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How central are clients in sexual networks created by commercial sex?

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Sex workers are traditionally considered important vectors of transmission of sexually transmitted infections (STI). The role of clients is commonly overlooked, partially due to the lack of evidence on clients' position in the sexual network created by commercial sex. Contrasting the diffusion importance of sex workers and their clients in the map of their sexual encounters in twoWeb-mediated communities, we find that from diffusion perspective, clients are as important as sex workers. Their diffusion importance is closely linked to the geography of the sexual encounters: as a result of different movement patterns, travelling clients shorten network distances between distant network neighborhoods and thus facilitate contagion among them more than sex workers, and find themselves more often in the core of the network by which they could contribute to the persistence of STIs in the community. These findings position clients into the set of the key actors and highlight the role of human mobility in the transmission of STIs in commercial sexual networks.

Prostitution is a phenomenon seen at all times in all cultures around the Globe[1]. The market for commercial sex can be represented as a graph, in which the vertices represent sex buyers (clients) and sex sellers (sex workers) and the edges map the sexual encounters among them. Such client-prostitute networks are naturally connected to sexual networks of the general population through noncommercial sexual encounters of both sex workers and their clients. While noncommercial sexual partners cluster according to age, race, sexual activities, socio-economic status, physical attributes etc., providing natural barriers for disease transmission (see Ref. 2 and references therein), sex buyers are remarkably heterogeneous with respect to many of these characteristics[3]. Consequently, client-sex worker relations facilitate transmission across diverse socio-economic groups that might otherwise be disconnected. In addition, diffusion of diseases throughout a network relies on the existence of highly promiscuous individuals[2,4,5] and sex workers typically have a high number of sexual partners. As a result, commercial sex represents an important channel for STI transmission[4,6]. Even though particular groups of sex buyers (e.g. truck drivers, army recruits[7,8]) have received attention, little is known about the general role of sex buyers on the market and the existing policies have in fact been criticized for targeting suppliers while ignoring the demand for commercial sex[6,9–12].

Data on structures of commercial-sex networks are almost non-existent (see Refs. 13, 14 for two exceptions). Combining data from U.S. sex surveys and studies on commercial sex, Brewer et al.[15] find out that sex workers and sexual encounters with them are highly underrepresented in general-population surveys. Hence, little information about the connection of commercial sex with general populations can be obtained from these surveys. This lack of reliable data prevents researchers from evaluating the role of commercial sex in the diffusion of STIs and how it is linked to the general population. It also prevents policy makers from designing effective policies preventing STI diffusion both within the commercial sex market and to the general population.

As a result, many questions concerning commercial sex remain unanswered. Who are the key players? How central are clients in the sexual network created by commercial sex? Would policies targeted at clients be nearly as effective as policies targeted at sex workers? Evidence-based analysis of commercial sex is a prerequisite to answer these questions.

We characterize the organization of two online communities: the largest U.S. online community of sex workers and their clients oriented to men who have sex with men (MSM) and one high-end public forum oriented to heterosexual males in Brazil from Refs. 13, 14 (U.S. and Brazil, henceforth). The websites operate as mediators between the sex supply and demand. As both sex workers and clients are identified by unique usernames, it allows us to build the sexual network based on review records. A link between a client and a sex worker is established if the client posted a review of sexual services provided by the sex worker and the review was verified by the web administrator. An important effort is put by the administrators of both communities to maintain high credibility of posted reviews. Each review contains the usernames of both parties, the date, the meeting location, and other details. We analyze data from January 2005 to December 2011 in the U.S. and from September 2002 (the beginning of the community) to October 2008 in Brazil. In the U.S. data, we additionally exploit the interaction between the network and the geography of the encounters. Unfortunately, the geographical information about sexual encounters in Brazil is not available to us. More detailed account of both communities can be found in *Supplementary Information* (*SI*); Refs. 16, 17 and 13, 14 provide alternative descriptions of the U.S. and Brazilian communities, respectively.

The reported data allow us to perform exhaustive network analysis of each community, evaluate the role of clients for the cohesiveness of the system, and characterize the key players in both networks. On the other hand, the available data contain no information about the bridging capacity of clients from the commercial sex communities to general populations. Our analysis thus constitutes the first step in the evaluation of the role of the demand side of commercial sex in the global dynamics of STIs.

Naturally, the data present many limitations. First, the combination of the self-posting nature of the information and the stigmas associated to prostitution may prevent some clients from participating actively in the communities. We cannot thus be sure whether all clients post their reviews or whether they review all their encounters. Second, even though reputation matters in both communities, there is little control of clients' behaviors with respect to sex workers' in the website. We rely on the ability of the communities to self-monitor themselves and use the raw data in the analysis. Third, even though many socioeconomic phenomena, including prostitution, are increasingly organized on-line, the reported data still represent a sample of the corresponding submarket for commercial sex in each country. On-street prostitution oriented to MSM, much less monitorable than the on-line escort market, is relatively rare in the United States[18,19] and the on-line market is the primary medium for commercial male sex in the U.S.[16–18,20]. Hence, on-line data provide a relatively complete picture of this submarket for commercial sex[16]. As for Brazil, Rocha et al.[14] estimate that the data make up about 1% of sex workers in Brazil, a small fraction of the market. We are aware that these concerns limit the generalizability of our conclusions (see *Discussion*).

The previous research that uses these data differ substantially from ours. Refs. 16 and 17 use the U.S. data to analyze the determinants of the geographical distribution and prices of MSM prostitution; they do not exploit the network data. For the Brazilian data[13], study the feedback effects between the online and offline activities and the organizing principles behind the community structure. They report that the geography shapes the global organization. We show below that the geography also plays an important role from an individual perspective. Ref. 14 perform an extensive simulation analysis of disease dynamics in the Brazilian community, showing that the network topology slows down the disease dynamics whereas the temporal structure accelerates it. As a consequence, our simulation strategy considers both the network and temporal organization of the market. In contrast to these studies, our goal is to highlight the diffusion role of sex buyers vs. sellers in commercial sex.

Diffusion properties in networks. The resulting networks are by construction bipartite as direct links among clients or sex workers cannot exist (implying zero clustering coefficients, i.e. no connections between the neighbors of any node). Since general diffusion properties of bipartite graphs with degree correlations are not available, we follow the literature (e.g. Refs. 13, 21) and, in the first part of this study, analyze the network as static and one-mode reporting type-specific measures. In this approach, once a client reviews a sex worker, their link is built and regarded as persistent. Clients may post multiple reviews for the sex worker, but we treat these cases as a single link (i.e. we abstract from the frequency of each link). Frequencies of sexual encounters may matter for contagion, but we suspect that further communication between a sex worker and a client after the first encounter very likely occurs (if it does) by phone and thus outside the internet community. Indeed, very few encounters appear more than once in either data set.

The main focus of the network diffusion literature has been the degree distribution. The degree (D) of an individual measures the number of his sexual partners; the degree distribution keeps track of how the number of sexual partners is distributed in a population. Easier diffusion is associated with relatively high variance of the degree distribution[2,4,5].

Degree is a local measure of centrality and does not reflect how nodes "bridge" communities beyond their sexual partners. Betweenness (B) of an individual i determines the number of shortest paths between any pair of individuals (different from i) in the network that pass through i (*Methods*). Thus, B assesses how each node shortens distances among different parts of the network and thus facilitates contagion among them. Observe that by definition B is more sensitive to missing links than D. Betweenness (rather than degree) distribution determines diffusion properties of a network if (as in our case) not all the nodes/links are concurrently active. Diffusion is easier if the variance in betweenness is large[22].

Recently, Kitsak et al.[23] show that, in some circumstances, the best spreaders are nodes located in the core of the network, identified by the k-core decomposition (*Methods*). Coreness (C) is an alternative measure of global centrality that captures aspects different from both degree and betweenness. It can, for instance, assign low values to high-degree nodes in network peripheries or to nodes that constitute bridges among communities if they have low degrees.

A number of other characteristics have been shown to affect epidemic dynamics on networks (*Methods*). Giant component (GC) represents the maximal possible reach of a contagion initiated at one particular node. Assortativity (A) is the correlation between the number of links of two connected individuals. If $A > 0$ outbreaks happen very fast but do not extend too far, while if $A < 0$ such outbreaks are more difficult but if they occur they spread to larger fractions of the population[24]. Common sense predicts disassortative mixing in client-prostitute networks due to the different number of encounters between the two types of nodes. Average and maximal distances in the GC allow us to evaluate how far a disease has to transmit to affect most members of the GC and determine how fast the authorities have to react to prevent or stop the contagion: if distances are short preventive steps have to be fast, while larger distances may allow for slower but more effective interventions. Last, the epidemic threshold is a threshold probability of disease transmission, above which an outbreak may occur (i.e. the epidemics affects a non-zero fraction of nodes in large populations).

Static network analysis

There exist some common features in both communities and some important differences. First, U.S. and Brazil represent different socioeconomic realities. Prostitution is illegal in all but one U.S. state while legal in Brazil (even though employing sex workers, running a brothel etc. is prohibited)[25]. Natural differences arise due to the homosexual vs. heterosexual nature of each market. For instance, STI dynamics differ between MSM and heterosexual communities due to higher transmissibility in anal compared to vaginal sex[26]. There indeed exist large differences in the structural organization of the analyzed markets (Table 1). Moreover, whereas the Brazilian data only filter the most expensive section of the community[13,14], the U.S. data portray the whole community and online escort markets represent large fraction of commercial sex for MSM in the U.S.[16–18,20].

Table 1 | Network statistics in the U.S. and Brazil. Unambiguously, the organization of the Brazilian community is more favorable for the spread of STIs: it is more connected on average, almost everybody belongs to the GC, and the average and maximal distances are shorter even though the absolute size of the GC is larger. Indeed, any STI which transmits with probability larger than 11.7% during an intercourse will stabilize in the U.S. community, contrasting with 1.4% in Brazil. On the other hand, both communities are similar in the disassortativity (potential outbreaks will be slow but will affect large fractions of the population), the existence of a GC and non-existence of other important subgraphs, and short distances with respect to the size of each community (any member of the GC can reach any other one in at most 20 and 17 steps independently of their location in the U.S. or Brazil, resp.). Interestingly, despite the discrepancies in connectivities, the fractions of existing edges (out of all possible) are identical (0.018%). The architecture of both communities is more favorable for the spread of STIs than documented non-commercial sexual networks[21,35–38]: both communities are less fragmented and organized in disassortative architectures

	U.S.	Brazil
Number of vertices	5,678	16,730
Number of edges	5,817	50,632
Sex workers	1,778 (31.31%)	6,624 (39.59%)
Giant component	3965 (69.83%)	15,810 (94.50%)
Second largest component	18 (0.30%)	8 (0.05%)
Assortativity	−0.119	−0.089
Average distance (in GC)	7.7	5.8
Diameter (in GC)	20	17
Epidemic threshold	0.117	0.014

Finding common features in such different communities thus suggests that any finding may hold more generally.

Clients' vs. sex workers' position in the networks. In both communities, the degree distributions of the whole network, clients, and sex workers are far from distributions of random networks and, even though they exhibit fat tails, they differ considerably from distributions generated by theoretical scale-free graphs[27] (Fig. 1). In absolute terms, sex workers are more central than clients locally (D) and globally (B) (Kolmogorov-Smirnov tests, $P < 0.02$). In contrast, while the coreness measure is higher for sex workers in the U.S. network ($P < 10^{-7}$), it is statistically indistinguishable from clients' in Brazil ($P = 0.20$). Relative to the means, the variance of D and B are high for both clients and sex workers; the coefficients of variation are comparable for clients and sex workers in case of the three measures (*SI Tables 1–4*). Altogether, sex workers are more central generally but the above figures suggest that clients should not be overlooked (especially in Brazil) and the coefficients of variation point to the presence of a set of very central actors on both sides of the market.

Immunization strategies. The key policy question is to determine the best strategy to inhibit contagion. Network theory highlights the role of central individuals[4,28], literature on prostitution stresses the role of sex workers[10–12,18], while recent evidence brings forward the increased need to monitor movements of individuals[29], due to the changes in social and movement patterns of the population in the last decades. To analyze this issue, we remove members of the society according to several criteria; this may represent a real removal of individuals from the network but it also simulates their full immunization against a pathogen (*Methods*).

Since network-based removal largely outperforms both random and travelling-based strategies (*SI*), we illustrate how the removal of both locally and globally the most central individuals affects the

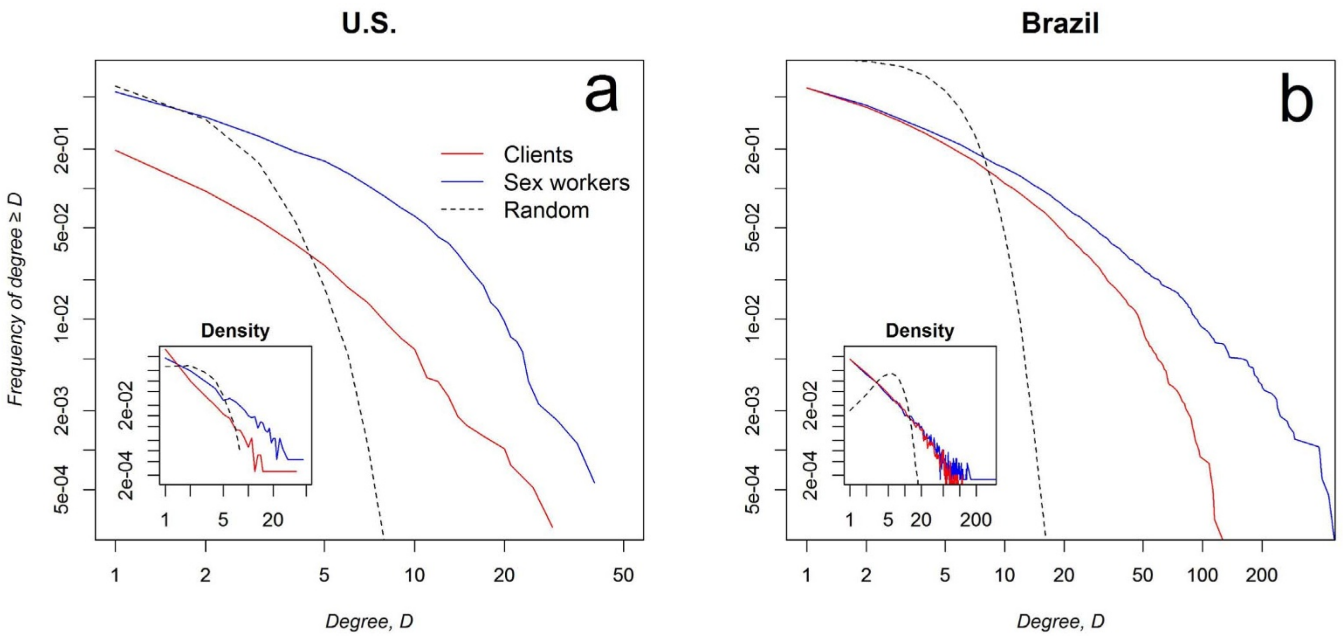

Figure 1 | The (inverted) cumulative degree distributions in (a) U.S. and (b) Brazil (Insets: Densities): the existence of nodes with large number of sexual contacts is indicated by the tails of the distribution being fatter than the tails of a comparable randomly-generated network.

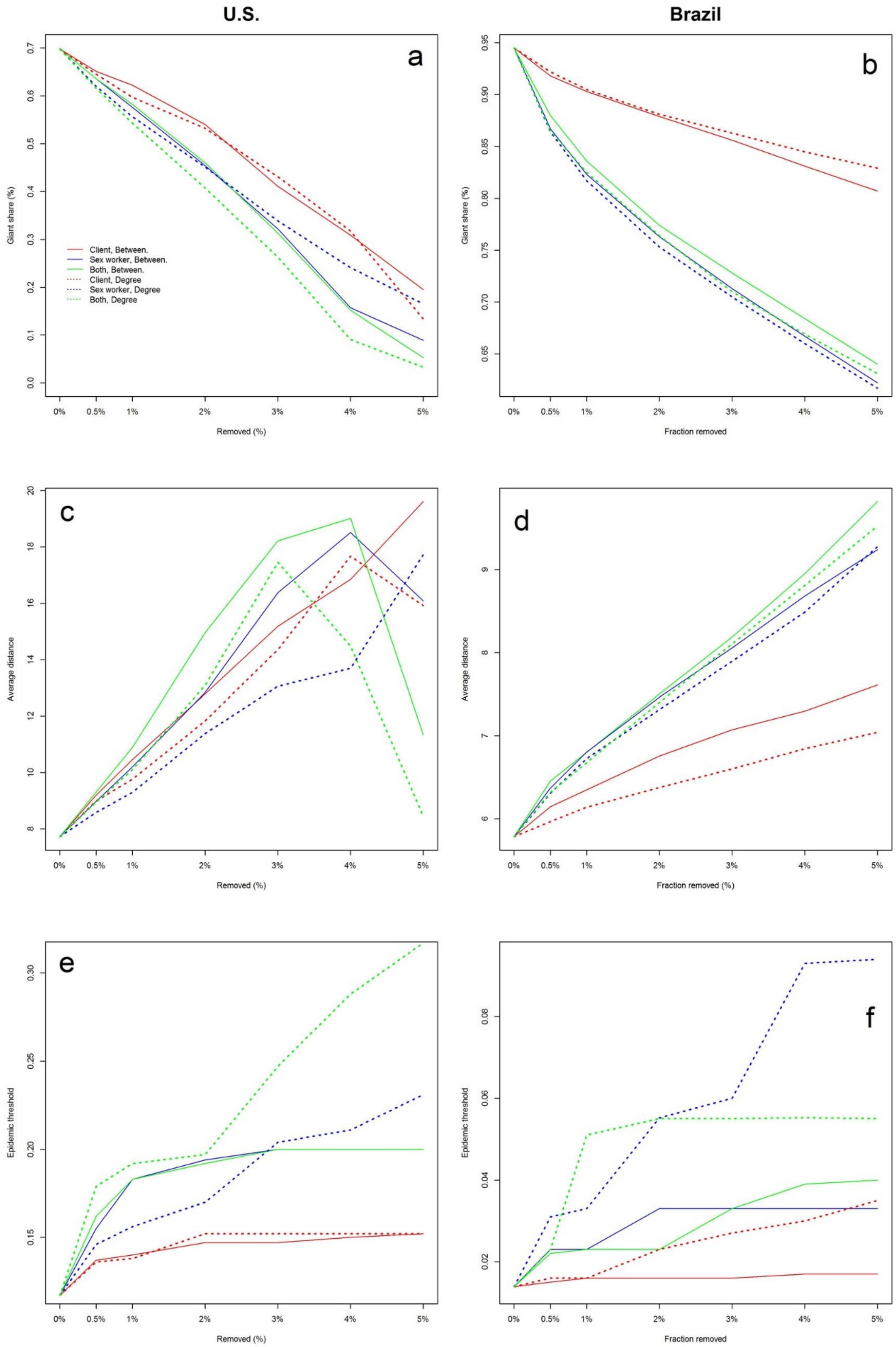

Figure 2 | Removing the most central individuals from the U.S. (left) and Brazilian (right) networks in descending order (%, x-axis) according to several criteria: (i) local centrality (number of sexual partners; dotted lines), (ii) global centrality (betweenness; solid lines) and according to agents' types: (1) clients (red), (2) sex workers (blue), (3) type-independent (green). (a,b) The share of the GC (c,d) Average distance (e,f) Epidemic threshold. The most effective strategy to inhibit contagion is the type-independent removal; type-dependent targeting always leaves in the network some very central individuals who maintain certain degree of connectivity and closeness in the graph. This effect is weaker in Brazil. Both type-dependent policies perform similarly in the U.S., but targeting sex workers outperforms targeting clients in Brazil.

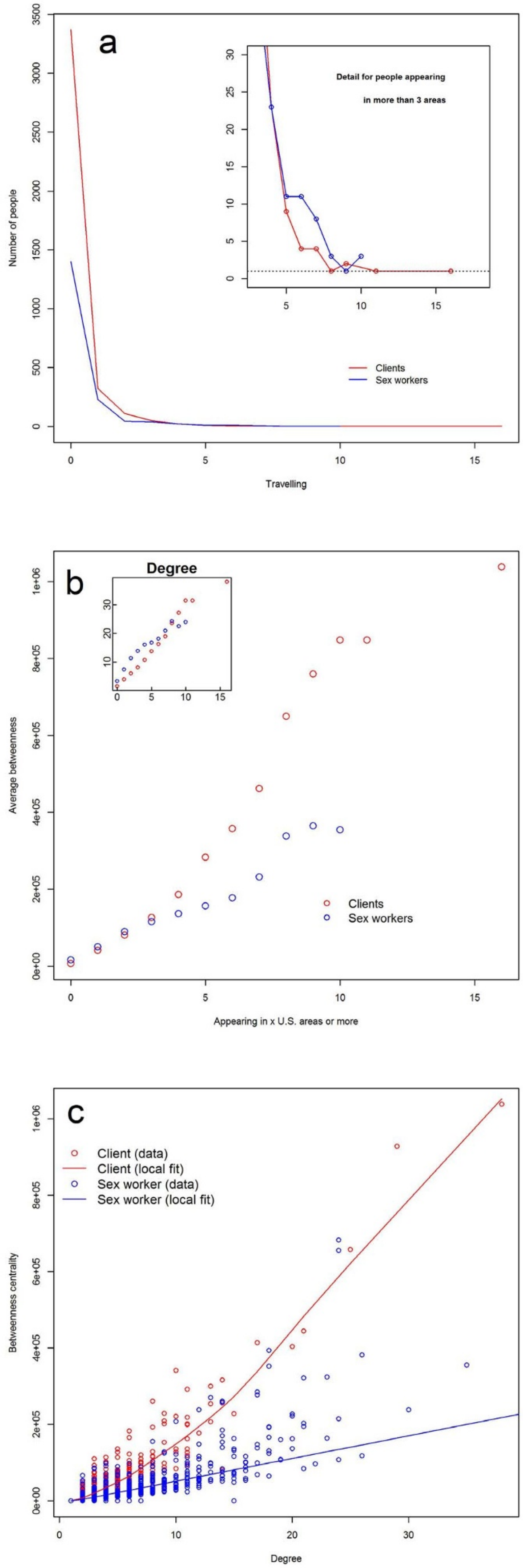

Figure 3 | Network position and traveling in U.S. (a) The distribution of the number of areas actors travel to (Inset: Detail for frequent travellers, $x \geq 4$): clients and sex workers are no different if we focus on frequent travellers; (b) Average betweenness centrality for different subsets of the most travelling individuals (Inset: Degree): as agents appear in more U.S. areas the average impact of clients on bridging different parts of the network increases in comparison with sex workers and this difference is not due to differing connectivity conditional on travelling (Inset); (c) Betweenness centrality in function of degree: with the same number of connections, clients shorten network distances more than sex workers. The same effect is observed for coreness and in Brazil (*SI Figure 4*).

diffusion properties of the empirical networks, distinguishing type-dependent and type-independent removal (Fig. 2).

Even though targeting sex workers is generally more successful inhibiting contagion than targeting clients, the most effective way to slow contagion is to target the most central individuals independent of their type. Local and global measures perform similarly but the epidemic threshold increases more if locally central individuals are removed. There is no optimal policy to target assortativity (*SI Figure 1a,b*). Only indiscriminate targeting is unambiguously effective in lowering maximal betweenness in both networks; type-dependent removal of the globally most central nodes can actually increase maximal centralities in both networks (*SI Figure 1e,f*). Hence, considering the most central clients and sex workers indiscriminately for immunization or reeducation may improve the prevention of STI diffusion with respect to policies targeting solely sex workers.

Determinants of Network Centrality and the Geography of Commercial Sex. Given the diffusion role of network centralities, we use the U.S. data to analyze the determinants of agents' positions in the network (*SI*). The analysis uncovers that there are important differences between the demand and the supply and that travelling is a crucial determinant of centrality.

Among clients and sex workers, 13.61% and 21.26% respectively appear in more than one U.S. statistical area (area, henceforth). Below, the variables *travel* and *travelling* refer to the number of areas an actor appears in (minus one) and *travelers* are individuals appearing in at least two areas. There are large correlations between the number of regions an agent appears in and the number of sexual partners, betweenness centrality, and coreness ($P < 10^{-7}$). Traveling *alone* can explain around 50% of centrality, the percentage considerably higher for clients than sex workers and for D and B than C (*SI Table 5*). If we remove all individuals appearing in more than one or two U.S. areas, the network properties are affected drastically and global pandemics from one particular node are no longer possible (*SI Table 6*), illustrating the key role of travellers in the network even though they represent a small fraction of actors on the market. Hence, the geography of sexual encounters in the market is important. Clients appear in fewer regions on average (Wilcoxon rank-sum test, $P < 10^{-7}$), but the difference disappears if we focus on more systematic travellers ($P > 0.2$ for individuals appearing in more than 3 areas; Fig. 3a).

Betweenness centrality reveals that clients bridge a larger number of distinct pairs of other network members than sex workers conditional on travelling and this difference rises with travelling (Fig. 3b). Since this observation cannot be attributed to the number of sexual partners (Fig. 3b, Inset), it suggests type-specific travelling patterns. To test this hypothesis, we analyze what determines the frequency of appearances of travelling clients and sex workers in the 20 most important (from the perspective of sexual encounters) areas. These frequencies are highly correlated between the two types ($\rho = 0.99$; $P < 10^{-7}$), but the analysis reveals that the movements of the most mobile sex workers are more predictable using standard socio-economic characteristics than the travelling patterns of clients (*SI*). The main difference is the importance of area-level economic activity for the appearance of sex workers, which does not seem to influence the demand for sex. Hence, clients' movements within the

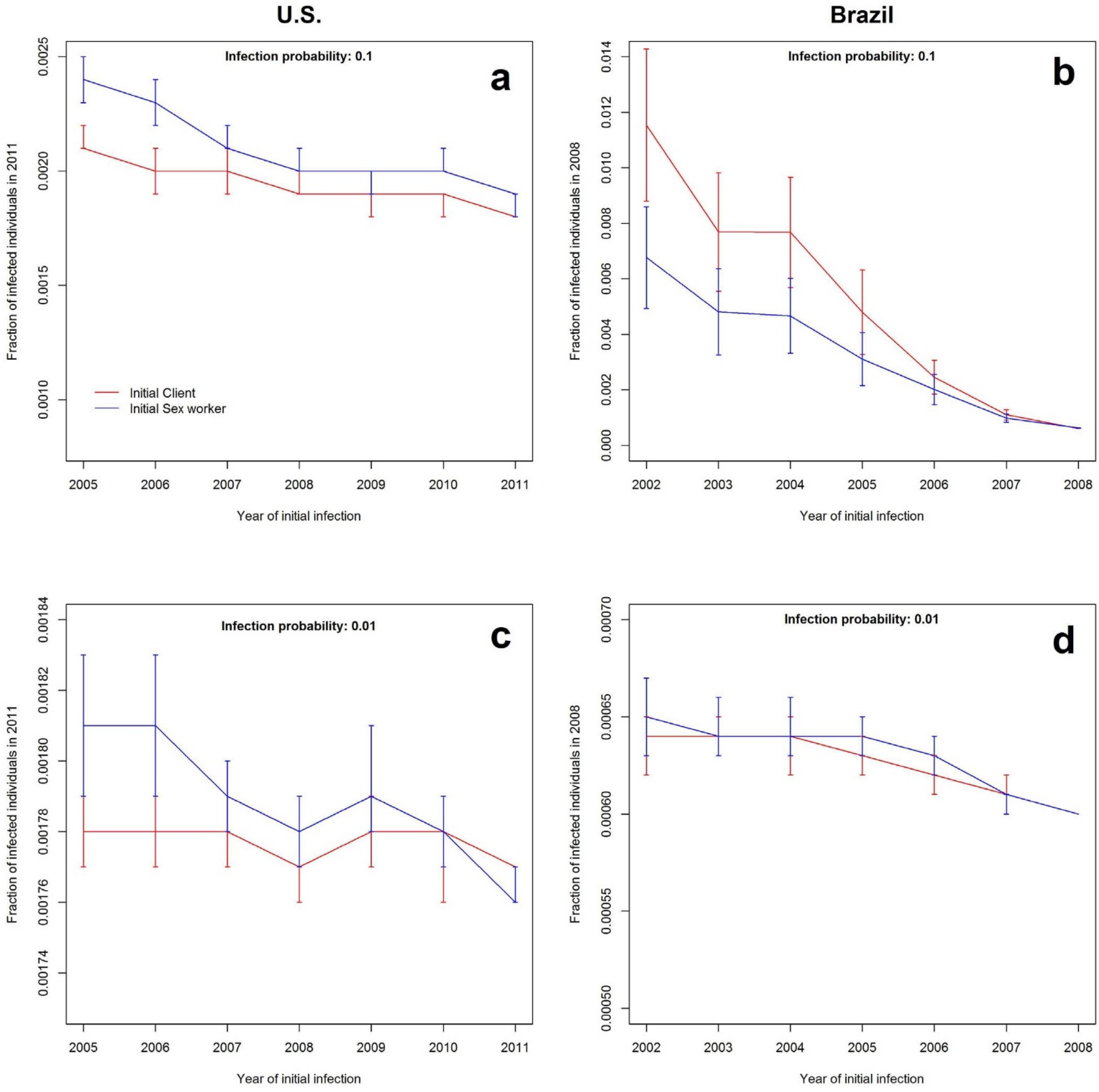

Figure 4 | Average outbreak sizes at the end of (a,c) December 2011 in the U.S. and (b,d) October 2008 in Brazil (%, *y*-axes) in function of the year of the initial infection (*x*-axes) and for transmission probabilities 10% (top) and 1% (bottom); 10 randomly selected clients initially infected (red) vs. 10 randomly selected sex workers (blue); vertical lines plot the 95% confidence intervals from 100 repetitions of each parameter constellation: both clients and sex workers have comparable impact on the introduction of STI into the communities. The results are robust to other parameter specifications (*SI*).

U.S. differ from travelling patterns of sex workers and the former are less predictable. This is reflected in the impact of client links on their global centrality: the average effect of each link of a client increases his betweenness more than the connections of sex workers (Fig. 3c), a phenomenon also present for coreness and in Brazil (*SI Figure 4*). We observe no tendency of travelling clients to seek out (non-)travelling sex workers (*SI Table 7*).

Regression analysis confirms that sex workers are more central locally and globally in absolute terms ($P < 10^{-7}$) and their local centrality exhibits higher sensitivity to travelling ($P < 10^{-7}$). Workers serving one additional area increase their number of encounters by 2.40; if a client appears in an additional region his number of sexual contacts increases by 1.70, a number significantly larger than one ($P < 10^{-7}$) suggesting that traveling clients regularly change their sex worker contacts. Overall, this corroborates the traditional view that sex workers are the key actors on the market.

In contrast, clients' global centralities (measured by both *B* and *C*) are more sensitive to travelling ($P < 10^{-7}$). Clients form part of the "bridge" (the shortest path) between almost 9,000 (and 10,000 in the GC) pairs of different members of the network *more* than travelling sex workers with each additional region they appear in. Thus, clients have higher absolute betweenness centrality if we focus on travelers and they thus allow STIs to travel faster across different network neighborhoods than sex workers (Fig. 3b). In the same vein, travelling clients have higher coreness than comparable sex workers, contributing to the persistence of pathogens. This positions travelling clients into the key actors of the community. The association between centrality and travelling also reveals non-linearities that reinforce the global importance of mobile clients in the system (*SI*). Individual characteristics play little role explaining the centrality of sex workers (*SI*), reinforcing the role of travelling in the market organization.

To further highlight the role of travelling individuals in the community, we group people into subsets according to whether their degree is larger or equal to a certain value, such that the $D \geq 1$ set contains the entire network, the $D \geq 2$ set pools all individuals with more than one sexual contact, etc. Even though unorthodox, this approach allows us to focus on the average characteristics of subgroups of the most central individuals with varying degrees of (local) centrality. This variable uncovers that, conditional on the centrality of the group, clients travel more and the difference between clients and sex workers enlarges with the groups' centrality and clients' centrality can be almost entirely explained by travelling (*SI*). This alternative approach reinforces further the finding that clients, particularly those appearing in many U.S. areas, are central players in the network.

Spatiotemporal analysis

The above analysis has abstracted from the bipartite nature of the networks and their temporal structure. To incorporate these features, we simulate a stochastic spread of a pathogen on both observed networks. The crucial feature of the simulations is that people can only infect their future contacts. This is important because Ref. 14 reports that the temporal structure accelerates contagion in the Brazilian community. Since the objective of the simulation scenario is to focus on the diffusion role of each type of actor, we abstract from the complexities of any particular disease or differing risk depending on the type of sexual activity, simulating the simple Susceptible-Infected model for a variety of transmission probabilities. The objective is to contrast the scenario in which the initial contagion is introduced by 10 randomly selected clients vs. 10 randomly selected sex workers for two transmission probabilities, 1% and 10% (*Methods*).

We observe certain differences between whether sex workers or the clients start the diffusion but the differences are not generally significant independent of the country, how long the pathogen travels along the network, and the transmission probability (Fig. 4). Thus, the temporal dynamics and the bipartite structure corroborate that clients are as important as sex workers for disease transmission in the empirical networks. This conclusion is robust to parameter specifications (including lower and higher transmission probabilities) not included in Fig. 4.

Discussion

Exploring data on sexual encounters between sex workers and their clients in the U.S. and in Brazil reveals that clients play a role as important as sex suppliers in the organization of the market for commercial sex. Sex workers are more important locally as they naturally have more sexual partners in a given area, whereas clients have higher impact on the global structure of the market. Due to their differing travelling patterns, sex buyers shorten distances between distant parts of the network more than sex sellers. As a result, conditional on the number of sexual partners, clients are globally more central than sex workers and this difference increases as we focus on the most connected individuals, a phenomenon observed in both networks and using two alternative measures of global centrality (*SI Figure 4*). These observations reveal that both sides of the market play an important (even though different) role in its organization and none of them should be overlooked.

It is difficult to hypothesize whether these conclusions generalize to other cultures or submarkets for commercial sex. Important differences already exist between the two analyzed communities and some results seen in one do not appear in the other. In addition, the data sets only represent samples of each market, missing data are very likely, and the analyzed markets are not closed systems, biasing the diffusion importance of the communities downwards. We cannot directly address these issues with our data. Inarguably, more research analyzing the organization of other markets and the interconnection among different submarkets is necessary. We consider our research to be the first step in this direction. However, nothing can be deduced from our data about the position of each client in the sexual network outside the commercial sex. Active sex buyers may well be active in noncommercial sexual networks or they might rather be active hiring sex workers because they lack other type of sexual contacts. Similar ignorance prevails concerning the noncommercial sexual encounters of sex workers. If we would like to understand and prevent STIs from traveling between the commercial and non-commercial sexual networks, further investigation has to relate the sexual behaviors of both sex buyers and sellers within and outside the commercial sex communities.

To mention other limitations, to be able to concentrate on the position of sex buyers our study is more suitable for the evaluation of emergent or early stages of diseases. This is a highly relevant point because e.g. HIV is not an emergent pathogen. For the same reason, our simulation strategy reflects the simple Susceptible-Infected model, without any possibility of recovery and without mimicking the properties of any particular pathogen. Some STIs (e.g. chlamydia) can be cured and one becomes susceptible again. Interested readers are referred to Ref. 14 for a more exhaustive analysis of disease dynamics under different model specifications in the Brazilian community. Another unexplored element of pathogen diffusion in sexual networks created by commercial sex is the concurrency of encounters[30,31]. There are very few repeated encounters in our data, but it is possible that repeated contacts occur by other means and are thus unobservable to us. The research indeed reports that repeated and long-term sexual contacts between sex workers and clients are not uncommon[32,33]. Last, our analysis abstracts from safe-sex practices of clients and sex workers as well as from the particular sexual services provided during the encounters. Nevertheless, these aspects clearly play an important role in disease transmission.

These considerations notwithstanding, clients are important in both communities. Our findings thus convey an interesting message for policies targeting the diffusion of STIs within the commercial-sex community as well as from the commercial sex to general populations: the demand side of the market should be actively targeted by safe-sex campaigns but the campaigns should be type-specific as sex sellers and buyers play different roles in the connectivity of the global organization. Our results also underscore the importance of the global approach to prevent STI diffusion and the HIV/AIDS pandemic and combining network data with movement patterns of individual actors, as travelers will naturally connect different countries and continents the same way they connect different U.S. areas or Brazilian cities[13,14]. Such a global approach has already proved crucial during several recent outbreaks of non-STI diseases, such as SARS or swine flu, and their close link to human movements (e.g. Ref. 29).

Methods

Network measures. Several individual network measures are used in the main text. Degree, D, is the number of sexual contacts. Betweenness centrality, B, of an individual i measures the number of shortest paths (geodesic distances) between all the pairs of individuals in the population (different from i) that pass through node i and is defined as

$$B(i) = \sum_{j \neq k \neq i} \frac{\sigma_{jk}(i)}{\sigma_{jk}} \quad (1)$$

where σ_{jk} is the number of shortest paths between nodes j and k and $\sigma_{jk}(i)$ is the number of such paths that go through node i. The coreness of a node is computed using the k-core decomposition algorithm. First, all $D = 1$ nodes are removed from the network. Since the removal may lead to new $D = 1$ nodes, the removal further follows until all $D = 1$ nodes are removed in all steps. All the removed nodes form the 1-core of the network. Once finished, the same procedure follows with the $D = 2$ nodes, leading to the 2-core of the network and so on. Each layer receives the number corresponding to the degree of the layer and higher values of coreness correspond to belonging closer to the core of the network. Giant component (GC) is the largest connected subset of nodes in the network. Assortativity (A) is the correlation between the number of links of two connected individuals. If $A > 0$, high-degree individuals cluster together whereas people with low number of contacts tend to link up with other low-degree nodes; if $A < 0$, popular individuals tend to be connected to low-degree nodes. Average distance measures the average number of edges between the individuals in the GC. Diameter is the maximal distance between two members of the GC. Whether an outbreak can occur is determined by an epidemic probability threshold λ_c, computed as the inverse of the largest eigenvalue of the adjacency matrix of the network[34].

Immunization. We analyze an extreme example of immunization, in which some people are considered fully immune against a pathogen. We select certain percentages of nodes (0.5, 1, 2, 3, 4, 5%) according to four criteria, remove them from the network, and present some network properties after these removals. This is analogous to immunizing these nodes and study only the subnetwork through which STIs can travel. The four removal criteria used are: (i) random removal or removal based on (ii) travelling (iii) local centrality, D (iv) global centrality, B. Since random and travelling-based removal have small impact on the network relative to the nework-based criteria (*SI*), we only report the removal of the most central individuals according to D and B in the main text and contrast three scenarios: removal of the most central clients, sex workers, and type-independent removal.

Simulations. We apply the Susceptible-Infected model. Initially, all nodes are susceptible and we infect randomly 10 clients or 10 sex workers in January of each year 2004–2011 (U.S.) and September of each year 2002–2008 (Brazil). Since the U.S. data are labelled on monthly basis, we organize the Brazilian data in the same way and accelerate the contagion by infecting with probability $p = 0.1$ or 0.01 the initial-period sexual partners of the 10 initially infected individuals. There is no recovery rate in the Susceptible-Infected model. All the nodes infected in the initial month infect all their current and future partners with probability p; never their past encounters. The newly infected transmit the pathogen to their current and future partners with probability p. This process follows and we report the average outbreak size at the end of December (October) of 2011 (2008) and 95% confidence intervals in 100 repetitions of each parameter specification. *SI* considers other parameters constellations.

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Author contributions

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