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Untapped capacity of place-based peer-to-peer resource sharing for community resilience

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During and after a disaster, people share resources with family, friends and neighbors to tide them over difficult times. The conventional top-down approach for disaster relief overlooks the wealth of critical resources that exist within communities. Here we explicitly model place-based peer-to-peer (P2P) resource sharing and evaluate its impact on community resilience to disasters. Using data from two urban communities in Seattle, Washington State, we confirm substantial untapped capacity for enhanced community resilience through place-based P2P resource sharing. Under a 5-day isolation scenario, place-based P2P sharing can reduce a community's resilience loss by 13.4–100%; on average, 22–44 social ties per household support an 80% sharing rate of surplus resources. These findings suggest that place-based P2P sharing could be a viable strategy for disaster response across US communities, in addition to the current, government-led effort. Our methodological framework is transferable to other urban communities interested in enhancing disaster resilience.

When a disaster strikes, people come together to help one another: they share resources, pass along information and volunteer to take on tasks outside their usual domains[1]. These kinds of post-disaster mutual support activities are widely documented. Recent examples include neighbors helping neighbors escape from flooding using rafts improvised from inflatable mattresses during Hurricane Matthew in Rowland, North Carolina in 2016[2]; social media-enabled mutual assistance during the Texas Freeze in February of 2021[3]; and households with solar capacity sharing their energy supply with others after Hurricane Fiona struck Puerto Rico in 2022[4]. Although federal emergency response protocol (for example, the Federal Emergency Management Agency's National Incident Management System[5]) tends to adopt a top-down approach to the gathering and distribution of relief resources via preidentified jurisdictional and organizational structures, local emergency responders realize they will probably rely on local resources following a major disaster[6].

The propensity of local social and civil networks to step up and provide aid in disasters in the absence of government capacity has been widely reported[7,8]. A recent survey in Washington State showed that a great proportion (≥90%) of respondents are willing to share different types of resources (for example, water, food, sanitation and shelter) with family, friends and neighbors during times of disaster[9]. About one-third of the respondents expected to turn to their social ties (family, friends and neighbors) for resources, while another one-third would turn to local retail stores, and only a small percentage (≤5%) of the respondents expected to turn to the government for post-disaster assistance with critical resources such as food. These numbers suggest that place-based peer-to-peer (P2P) sharing of surplus resources has the potential to fill important gaps in the immediate aftermath of a major disaster that cannot be addressed by emergency response agencies, thereby enhancing a community's resilience to disaster. Here, place-based P2P resource sharing refers to sharing with relatives

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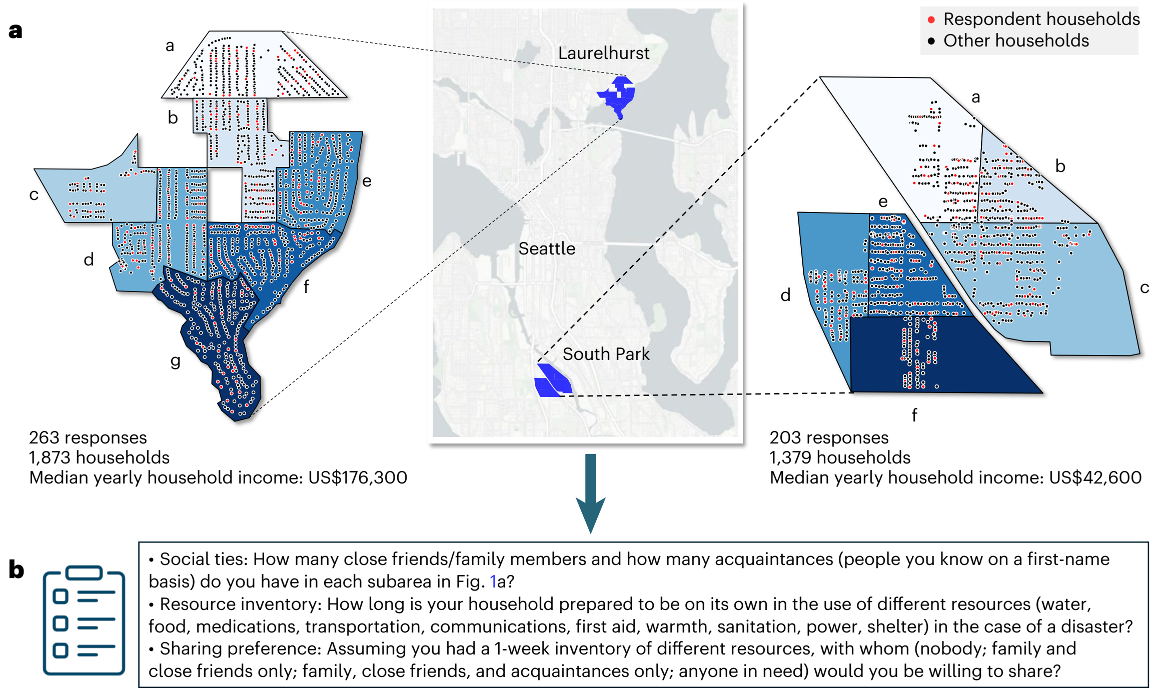

Fig. 1 | Study area. a, Study community overview. This study conducted a survey in two Seattle neighborhoods, Laurelhurst and South Park. Each neighborhood was divided into subareas, for example, labeled as a–g in Laurelhurst and a–f in South Park and represented in the blue color scheme, to facilitate the identification of local social ties. **b**, The household survey questions utilized in this paper (see Supplementary Section 1 for details). Map tiles by Stamen Design, CC BY 3.0; map data from OpenStreetMap, CC BY-SA 2.0.

and friends (strong social ties), acquaintances (weak social ties) and strangers within a geographically bounded community.

Although recognizing the importance of social and behavioral aspects of disaster response[10], a substantial literature focuses primarily on the capabilities of physical infrastructure, such as resilience assessments/enhancements of water delivery systems[11,12], power systems[13,14], transportation systems[15,16], and ambulance and fire and rescue services[17]. In contrast, P2P resource sharing constitutes mutually supportive behavior fostered by social capital[18–20], or the range of resources to which an individual has access via their social ties. Many studies have examined the contribution of social capital to community resilience[21,22]. For example, qualitative studies have demonstrated that established social ties have the potential to effectively disseminate information[23], promote collaborative behavior[24] and support more rapid household recovery[25,26] in disaster scenarios. However, as far as we are aware, no previous study has quantitatively evaluated the potential impact of social-tie-enabled P2P resource-sharing activities on community resilience. An important question remains unanswered: To what extent can place-based P2P resource sharing improve a community's resilience against disasters? We define resilience as the capacity of a community to sustain essential functionalities such as providing food, sanitation and housing when it is isolated from outside assistance after a disaster.

Place-based P2P resource sharing requires a complete social network comprising every household within a community. We develop a framework that can generate complete social networks with consistent topological properties as compared with those in the survey data collected from the community. Based on the complete social networks, we then construct P2P resource-sharing networks in which nodes, representing households, have attributes on resource inventories and links denote preferences for sharing different resources with a strong tie, a weak tie or a stranger. This P2P resource-sharing network is the basis of the optimization model that allocates resources among peers (nodes) according to individual households' sharing preferences. Last, we measure the resilience loss of the community, which is defined as the product of the number of households with a resource shortage and the number of days they experience the shortage. This methodological framework is scalable to other urban communities interested in assessing its potential enhancement of community resilience via P2P resource sharing.

Using the framework described above, we demonstrate the potential of place-based P2P resource sharing for enhancing community resilience in two characteristically different urban communities in Seattle, Washington State. We show that, compared with the no-sharing case, place-based P2P resource sharing can reduce resilience loss by 13.4–100% for ten essential resources in the two communities. We also find that increasing the number of social ties has a positive effect on place-based P2P resource sharing; on average, 22.0 and 43.9 social ties per household are sufficient to redistribute 80% of the surplus resources to those in need in the two communities. For individual households, strong ties are about 1.5–3 times more effective than weak ties in securing needed resources to ensure survival. We argue that place-based sharing as demonstrated by this study has the potential to enhance community disaster resilience. We discuss this point in 'Discussion'.

Study communities

A major port city and technology hub of approximately 737,000 inhabitants, Seattle and its surrounding region are vulnerable to a range of hazards, including earthquakes, flooding and windstorms, that could potentially isolate communities from critical resources. Seattle was selected for this case study owing to local initiatives focused on community-based disaster preparedness such as the Seattle Neighborhoods Actively Prepare program and the all-volunteer Seattle Emergency Communication Hubs Network, which facilitates community-based disaster preparedness efforts.

To better understand the potential for enhancing community resilience given the variability in everyday access to resources, we selected the Seattle neighborhoods of Laurelhurst and South Park as case study communities (Fig. 1a). In addition to varying substantially in terms of sociodemographic characteristics (Supplementary Table 1), the two communities also represent a range of quality-of-life standards. A legacy of pollution due to South Park's industrial location and historic disinvestment in the community have contributed to a 13-year difference in expected life span compared with Laurelhurst, a wealthy single-family residential neighborhood[27].

Working together with local volunteer organizations in each of the study communities, we developed and distributed a random sample survey asking participants about their (1) household resource inventory; (2) community social networks (strong and weak social tie information); (3) sharing preferences for ten essential resources including water, food, medication, first aid, warmth, transportation, communications, sanitation, power and shelter after the occurrence of a major disaster (Fig. 1b); and (4) sociodemographic characteristics. Survey respondents were offered a US$5 Amazon e-gift card in exchange for completing the survey. Target sample sizes are calculated following Dillman[28], using information from a pilot survey in Laurelhurst (Supplementary Section 1). Final sample sizes were 263 in Laurelhurst and 203 in South Park, corresponding to 35.9% and 16.9% response rates, respectively. We classify the first five (water, food, medication, first aid and warmth) as survival resources and the other five as infrastructure resources. Further details about the survey and responses can be found in Supplementary Section 1.

Place-based P2P resource sharing modeling and resilience assessment

The proposed methodological framework shown in Fig. 2a comprises four steps: (1) place-based social network construction, (2) P2P resource-sharing network construction, (3) P2P resource-sharing model and (4) resilience loss analysis. This framework allows conducting a whole-community resilience loss analysis based on a random sample and explicitly considers the role of social ties in place-based P2P sharing of different types of essential post-disaster resources.

The first step of the methodological framework is to construct complete social networks for a community because, as observed from the survey responses, the existence and the type of social ties affect peoples' sharing behavior. However, having a complete network of social tie information requires asking every household whom they know within their community, which is both financially and logistically infeasible[29]. To address this challenge, we propose a novel method for generating household-to-household social networks consistent with various network properties observed from the survey responses, including node degree distribution[30], the distance decay effect[31,32] and proportions of strong and weak ties. In the context of our study, strong ties represent relationships with family and close friends, while weak ties constitute acquaintances.

Second, based on the complete social networks generated, we further utilize households' sharing preferences to construct P2P resource-sharing networks. In the network, node attributes are the inventories of different types of resources generated according to the survey response data. Directed links indicate the potential for sharing a resource from one household to another, reflecting households' sharing preference toward different types of social ties. The link weights describe sharing priorities. By default, we assume that, all else being equal, a household would prefer sharing first with their strong ties, followed by weak ties and then strangers.

Third, we develop a P2P resource-sharing optimization model based on the constructed P2P resource-sharing networks to determine the amount of surplus resources shared with which households. The model considers three key factors: the isolation period, the resource sharers' behavior and the resource receivers' behavior. The isolation period is the time during which a community is cut off from the outside and must rely on its own resources to survive. Within the isolation period, resource sharers will share their surplus resources through the P2P resource-sharing network, and the resource receivers will ask only for the resources they need to survive the isolation period. Thus, the resource-sharing model calculates the exact amount of resources that will be shared between each pair of households in the community.

Last, we measure the resilience loss of the community[33,34], which is defined as the product of the number of households with a resource shortage and the number of days they experience the shortage (Fig. 2b). Refer to Methods for details and Supplementary Section 2.2 for model assumptions.

Results

Capacity of place-based P2P resource sharing for community resilience

We compare resilience loss for each of the ten resources noted above between two scenarios: with and without place-based P2P resource sharing. The results are shown in Fig. 3a for Laurelhurst and Fig. 3b for South Park. A 5-day isolation period is assumed for this study, given that a household may have up to 7 days of resources. The lower the value of resilience loss, the more resilient the community.

Two observations can be made from Fig. 3. First, place-based P2P resource sharing substantially enhances resilience in both communities. Under the 5-day isolation scenario, place-based P2P resource sharing reduces resilience loss by 20.4–100% for Laurelhurst and by 13.4–100% for South Park, depending on the resource type. This provides quantitative support to existing qualitative research (for example, refs. 23,35) discussing the impact of social capital on community resilience. In addition, survival resources have a greater effect on reducing resilience loss (by an average of 80.3% in Laurelhurst and 79.3% in South Park) compared with infrastructure resources, for which an average reduction of 54.3% is observed in Laurelhurst and 53.9% in South Park.

Second, both communities exhibit similar trends in the amount of resilience loss that can be reduced through place-based P2P resource sharing. Resilience loss reduction is the greatest for food, medication, first aid, warmth and transportation. The smallest reduction is for power, followed by water. The reductions for sanitation, communications and shelter are moderate, ranging from 35.9% (sanitation for Laurelhurst) to 62.9% (communications for South Park). This result is due to the similar resource inventory profiles of the two communities (Supplementary Fig. 5). We also note that both communities are least prepared with power and water, followed by sanitation, shelter and communications. Conversely, both are most prepared with food, medication, first aid, warmth and transportation.

How many ties are sufficient to facilitate resource sharing?

The goal of place-based P2P resource sharing is to redistribute surplus resources to those in need, thereby reducing community resilience loss. Social ties act as an important channel for this sharing and redistribution, but how many social ties are sufficient for facilitating place-based P2P resource sharing? To answer this question, we scale up and down (based on the status quo) the number of household social ties in the community to examine how the sharing rate of surplus resources changes and how resilience loss is consequently affected. The sharing rate is defined as the proportion of surplus resources that are shared within the community. In addition, we take the no-sharing case as the baseline and also consider a theoretical case of the complete graph, in which each household is strongly connected to every other household in the community and, thus, the maximum sharing rate as well as maximum resilience loss reduction can be achieved.

The most notable finding from Fig. 4 is that, while the maximum sharing rate of surplus resources via the complete graph requires an incredible number of social ties (1,872 for Laurelhurst and 1,378 for South Park), only a tiny percentage of them (about 1% for Laurelhurst and 3% for South Park) is needed to achieve an 80% sharing rate for all surplus resources. For Laurelhurst, this constitutes 22 ties (strong and weak) per household, which is less than what the residents already have (27.6). This is not the case for South Park, which will require 43.9 ties to

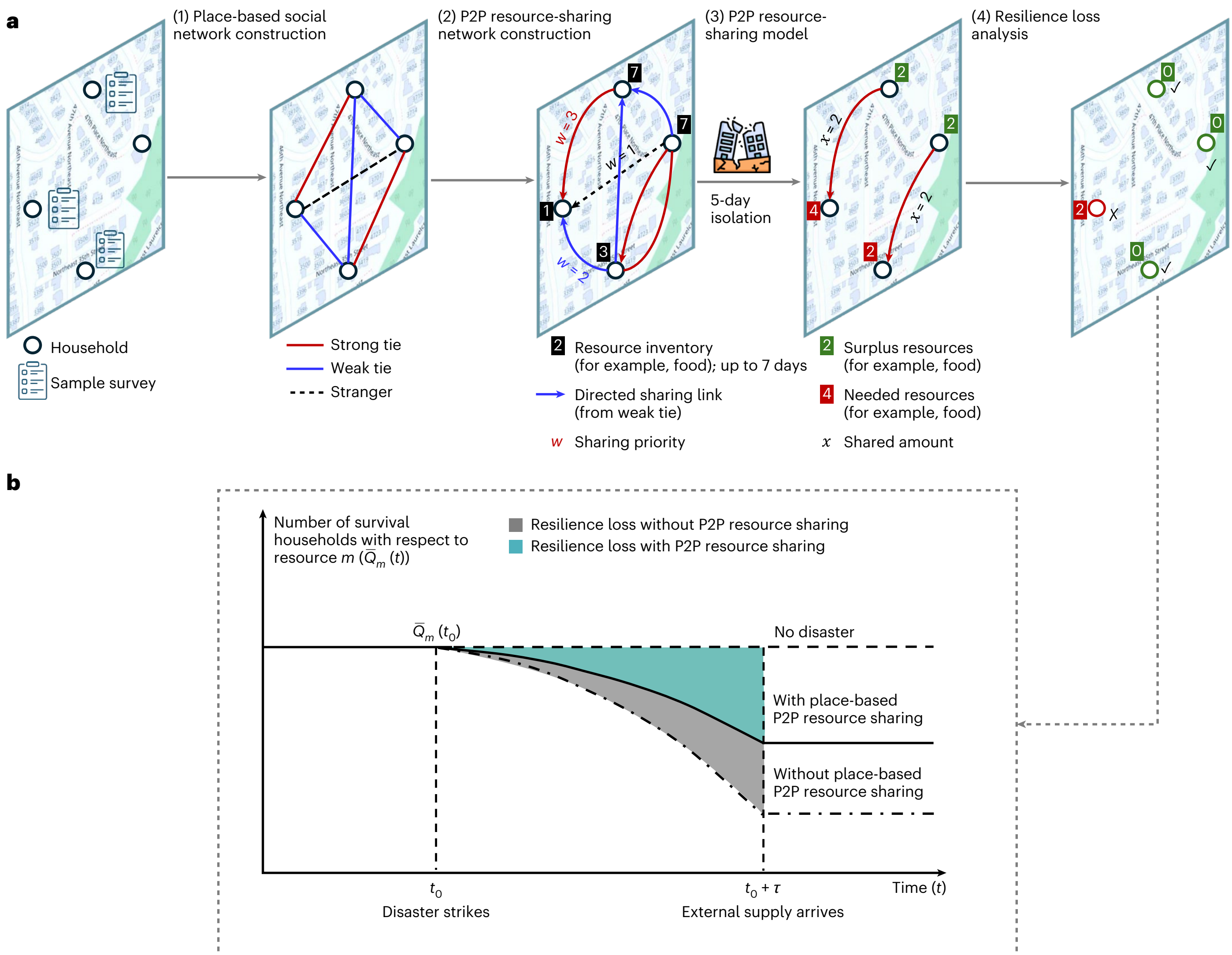

Fig. 2 | Methodology. a, The methodological framework. (1) Place-based social network construction: using survey responses from a random sample, we construct complete social networks for a community. (2) P2P resource-sharing network construction: based on the generated complete social networks, we further utilize the survey data to construct resource-sharing networks where each node (household) has its resource inventories, (directed) links indicate a household's sharing preferences (with whom one is willing to share which resource), and link weights w describe sharing priorities to different recipients. For clarity, this figure shows only a single type of resource (food). For different types of resources, there exist different resource-sharing networks as the sharing preferences may vary according to the resource. (3) P2P resource-sharing model: a P2P resource-sharing model is then constructed to simulate the resource-sharing outcomes x within the two communities under isolation. (4) Resilience loss analysis: we construct the resilience loss metric to quantify the role of social ties and P2P resource sharing in reducing a community's loss of resilience during an isolating disaster. **b**, A graphical illustration of community resilience loss on resource m. Resilience loss is the product of the number of households experiencing resource shortage and the duration for which those households experience a shortage during the isolation period.

reach the 80% sharing rate—about four times the number of social ties residents currently have (10.8).

Further, even without social ties, place-based P2P sharing activities still occur in both communities, as some generous households are willing to share their surplus resources with anyone (see Supplementary Fig. 6 for details). Remarkably, the surplus resources from these generous households are sufficient to fulfill all medication, transportation and warmth needs in both communities, in which case no more sharing is necessary as evidenced by the horizontal lines in Fig. 4a,b and the corresponding zero resilience loss in Fig. 4c,d. For scarcer resources, the sharing rate is highest for first aid and lowest for shelter in both communities, suggesting that, during times of disaster, people are more inclined to share essential life-sustaining resources (for example, first aid supplies) with strangers but are less willing to do so for more private resources that might involve sharing one's home (for example, shelter).

Figure 4 illustrates a general trend of increased sharing rates of surplus resources and lower resilience loss as the number of social ties increases. What is remarkable is that, for both communities, the sharpest increase in sharing rate, ranging from 16.2% (first aid) to 45.1% (power) in Laurelhurst and from 20.4% (first aid) to 43.8% (power) in South Park, occurs when the average number of social ties per household increased from 0 to approximately 6, illustrating the notable impact even a small number of social ties can have on P2P resource sharing and community resilience.

The effect of strong versus weak ties on the survival of individual households

Previous studies indicate that the number of social ties an isolated individual has will affect the likelihood of receiving assistance from others as well as survival rates in life-or-death situations[20,21,36]. We further

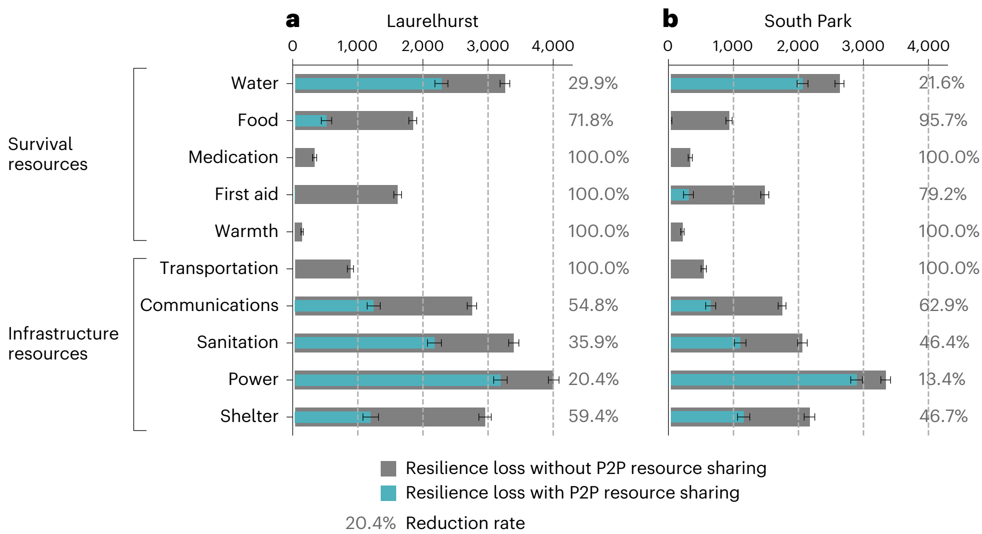

Fig. 3 | Resilience loss comparison. a,**b**, Resilience losses in the Laurelhurst neighborhood (**a**) and the South Park neighborhood (**b**) under 5-day isolation. Each subfigure compares the community resilience losses with and without P2P resource sharing. Mean values ± standard deviation (error bars) of 100 realizations are presented for different resources. On average, compared with the no-sharing case, place-based P2P resource sharing can reduce between 20.4% and 100% resilience loss for Laurelhurst and between 13.4% and 100% resilience loss for South Park, dependent on the resource type. More details can be found in Supplementary Section 4.

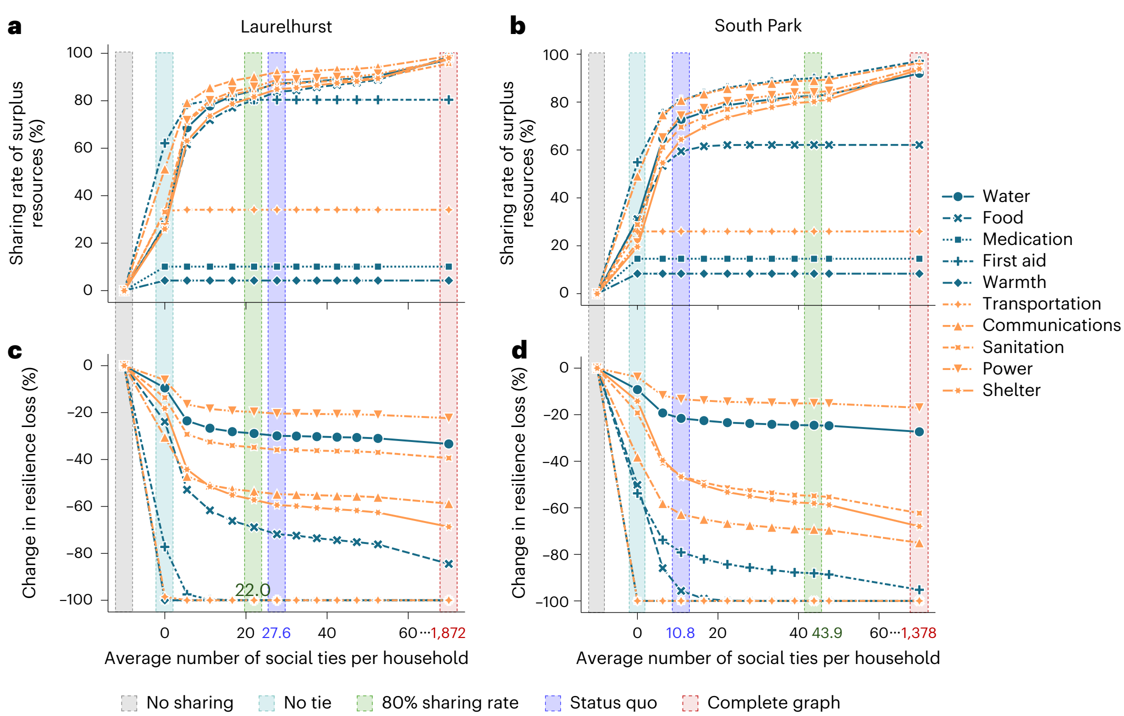

Fig. 4 | Effects of social ties. a–**d**, The impact of the number of social ties on the sharing rate of surplus resources in Laurelhurst (**a**) and South Park (**b**) and on resilience loss in Laurelhurst (**c**) and South Park (**d**). Mean values of 100 realizations are presented for different resources. Taking the no-sharing case as the baseline, the no-tie case denotes where resource sharing occurs merely between strangers since some respondents indicate that they are willing to share with strangers; the status quo case shows the average numbers of social ties per household in Laurelhurst and South Park as reported in our survey, respectively; the maximum sharing rate, as well as the maximum resilience loss reduction, are achieved by a complete graph, in which each household is connected to every other household in the neighborhood with a strong tie; the 80% sharing rate represents the case in which at least 80% of the surplus resources are shared with those in need within the community, except for the resources for which zero resilience loss has already been achieved. Note that several lines (for example, food, medicine, warmth and transportation in South Park) become horizontal in **a** and **b** because they achieve zero resilience loss as shown in **c** and **d**, that is, there is no longer any need to share.

explored the role of strong and weak ties in improving household survival rates. Here, we focus on households with resource shortages in the two communities and divide them into different groups according to their total number of strong and weak ties. The survival rates, representing the proportions of households receiving sufficient resources for each resource category, are shown in Fig. 5, in which each dot represents a group of households having a certain number of strong ties and weak ties.

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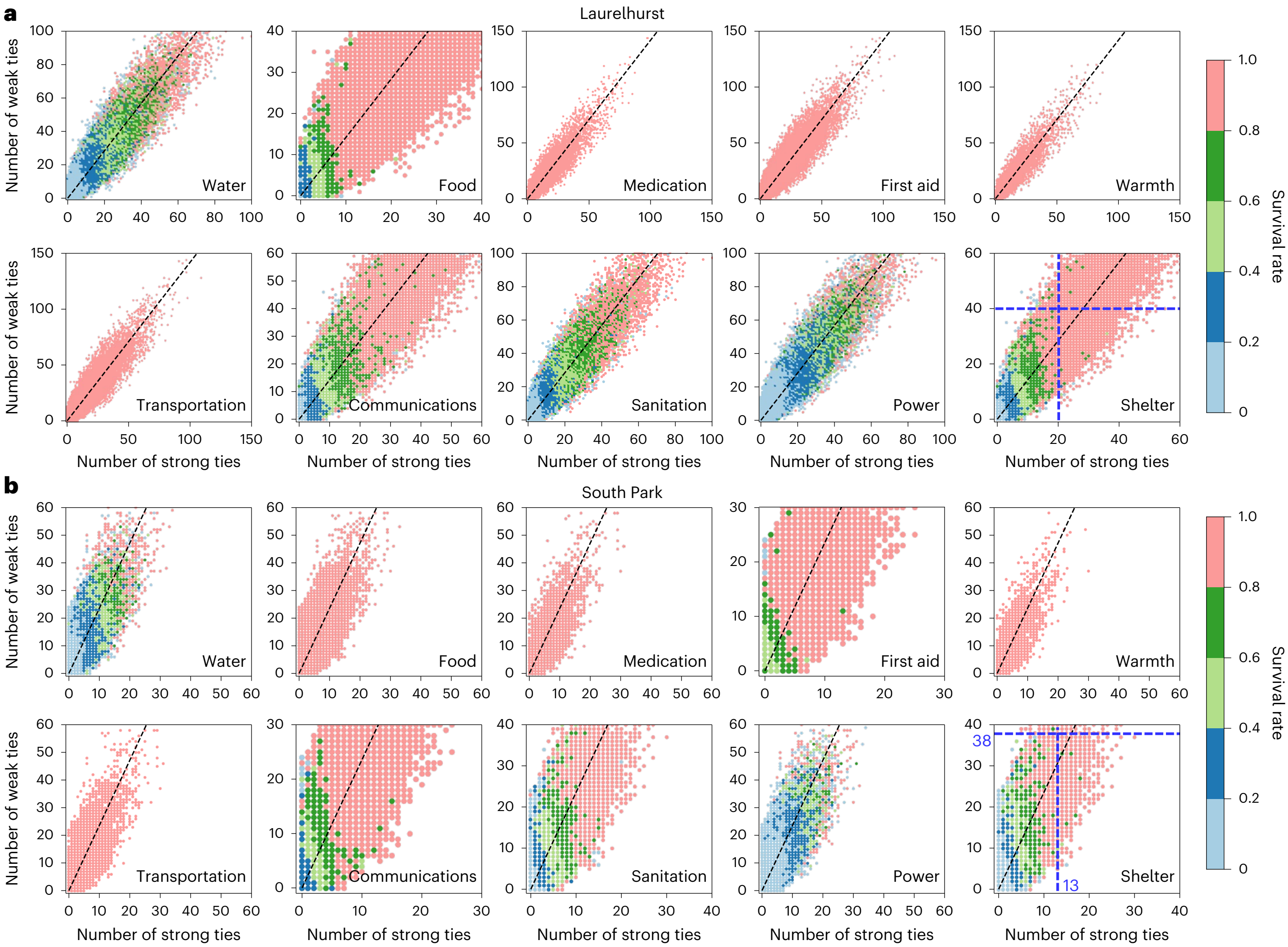

Fig. 5 | Number of social ties and survival rates. a,**b**, The survival rates of resource-shortage households after receiving resources from others in Laurelhurst (**a**) and South Park (**b**) with 100 realizations. Strong ties are about 1.5–3 times more effective than weak ties in improving survival rates. For example, to achieve at least an 80% survival rate for shelter in Laurelhurst, a household needs to have at least 20 strong ties or at least 40 weak ties, and the corresponding numbers for South Park are 13 strong ties or 38 weak ties. The dotted black lines represent the average proportions of strong ties and weak ties a household has in Laurelhurst and South Park. In Laurelhurst, strong ties constitute 41.3% of all community ties, while weak ties comprise 58.7%. In South Park, 29.8% of all social ties are strong ties, while 70.2% are weak ties.

As expected, the more social ties a household has, the higher its survival rate. One may notice that, for individuals, strong ties seem to be more effective than weak ties in improving survival rates—but to what extent? The results in both communities show that strong ties are about 1.5–3 times more effective in a disaster scenario, depending on the resource type and the community. For example, to achieve at least an 80% survival rate for shelter in Laurelhurst, a household needs to have at least 20 strong ties or at least 40 weak ties (Fig. 5a, shelter), and the corresponding numbers for South Park are 13 strong ties or 38 weak ties. These results do not undermine the significance of weak ties[37], which are a major component of social networks in both communities. According to our survey results, weak ties account for 58.7% of social ties in Laurelhurst and 70.2% in South Park.

Natural sharing priority versus equal sharing priority

Naturally, survey respondents most preferred sharing with their strong ties, followed by weak ties and finally strangers (strong ties > weak ties > strangers). Many studies confirm this natural sharing priority (for example, refs. 38–40). This tendency is also confirmed in the survey responses of the two studied communities. Take Laurelhurst as an example: the greatest percentage of households is willing to share water with strong ties (97.3%), while 58.4% are also willing to share with weak ties and only 27.6% are willing to share with strangers (Supplementary Fig. 7). On the other hand, equal sharing priority is a utopian case in which there is no preference in sharing with respect to the strength of a tie (or, strong ties = weak ties = strangers). Thus, from a policy perspective, a relevant question is 'what difference in resilience loss reduction can be observed when comparing natural versus equal sharing priority'?

Table 1 shows that, while equal sharing priority indeed further reduces resilience loss, the reductions are quite marginal. Enforcing equal sharing priority decreases resilience loss by less than 6 units in Laurelhurst and less than 12 units in South Park, suggesting that the natural sharing priority enables a 'suboptimal' outcome that is very close to the optimal one. It follows that efforts to increase and strengthen social ties within a community (Fig. 4) are likely to be more fruitful than promoting equal sharing priority.

Discussion

Across the United States and globally, the increasing frequency and intensity of climate-related disasters will undoubtedly place an aggravated burden on federal and state relief efforts that continue to rely on top-down approaches to disaster response. Following a disaster, some

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Table 1 | The average resilience loss (RL) with natural or equal sharing priority (5-day isolation) under 100 realizations

Community	Resource	RL with naturalsharing priority	RL with equalsharing priority	Change in RL
Laurelhurst	Water	2,284.0	2,283.7	0.3
	Food	519.5	513.8	5.7
	Medication	0.0	0.0	0.0
	First aid	0.3	0.2	0.1
	Warmth	0.0	0.0	0.0
	Transportation	0.0	0.0	0.0
	Communications	1,244.0	1,242.2	1.8
	Sanitation	2,176.8	2,176.2	0.6
	Power	3,189.4	3,189.3	0.1
	Shelter	1,198.3	1,195.3	3.0
South Park	Water	2,063.2	2,063.1	0.1
	Food	40.1	28.3	11.8
	Medication	0.0	0.0	0.0
	First aid	308.1	302.7	5.4
	Warmth	0.0	0.0	0.0
	Transportation	0.0	0.0	0.0
	Communications	649.2	646.0	3.2
	Sanitation	1,104.1	1,103.0	1.1
	Power	2,894.9	2,894.9	0.0
	Shelter	1,156.9	1,155.5	1.4

time is typically required for relief resources to arrive in the affected areas, and these resources are often then distributed through predesignated organizations (for example, the Red Cross) at preidentified sites (for example, churches or civic buildings). Given this backdrop, this study answers the following question: To what extent can place-based P2P resource sharing improve a community's resilience against disasters? While government-led relief efforts can be extremely valuable, we show the potential of place-based P2P resource sharing as an additional valuable strategy in disaster relief efforts. This framework developed in the study can be applicable to other urban communities interested in assessing their potential for P2P resource sharing and identifying opportunities to improve its disaster preparedness as well as its overall resilience to disruption.

Our findings are potentially generalizable to other urban communities in the United States. The two study communities, although both in Seattle, are characteristically different in terms of income, racial composition, housing tenure and land use patterns, reflecting social and environmental factors that result in a 13-year difference in life expectancy between the two neighborhoods. A key finding of this study is that both communities exhibit considerable potential in place-based P2P resource sharing that will greatly enhance their disaster resilience. Fundamentally, this potential is based on numerous observations and reports showing that, when a disaster strikes, people often step up to help others, taking on roles outside of their usual domains. Contrary to the conventional myth that often associates disaster with antisocial behavior and passivity, disasters in fact bring out the best in us, as Quarantelli, America's prominent sociologist on disaster research, documented and proved[41,42]. This study also supports this generalizability conjecture.

Place-based P2P resource sharing can be a promising means of enhancing community resilience across a range of hazard scenarios. Different types of hazards will affect communities' resource inventories and sharing preferences differently (for example, a severe earthquake is likely to destroy more resources than a windstorm), and when one's own resource inventory is reduced, one may become less willing to share. We conducted additional sensitivity analyses with respect to varying levels of resource inventories, willingness to share and isolation period (Supplementary Section 5). We show the following: (1) even with a small amount of surplus resources, fewer number of social ties or lower levels of willingness to share (less than what the communities already have), there is still a substantial reduction in resilience loss; (2) at the status quo, both communities in fact have already reached a close-to-maximum sharing rate or reduction rate in resilience loss; and (3) even with a longer isolation period, place-based P2P resource sharing can still play an important role in reducing resilience loss.

This is not to say that the two socioeconomically different communities will have the same capacity through P2P sharing. We find that the amount of reduction in resilience loss is slightly less for South Park compared with Laurelhurst. Given that the amount of resource inventory (Supplementary Fig. 5) in South Park is not less than that in Laurelhurst nor their sharing preferences (Supplementary Fig. 6), the likely reason is that South Park has fewer number of social ties on average than Laurelhurst. The average number of strong and weak ties for Laurelhurst and South Park is 27.6 and 10.8, respectively (Supplementary Table 5). More studies are desired to evaluate this speculation.

Seattle, a front-runner in disaster preparedness efforts, recognizes the value of community resources during disasters. The city actively coordinates and helps communities establish hubs and networks[43,44]. These efforts do not diminish the value of government-led relief efforts. In fact, community-based disaster preparedness and relief efforts enhance government support: they help bring federal funding to the community level. The results from this study suggest that other cities can also consider developing similar community-based programs, thereby better positioning themselves to realize the potential benefits of place-based P2P resource sharing following disasters.

Beyond urban community settings such as those researched in this study, there can also be potential for place-based P2P resource sharing to improve the resilience of rural communities, although with additional methodological challenges. Our data collection effort that supported this study also included a rural Washington State community, the city of Westport. Located on the Pacific Coast, Westport is a maritime community of approximately 2,100 majority white and English-speaking year-round residents with a median annual household income of US$37,600, a poverty rate of 17.5% and a fluctuating but important population of seasonal workers, many of whom do not speak English at home. We find that Westport's willingness to share and resource inventory profiles are highly consistent with those of both Laurelhurst and South Park despite its rural character[9].

Since the study is based on random samples where randomly chosen participants decide whether to participate in the survey or not, there can still be potential biases that compromise the generalizability of the results. In other words, survey respondents could have more social ties and are more willing to share resources than non-survey respondents. These potential differences cannot be discerned through a sample, since non-survey respondents do not provide any data. As noted earlier, our sensitivity analyses show that, even when the communities have a much lower number of social ties and lower levels of willingness to share than the currently observed levels, there is still considerable gain in P2P sharing (Supplementary Section 5). Nevertheless, since we cannot discern for sure the differences between survey and non-survey respondents, we acknowledge that biases can still exist. In addition, the study results are based on two communities, exhibiting different network topological attributes (Supplementary Section 3.1); there are other network structures not studied by the current study, and they could potentially affect the study results. This points to a future research direction examining how network topology may affect P2P resource sharing during a disaster.

The present study does not address the range of sharing behaviors that might actually occur in a disaster, which raises many questions to be addressed via follow-up studies. One future inquiry is about the actual mechanism of sharing. P2P resource sharing can be hierarchical, for example, through a set of block captains with each captain responsible for a group of households within a community. One of the study communities (Laurelhurst) already has such a structure in place and expects block captains (each of whom is responsible for approximately 20 households) to distribute resources and information when needed. Research is required to determine the extent to which such a structure is effective under different hazard conditions as well as determining the best means for designating block captains. Examining the role of social network structure in sharing outcomes, as demonstrated in the WiFi sharing game study by Shirado et al.[45], is another potential avenue for future research as more studies emerge examining different focal communities. In addition, for studies that focus on recovery, incorporating diverse data sources such as mobile phone locations, satellite imagery and social media data[46] is another future direction. Further, leveraging sharing economy platforms[47–50] may complement place-based P2P resource sharing efforts and further enhance a community's disaster resilience. Importantly, the present study does not negate the value of top-down, centralized resource distribution strategies during disasters. We view place-based P2P resource sharing as complementary to these status-quo protocols, as it constitutes an untapped means of access to critical resources for communities worldwide during times of need.

Methods

This study complies with all relevant ethical regulations and is approved by the Institutional Review Board at the University of Washington. Informed consent was obtained from all survey participants.

We used the programming language Python (version 3.11.4) with common packages such as Pandas (version 1.5.3) and Seaborn (version 0.13.1) for data preprocessing, calibration, simulation and visualization. We used Gurobi (version 10.0) under an academic license to solve the optimization models. All the map data used in this paper come from OpenStreetMap and are plotted by the open-source Python library GeoPandas (version 0.13.2).

Place-based social network construction

To generate social networks based on the survey responses, we consider three features: (1) node degree distribution[30], which characterizes the number of social ties each household has, (2) distance decay effect[31,32], which reflects the probability of social tie existence to decay with increasing geographical distance, and (3) the proportion of strong and weak ties, which can be directly obtained from survey responses.

We adopt the negative binomial (NB) distribution to model the node degree distribution of the social network in each community. The probability mass function (PMF) of the NB distribution is given by

$$f(k;n,p) = \frac{\Gamma(k+n)}{k!\,\Gamma(n)} p^{n}(1-p)^{k}, \quad (1)$$

where k is the number of social ties a household has; $\Gamma(\cdot)$ is the gamma function; and n and p are the parameters to be estimated. The log-likelihood function of NB distribution is

$$l(K;n,\rho) = \sum_{k\in K}\left[\log\frac{\Gamma(k+n)}{k!\,\Gamma(n)} + n\log\rho + k\log(1-\rho)\right], \quad (2)$$

where K is the set of numbers of social ties in the survey responses. Using the survey data, the maximum likelihood estimates of those parameters are $n = 0.788$ and $\rho = 0.026$ for Laurelhurst and $n = 0.827$ and $\rho = 0.067$ for South Park (see Supplementary Fig. 9 for details).

The distance decay effect of social ties can be well described by the power-law function[31,32]

$$p(d_{ij};\beta) \propto d_{ij}^{\beta}, \quad \forall i \in N, j \in N, \quad (3)$$

where $p(d_{ij};\beta)$ is the probability of the existence of a social tie between two nodes (households) i and j; d_{ij} is the geographical distance between them; and β is the power parameter to be estimated. Equation (3) is defined for individual-to-individual social ties, while the survey asked only for the number of individual-to-subarea social ties (Fig. 1b). To estimate β, we aggregate equation (3) into an individual-to-subarea form

$$p_z^i(\beta) = \frac{\sum_{j\in N_z, j\neq i} p(d_{ij};\beta)}{\sum_{j\in N, j\neq i} p(d_{ij};\beta)}, \quad \forall i \in N_{smp}, z \in Z, \quad (4)$$

where $p_z^i(\beta)$ denotes household i's expected proportion of social ties in subarea z; N is the set of households in the community; N_z is the set of households in subarea z; N_{smp} is the set of sampled households; and Z is the set of subareas in the community. Let $\mathbf{P}(\beta)$ be the vector of $p_z^i(\beta)$ for the sampled households given β and $\mathbf{P}_{obs}$ be the vector of the observed proportion of social ties that sampled households have in different subareas. We solve a least-square problem ($\hat{\beta} = \arg\min_{\beta} \|\mathbf{P}(\beta) - \mathbf{P}_{obs}\|_2^2$) to estimate $\hat{\beta}$. The results show that $\hat{\beta} = -1.3$ for Laurelhurst and $\hat{\beta} = -1.4$ for South Park.

The estimated node degree distribution and distance decay function are utilized to generate node degree and configure social ties through a network configuration procedure adapted from refs. 51–53, followed by a random differentiation of strong and weak ties based on the surveyed proportion (see Supplementary Section 3 for details). The final product of the above process is the place-based social network $G_{tie} = (N, A_{tie} = \{A_{tie}^{strong}, A_{tie}^{weak}\})$ where A_{tie}^{strong} and A_{tie}^{weak} are the sets of undirected links representing strong ties and weak ties, respectively, as illustrated in step 1 of Fig. 2a.

P2P resource-sharing network construction

We randomly assign sharing preferences for different resources to households in the community according to the distributions obtained from surveys (Supplementary Fig. 6). These preferences can range from (1) nobody to (2) strong ties only, (3) strong ties and weak ties only, and (4) anyone. This allows us to convert the social network $G_{tie} = (N, A_{tie})$ into directed P2P resource-sharing networks $G_{share} = (N, A_{share} = \{A_{share}^m, m \in M\})$, where A_{share}^m is the set of directed sharing links for resource m and M is the set of resources.

Previous research has emphasized that peoples' willingness to share tends to decrease as the strength of social ties diminishes[38–40]. This implies that, while a household may express a general willingness to share with anyone, it is more inclined to prioritize sharing with strong ties, followed by weak ties and finally strangers, that is, strong tie > weak tie > stranger. To model this phenomenon, we assign different sharing priorities w_{ij} on different types of links in the sharing network. Specifically, for each pair of households ij, we set $w_{ij} = 3$, 2 and 1 for if they have a strong tie, weak tie or they are strangers, respectively. This results in a P2P resource-sharing network $G_{share} = (N, A_{share}, W)$, where W is the set of link weights, as depicted in step 2 of Fig. 2a.

We utilize the resource inventory distributions obtained from survey data (Supplementary Fig. 5) to draw resource inventory (in a unit of days) realization q_i^m for each household i and resource m, resulting in a resource inventory vector $q = (q_i^m, \forall m \in M, i \in N)$ for a community.

P2P resource-sharing model

We consider the following assumptions of the place-based P2P resource-sharing behavior.

- Isolation period: the community will be isolated for τ days, during which it must rely upon its existing resources to survive.
- Shared resources: each household i shares a maximum surplus amount of $g_i^m = \max\{q_i^m - \tau, 0\}$ for resource m.

- Requested resources: each household *j* requests a maximum shortage amount of $r_j^m = \max\{\tau - q_j^m, 0\}$ for resource *m*.

A continuous variable $x_{ij}^m \geq 0$ is introduced to model the amount of resource *m* shared from household *i* to household *j*. Based on these assumptions, the P2P resource sharing is cast as a linear program (LP):

$$\max f(x) = \sum_{m \in M} \sum_{(i,j) \in A^m_{share}} w_{ij} x_{ij}^m \quad (5a)$$

$$\sum_{j \in N_i^{m+}} x_{ij}^m \leq g_i^m, \quad \forall i \in N, m \in M \quad (5b)$$

$$\sum_{i \in N_j^{m-}} x_{ij}^m \leq r_j^m, \quad \forall j \in N, m \in M \quad (5c)$$

$$x_{ij}^m \geq 0, \quad \forall (i,j) \in A, m \in M, \quad (5d)$$

where N_i^{m+} and N_j^{m-} are the resource receivers of node *i* and resource sharers of node *j* for resource *m*, respectively. In this model, the objective function equation (5a) aims to maximize the total amount of shared resources, taking into account the respective sharing priorities of households within a community. Constraint equation (5b) ensures the total amount of shared resources does not exceed the extra resource each household has, while constraint equation (5c) ensures that the total amount of resources each household receives does not exceed its need. Equation (5d) specifies the variable domain. Finally, model 5 is a linear programming problem, which can be readily solved by many optimization solvers such as CPLEX and Gurobi. After resource sharing, the final amount of resources *m* possessed by household *i* is denoted by h_i^m:

$$h_i^m = q_i^m - \underbrace{\sum_{j \in N_i^{m+}} x_{ij}^m}_{\text{Shared amount}} + \underbrace{\sum_{j \in N_i^{m-}} x_{ji}^m}_{\text{Received amount}}, \quad \forall i \in N. \quad (6)$$

Resilience loss analysis

The proposed methodological framework relies on simulation to generate social network and P2P resource-sharing network realizations for communities. For each experiment, we run $s = 1, ..., 100$ realizations and obtain the final resources of each household in the two communities. Given realization *s* and for a specific resource *m* at time *t*, the number of survival households, those that possess resource *m* in quantities greater than or equal to *t*, is denoted by $Q_m^s(t) = \text{count}\{h_i^m \geq t, \forall i \in N\}$. The average across realizations *s* for resource *m* is denoted by $\bar{Q}_m(t)$.

To quantify the resilience loss of a community for a specific resource *m* during the isolation period, we adopt and modify the well-known resilience loss metric proposed by Bruneau et al.[34]. This metric, initially designed to assess seismic resilience loss, can be adapted to measure the loss of community resilience caused by resource scarcity during an isolation period:

$$RL_m = \int_{t_0}^{t_0+\tau} [\bar{Q}_m(t_0) - \bar{Q}_m(t)]dt, \quad (7)$$

where t_0 is the starting time of the disaster and τ is the duration of isolation days before external supply arrives. Fig. 2b provides a graphical illustration of the resilience metric. The area above the survival curve $\bar{Q}_m(t)$ (the light-blue area) reflects the resilience loss of the community with respect to resource *m*, which can be interpreted as the product of the number of households in resource shortage and the duration of time they experience the shortage. A larger resilience loss indicates poorer performance.

Statistics and reproducibility

Random sampling was used for the data collection in the two study communities. The participating households were chosen at random from a list of all household addresses in each study community. The sampling frames were constructed using a combination of county assessor's data and purchased address databases. We calculated the target sample size for both communities following Dillman[28]. Final sample sizes were 263 in Laurelhurst and 203 in South Park, corresponding to 35.9% and 16.9% response rates, respectively. Only adults 18 years of age or older were eligible to respond to the survey.

We excluded survey responses with missing information, and this resulted in slightly different responses for different analyses. For Laurelhurst (263 total responses), the exclusion resulted in 246 survey responses for degree distribution calibration, 235 survey responses for distance decay function calibration, 249 survey responses for resource inventory PMF estimation and 249 survey responses for sharing preference PMF estimation in Laurelhurst (in total, 263 survey responses). For South Park (203 total responses), the exclusion resulted in 112 survey responses for degree distribution calibration, 101 survey responses for distance decay function calibration, 195 survey responses for resource inventory PMF estimation and 195 survey responses for sharing preference PMF estimation.

Due to the nature of the study, randomization and blinding were not used. The data collection and the simulation analyses carried out in the study are reproducible in any other community.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The survey data collected in the study contain household mailing addresses and names, and this part of the data is not available due to privacy issues. However, the generated aggregated data during the current study are available via GitHub at https://github.com/UW-THINKlab/P2P_sharing_open_source.

Code availability

The code used for the analysis is available via GitHub at https://github.com/UW-THINKlab/P2P_sharing_open_source.

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Author contributions
Study conception: C.C. and K.I.; research design: C.C. and Z.L.; data collection: K.I.; data analysis: Z.L.; paper preparation—original writing: Z.L. and C.C.; paper preparation—editing and review: C.C., Z.L., K.I. and A.C. All authors reviewed and approved the paper.

Competing interests
The authors declare no competing interests.

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	We conducted a survey on three communities in Washington State: two urban communities in Seattle, and one rural community (City of Westport). A simple random sampling design was used in three study communities. Survey respondents were contacted by mail and presented with the option to either take the survey online or to request a printed copy.
Data analysis	We used the programming language Python (version 3.11.4) with common packages such as Pandas (version 1.5.3) and Seaborn (version 0.13.1) for data preprocessing, calibration, simulation, and visualization. We used Gurobi (version 10.0) to solve the optimization models. The code used for the analysis is available at https://github.com/UW-THINKlab/P2P_sharing_open_source.

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The survey data collected in the study contains household mailing addresses and names and that part of the data is not available due to privacy issues. However, the generated aggregated data during the current study is available at https://github.com/UW-THINKlab/P2P_sharing_open_source.

Research involving human participants, their data, or biological material

Policy information about studies with human participants or human data. See also policy information about sex, gender (identity/presentation), and sexual orientation and race, ethnicity and racism.

Reporting on sex and gender	Gender information is not relevant to this study.
Reporting on race, ethnicity, or other socially relevant groupings	The social demographical information (e.g., population density, median age, average income) and race and ethnicity of the study communities are introduced in Table S1 and Table S3 in the Supplementary Information.
Population characteristics	The social demographical information (e.g., population density, median age, average income) and race and ethnicity of the study communities are introduced in Table S1 in the Supplementary Information.
Recruitment	A simple random sampling design was used in the two study communities. Randomly-selected survey participants were contacted by mail and presented with the option to either take the survey online or to request a printed copy. There can be potential biases that survey respondents could have more social ties and are more willing to share resources than non-survey respondents.
Ethics oversight	The institutional review board at the University of Washington approved the data collection effort that resulted in data used in the current study.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

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Study description

This study models place-based Peer-to-Peer (P2P) resource sharing and evaluates its impact on a community's resilience to disasters. The study is quantitative, which is essentially generating many community-based social networks based on which peer-to-peer resource sharing is simulated. The generation of community-based social networks as well as households' resource preparedness are based on data collected from the two communities through random samples.

Research sample

Study sample comprises those households residing in the two urban communities (Laurelhurst and South Park) and responded to our survey. Only adults 18 years of age or older were asked to respond to the survey. Because of the random sampling approach, the samples are expected to be representative (in other words, people cannot self-select into the survey if they are not randomly selected in the first place). The sampling frames were constructed using a combination of county assessor's data and purchased address databases.

The two communities are very different in both socio-demographic profiles and their disaster preparedness effort. Laurelhurst, located in northeast Seattle, sits on a hilly peninsula extending into Lake Washington. Residents of Laurelhurst are predominantly White, wealthy, and well-educated. While primarily a single-family residential area, several high-profile institutions, including the University of Washington's Seattle campus, the University of Washington Medical Center, and Seattle Children's Hospital, are located on the neighborhood's periphery. Due to its lakeside location, some areas of Laurelhurst are susceptible to either liquefaction or landslide hazards. In the event of a high-magnitude earthquake, areas near the shore might be affected by seiches.

In contrast, South Park is an ethnically diverse and historically disinvested community located along the Duwamish Waterway industrial corridor in southeast Seattle. Approximately 40% of the neighborhood's voting-age residents are not U.S. citizens, 50%

	speak languages other than English at home, and more than 25% live on incomes below the poverty level. The neighborhood comprises a mix of residential, commercial, and industrial land uses. Many areas of South Park are highly susceptible to both liquefaction and high tide flooding as a result of the loose fill soils that lie under the neighborhood's heavily engineered landscape.
Sampling strategy	Random sampling was used to collect data in the two urban communities that serve as the focus areas for the study. Prior to the actual survey, we conducted a pilot survey for Laurelhurst for several purposes: 1) checking the readability of our survey instrument; 2) obtaining necessary information about variances of our key interest items such as household preparedness with different resources and willingness to share; 3) checking the response rate; and 4) checking the survey logistics in the field. Using the initial information from the pilot survey, we calculated the target sample size for both communities following Dillman (2011). Ns1 = [(Np) (p) (1-p)]/ [(Np-1) (B/C)^2 + (p) (1-p)] Where Ns1 = completed sample size Np = size of population (total households) p = proportion of population expected to select a given answer B = acceptable amount of sampling error (assumed 0.05) C = Z statistic associated with the confidence level (1.96 corresponds to the 95% level) Dillman, Don A. Mail and Internet surveys: The tailored design method--2007 Update with new Internet, visual, and mixed-mode guide. John Wiley & Sons, 2011.
Data collection	Survey respondents were contacted by mail and presented with the option to either take the survey online or to request a printed copy.
Timing	The survey was carried out between October 2019 and February 2020.
Data exclusions	We excluded survey responses with missing information, which resulted in 246 survey responses for degree distribution calibration, 235 survey responses for distance decay function calibration, 249 survey responses for resource inventory probability mass function (PMF) estimation, and 249 survey responses for sharing preference PMF estimation in Laurelhurst (in total 263 survey responses). In South Park with in total of 203 survey responses. The exclusion results in 112 survey responses for degree distribution calibration, 101 survey responses for distance decay function calibration, 195 survey responses for resource inventory PMF estimation, and 195 survey responses for sharing preference PMF estimation.
Non-participation	The response rates for the two urban communities are: 35.9% and 16.9% respectively.
Randomization	The data was collected using random sampling. This study does not involve any intervention, so randomized assignment does not apply.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Plants

Seed stocks	*Report on the source of all seed stocks or other plant material used. If applicable, state the seed stock centre and catalogue number. If plant specimens were collected from the field, describe the collection location, date and sampling procedures.*
Novel plant genotypes	*Describe the methods by which all novel plant genotypes were produced. This includes those generated by transgenic approaches, gene editing, chemical/radiation-based mutagenesis and hybridization. For transgenic lines, describe the transformation method, the number of independent lines analyzed and the generation upon which experiments were performed. For gene-edited lines, describe the editor used, the endogenous sequence targeted for editing, the targeting guide RNA sequence (if applicable) and how the editor was applied.*
Authentication	*Describe any authentication procedures for each seed stock used or novel genotype generated. Describe any experiments used to assess the effect of a mutation and, where applicable, how potential secondary effects (e.g. second site T-DNA insertions, mosiacism, off-target gene editing) were examined.*