villages of Likoma or even in the mainland of Malawi. Furthermore, given that marriages are traditionally formed between members of family groups who live in different villages, marriages are an important type of partnerships which may "bridge" several clusters of sexual partners: for example, someone from Ulisa village (northern side of Likoma) who has had several boyfriends there may marry someone from Makungulu (southern side of Likoma) and thus potentially create a path between these two places for the virus to travel.

The residence patterns for extra-marital partners are quite different and it is important to note that there are some profound gender differences when it comes to partner choices and preferences. For example, whereas both men and women found a third of their partners within their own village, men report engaging in relationships with someone from Chizumulu (nearby island) much more than women do. This is probably so because many of them travel there to go fishing as the best spots for "Kampango", a very prized catch, are found there. Men also tend to find their partners in the neighboring villages much more than women do, whereas women report engaging in partnerships with people from the market place a lot more. Especially and despite conventional wisdom, we find that women tend to engage in partnerships with people from the mainland at a higher rate than men. This might be the case because, as we mentioned earlier, marriage represents one of the only way through which women can hope to migrate outside of Likoma or because women tend to travel to the mainland more frequently to pursue some small business activities. Finally, women report having engaged in a relationship with someone that has since died at a much higher rate than men. This might be the case because of a certain age difference between partners, but is much more likely due to mortality from accidental causes (e.g. drowning during fishing, encounter with a crocodile) or from HIV-related diseases.

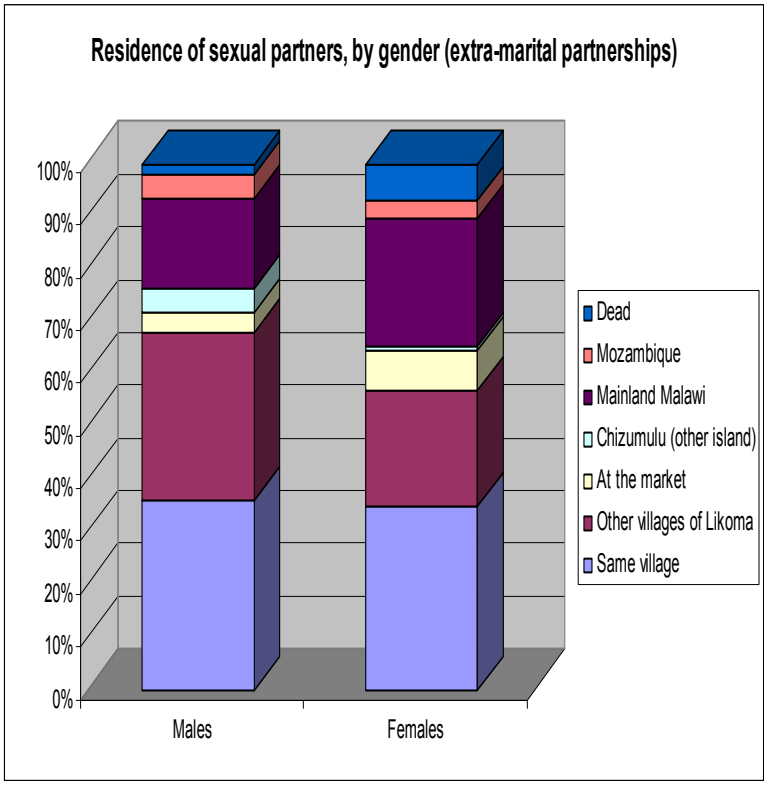


Fig. 4: Residence of extra-marital partners

Observed Sexual Networks in Likoma Island

Component size distribution

What kind of global network structure emerges from these levels of sexual activity and preferences governing partner choice? Table 2 presents the component distribution for the 1070 individuals we identified who are currently involved or have been involved in a relationship with someone in Likoma over the last 3 years. A component is a subgraph of a network in which all nodes from the subgraph are reachable from other nodes in the subgraph (Wasserman and Faust, 1994). Components are thus a major determinant of the extent to which a disease is able to spread in a population, since individuals can infect each other with sexually transmitted diseases only insofar as they are directly connected or indirectly connected through a chain of sexual relationships.

In Likoma, roughly 35 % of the respondents are included in small components of size less than 10, and in particular 20% of them are involved in isolated dyads, i.e. in partnerships where both male and female report each other as the sole partner they have had over the last 3 years. Most of these "exclusive" unions are longstanding marriages, but may also involve two young respondents who report each other as their first partner (unlike what would be implied by a preferential attachment mechanism of network formation). Components of size 3 are also fairly common in Likoma, especially those involving one male and two females, and intermediate size components on the other hand are relatively scarce. More strikingly, however, 65% of the population is connected together into one "giant" component of 685 people.

Size (number of people connected by chains of sexual relations)	**Proportion**
2 (isolated couples, i.e. dyads)	**20%**
3-10 (Intermediate size)	**15%**
685 (giant component)	**65%**

This structure is depicted in figure 2. This component is very heterogeneous in terms of the sexual activity of its members: whereas it includes many respondents with multiple partners, it also comprises many "terminal branches", i.e. respondents we have identified as engaged in only one partnership. A good number of these "dead ends" from a network standpoint are probably due to our study design, though: individuals located at the end of a line are often residents of out-of-sample villages and thus have not been interviewed. If this were the case, they may have reported one or several other partners and the graph we draw may actually have been even larger or denser. The size of this component is thus potentially truncated and needs to be considered as a conservative estimate.

The insertion of an individual in a component of small or large size might be a major determinant of the risk of HIV infection: indeed an individual with only one partner residing in this giant component may be at a significantly higher risk of contracting any STD than an individual with many more partners who is located in a much smaller disjoint component. In addition to sheer connectivity, the distance between any two individuals on the graph (i.e. the average number of connections that separated two individuals taken at random) is also a major determinant of HIV risk. In the case of Likoma, this giant component is very broad: the two individuals the furthest apart are separated by 27 relations, quite a long distance for the virus to travel. On average, however, the distance between two individuals taken at random is 10 steps (i.e. geodesic distance). Over the last 3 years, the large majority of adolescents and young adults of Likoma are thus linked together by a chain of sexual relations of varying lengths through which HIV or other sexually transmitted diseases may have diffused.

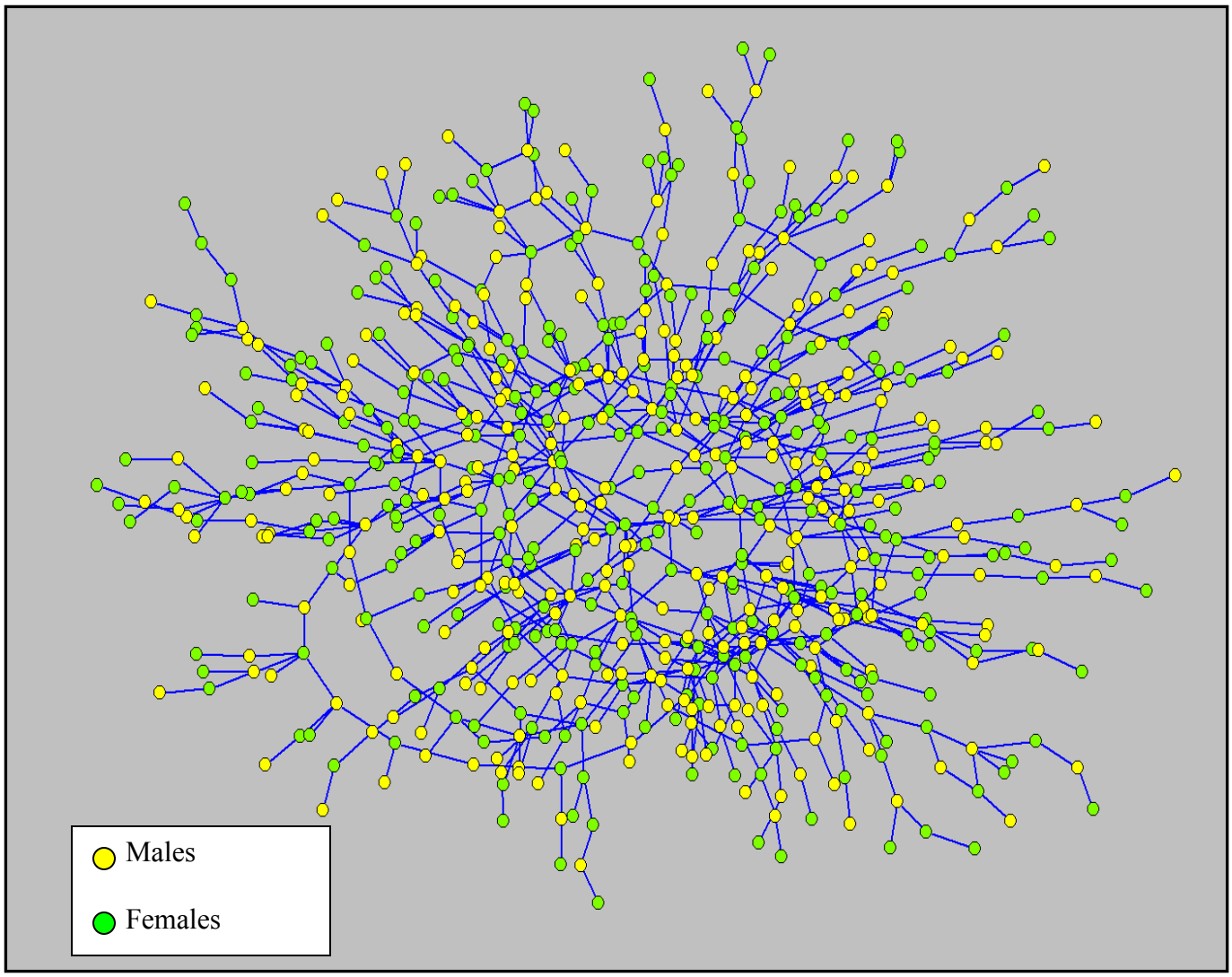


Fig. 5: largest connected component. N = 685. It comprises more than 65% of the population of the 7 villages surveyed.

Bicomponents and network cohesion

However frightening figure 3 may look, the literature on HIV spread in Africa lead us to expect the emergence of such a giant component. This literature argues that the connectedness of the graph is achieved primarily through the presence of (very) high activity individuals (e.g. men who have sex with hundreds of partners) or through the action of a highly connected "core" group (e.g. sex workers or bar girls and their patrons). Empirically however, the proportion of men patronizing prostitutes or engaging in other high-risk

sexual activities is only a weak predictor of the prevalence of HIV infection in a community (e.g 4 cities study). In this section, we confront these hypotheses to the structures we observe in Likoma.

We tested the pertinence of such a theoretical model of sexual mixing against the network we actually observe in Likoma in two ways. First, we tried to determine if a few "central" nodes could be responsible for this connectedness: we thus calculated an index of *network centralization* (Bonacich 1987), a measure indicating if some few nodes are critical in maintaining the network connected. This would be the case if, for example, some categories of men (businessmen, school teachers or other sugar daddies as depicted by journalistic accounts) accumulated a very high number of partners of all ages. This index appeared extremely low, suggesting that there were no single nodes who played such a role, and single-handedly linked otherwise disjoint components. Such a process of network formation (preferential attachment) is thus not responsible for the connectedness of the network we observe in Likoma.

Second, we tested a simple core – periphery blockmodel (i.e. we tried to rearrange the rows and columns of the sociomatrix into a submatrix of high-density and 3 submatrices of much lower density, see Borgatti and Everett 2004) to assess whether a group of people, rather than single individuals could be held responsible for connecting the graph. This would be the case if commercial sex work was highly prevalent, for example. We were indeed able to find such a (very small) region of somewhat higher density within this network, but the model provided a very poor fit to the data: the other 3 submatrices, which we expected to be very sparse, were only half as dense as the core. We thus rejected the hypothesis that a small group of highly active and densely connected people holds together this structure. Rather connectivity appears evenly distributed around the structure we observe, and the social processes responsible for the emergence of such a large connected component may be more complex than previously thought.

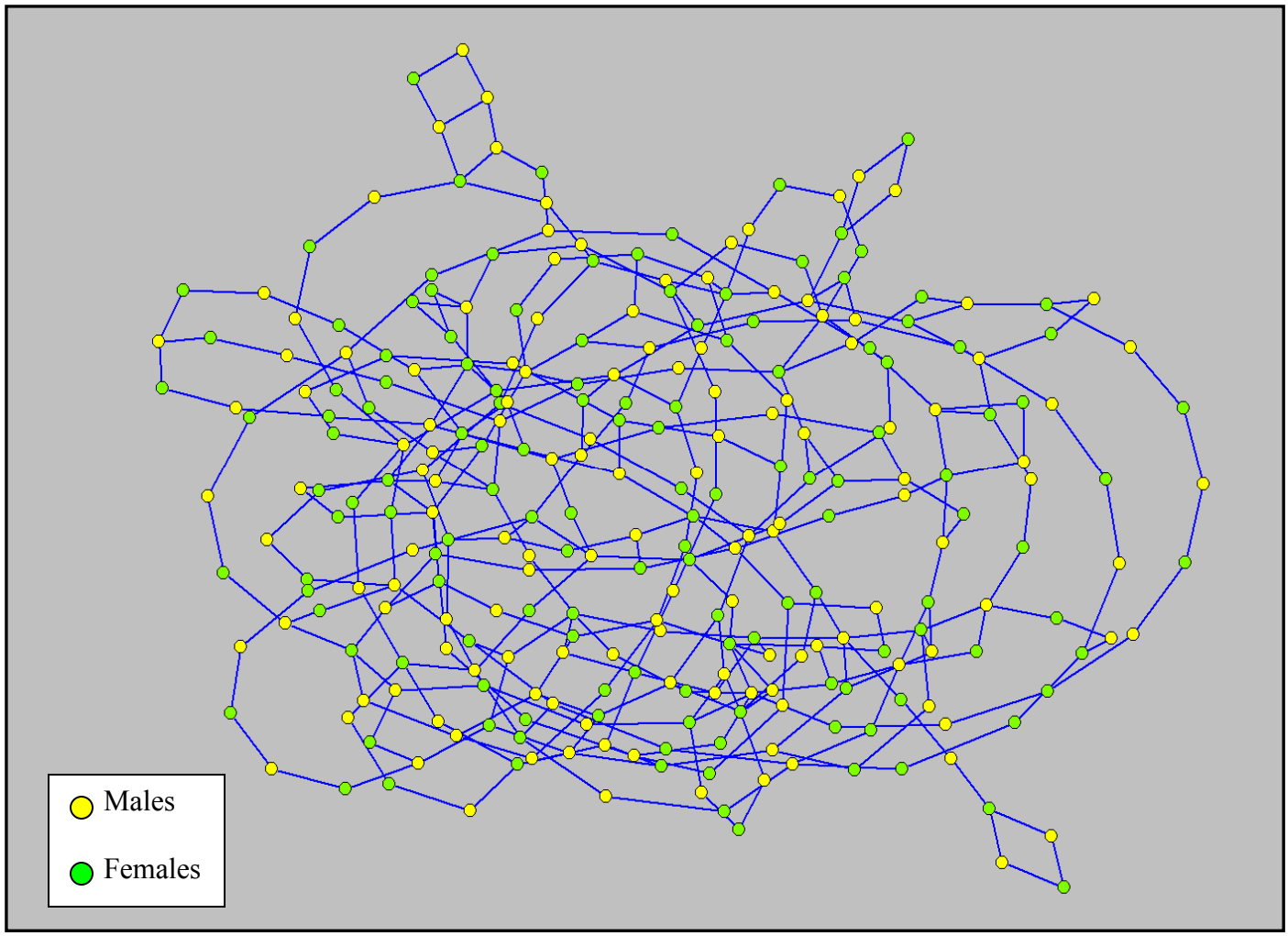


Fig. 6: largest bi-component in the within-Likoma network. This graph is a subgraph of the graph displayed in Fig. 5. It comprises 280 people (i.e. 20% of the sample)

In particular, within the largest connected component (fig. 6) we found a large bicomponent of 280 people (40% of the 1-component). A bicomponent is a subgraph that has a cut-set of size 2: we need to "remove" 2 nodes in order to break it into a smaller subgraph, generally to isolate a singleton. While this sounds relatively innocuous, a fundamental theorem of graph theory states that in such a structure, there will be *at least* two paths between any two nodes, and these paths will not go through the same nodes (Harary 1969). In concrete terms, this means that if we were to delete a path between two people on this subgraph, they would not become disconnected, as (at least) one alternate path exists. From the standpoint of STD diffusion– for example – let's imagine John, Paul, Jenny, Martha, Luke and Chrissy are connected in a bicomponent. In such an arrangement, an STD can flow from John to Martha, either through Paul and Jenny, or through Luke and Chrissy. Thus no actor or type of actor stands out in this network. In Likoma, the

connectedness of the observed sexual networks is thus not due to high volume of activity of a minority (unlike scale-free networks or core – periphery arguments). Quite to the contrary, it is the patterning of a relatively low number of ties (mean number of partnerships is 2.1) within the population that makes the structure we observed robust and cohesive (see White and Harary, 2001 or Moody and White 2003 for detailed analyses of structural cohesion in networks).

How does such a structure emerge? From a quick look at the data and the network pictures we displayed, it seems like a sizeable proportion of people at distance 2 or higher of each other in Likoma share one or more partners, thus creating short-length cycles. For example, two men can have had relationships with two of the same women as can be seen in the lower-right corner of fig. 6. As a comparison, Bearman et al. (2004) found that this structural feature was completely absent from the sexual networks of adolescents in a US high school and the only evidence of "cyclical" sexual networks we have comes from studies of "high-risk" populations in the US, such injecting drug users, men who have sex with men or prostitutes and their clients (e.g. Colorado Springs study, see Potterat et al. 1996). In Likoma, on the other hand, such a structure emerges in the general population and despite levels of reported activity (number of partnerships) that are much lower than those recorded in those US populations (Rothenberg et al. 1997).

A closer look at the social organization of sexuality on Likoma island

The previous developments have emphasized that the connectedness of the network of sexual relations in Likoma island was not due to the high level of activity of a minority (e.g. CSW). Rather, it was due to the patterning of ties within the population, and to the high proportion of people sharing one or several partners. In this final section, we explore the mechanisms behind the formation of this large bicomponent, i.e. the area of denser relations we identified in the graph. We do so by conducting a principal components analysis of the distances between members of this group. This procedure allows us to display the proximities between nodes on a 2-dimensions picture rather than in the 279 dimensions of the distance matrix: typically two individuals who are separated only by one or two steps in the networks will be very close to each other in PCA display. On the other hand, distant individuals will be far apart. The results of this analysis are presented in figures 7, 8a and 8b.

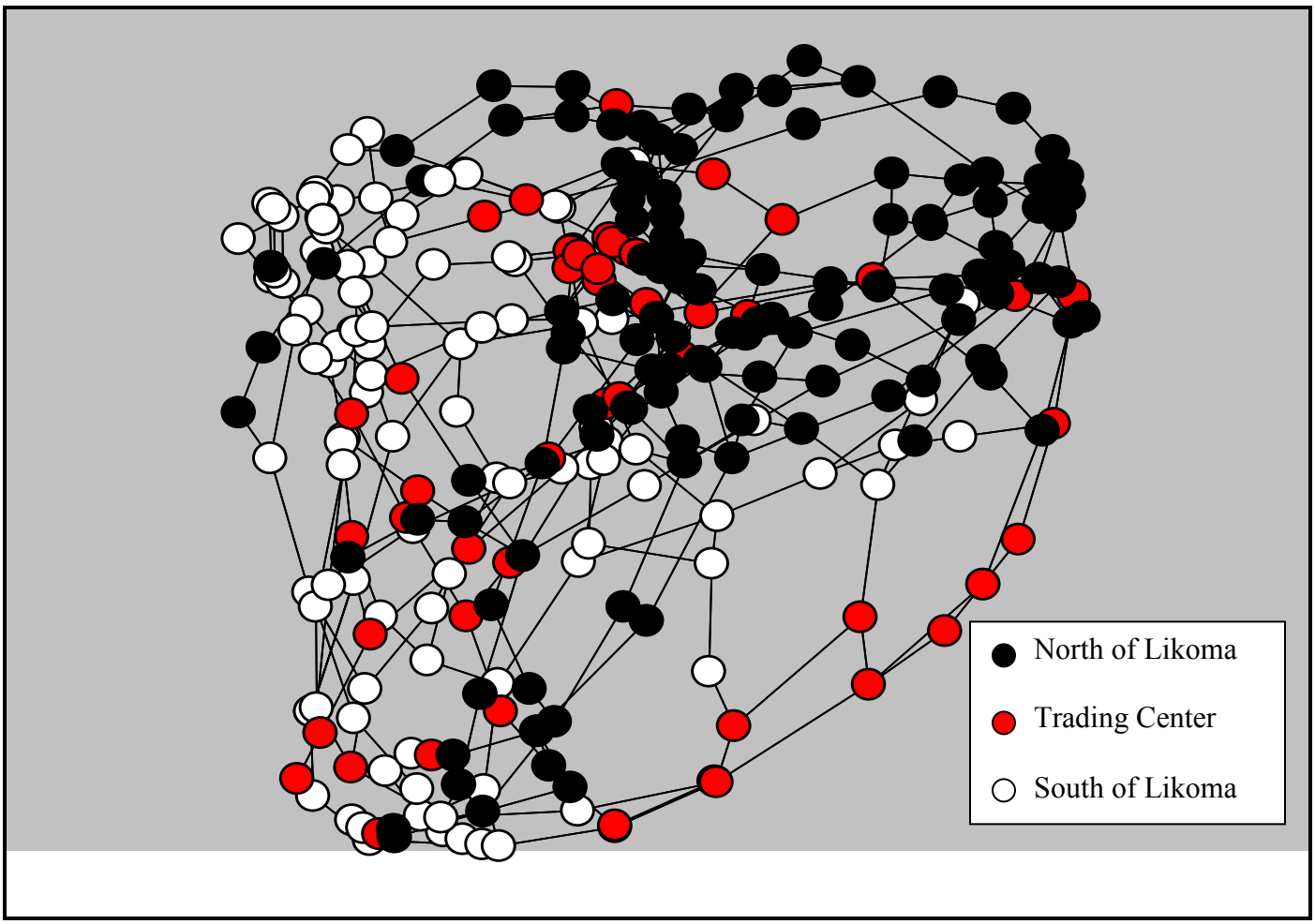
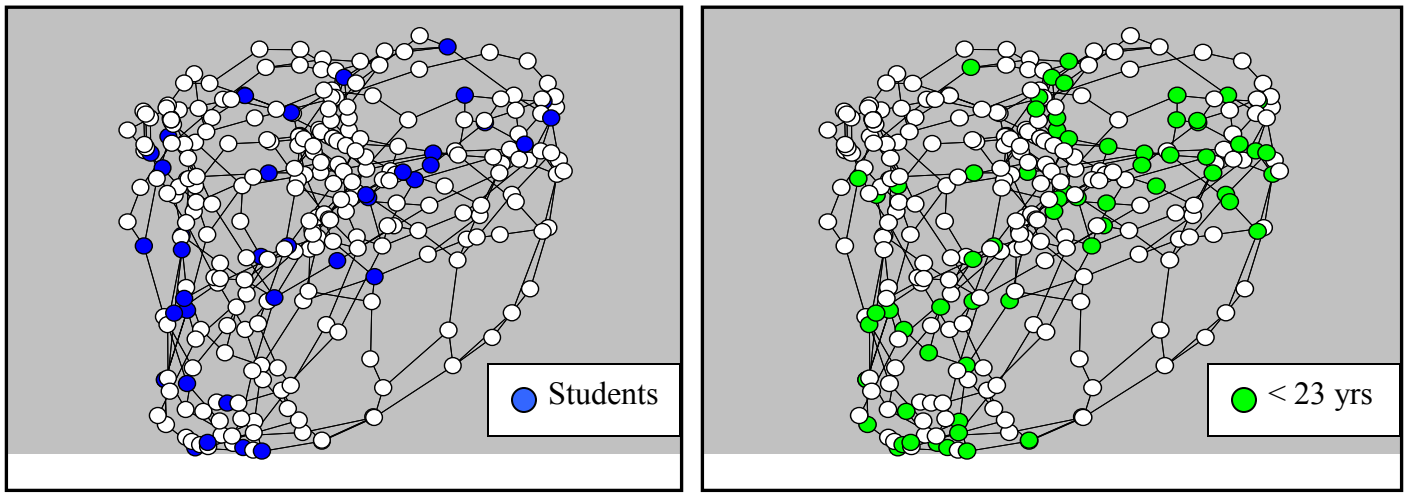


Fig. 7: Principal components analysis of the distances (geodesics) between members of the bicomponent. 50% of the variance is accounted for by this display. Graph is colored according to the residence of the individuals.

The two dimensions represented on this picture account for 50% of the variance in distances between individuals in the bicomponent. We notice that the graph exhibits 4 clusters: one at the upper left corner, one in the upper right corner, one a little above the center and one at the bottom of picture. This clustering and the proportion of the variance accounted for signal that the patterning of ties between individuals is not random, otherwise the points would have been displayed evenly in a circle or an ellipse (see Freeman, 2005). Quite to the contrary, the representation we obtain exhibits a definite order: the four clusters we identified are tied together by chains of nodes of variable length and density. For example, the chains that tie together the three clusters on the left of the picture are quite short and dense, whereas the chains connecting the lower cluster to the upper-right cluster appear long and fragile.

We thus try to find what the determinants of the clustering we observe are. In order to do so, we color individual dots on the graph according to various characteristics of the actors: fig 7 shows this approach for the residence of members of the bicomponent (whether they live in the north or in the south of Likoma, or whether they live in the trading centre), fig. 8a does the same but colors students from the Likoma secondary school instead. Eventually fig. 8b follows this approach and colors individuals younger than 22 years old in green.



A few patterns emerge from these figures. First of all, the bicomponent seems to be in part structured along geographical lines: a majority of the white dots (habitants of southern Likoma) fall in the upper left cluster, whereas the black dots (habitants of northern Likoma) tend to be found either in the upper-right corner or in the central cluster. This is consistent with the preferences for “local” partners that we described previously (see fig 3.).

Habitants of the trading centre (red dots), on the other hand, tend to cluster in the central region of the cluster but are also found in many other areas, in-between clusters. This suggests that they play a critical role in connecting otherwise disjoint or loosely connected clusters of individuals. For example, the chain directly connecting the lower cluster to the upper-right corner is exclusively made of individuals from the trading centre. Fig. 8a shows another group whose members act as bridges between otherwise distant populations: the students of the Likoma secondary school. They appear in blue on this picture, and we notice that they always are located in-between clusters, rather than in the middle of the denser

agglomerations of points. This is the case because they often have partners both at the school (where students come from all over the island or even the mainland of Malawi) and in their home villages.

Finally, in fig. 3b we explore the role of age in the formation of sexual networks in Likoma. In this display, young adults of less than 23 years old are colored in green. The resulting graph displays a striking pattern: whereas younger and older actors are relatively homogeneously mixed in 3 of the 4 clusters, younger adults are virtually absent from the upper left corner. Since habitants from South Likoma are concentrated within this cluster, we can hypothesize that the patterns of sexual mixing differ to some extent even at a very local level, i.e. between villages distant of 10 kms at the most.

Conclusions

In this paper, we have described in detail the structure of sexual networks in which adolescents and young adults residing in Likoma island are embedded. We have found that whereas a fifth of the population surveyed is part of dyadic (i.e. exclusive) relationships, 2/3 of the inhabitants of the island were linked together by a single chain of sexual relationships over the last 3 years. Furthermore, we found that, contrary to expectations from the epidemiological literature, neither a group of densely connected individuals (such as CSW and their patrons) nor a few extremely active "hubs" (such as "sugar daddies") are responsible for the connectedness of the structure we observe. Quite to the contrary, we found that inhabitants of Likoma are linked together by chains of sexual relations in a much more decentralized and complex fashion. Indeed, no individual or group of individuals "stands out" in that network, but because people tend to share partners (cycles), a very robust structure emerges.

This observation has some important implications for programs and HIV policies as most interventions are planned and evaluated using more "centralized" theoretical models (core/periphery, scale-free networks…) For example, mounting a "targeted attack" against high activity individuals or "hubs" might not prove so efficient in such a cohesive structure as Likoma. Another example: treating STIs has recently been suggested as the most cost-effective intervention to prevent HIV (Oster 2005), using a simple core-periphery model of sexual mixing. However, on the structure we observe, decreasing the infectivity of the virus would likely only delay its spread within the population rather than curtail it. Indeed if there are several potential paths between any two individuals in a network, rather than just one, the probability of infection does not decrease as fast as the infectivity of the virus. In such a network structure, the chances that a even a weakened virus will spread and infect a major proportion of a population remain high!