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Research Article

Food-trade-associated COVID-19 outbreak from a contaminated wholesale food supermarket in Beijing

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ABSTRACT

The re-emerging outbreak of COVID-19 in Beijing, China, in the summer of 2020 originated from a SARS-CoV-2-infested wholesale food supermarket. We postulated that the Xinfadi market outbreak has links with food-trade activities. Our Susceptible to the disease, Infectious, and Recovered coupled Agent Based Modelling (SIR-ABM) analysis for studying the diffusion of SARS-CoV-2 particles suggested that the trade-distancing strategy effectively reduces the reproduction number (R0). The retail shop closure strategy reduced the number of visitors to the market by nearly half. In addition, the buy-local policy option reduced the infection by more than 70% in total. Therefore, retail closures and buy-local policies could serve as significantly effective strategies that have the potential to reduce the size of the outbreak and prevent probable outbreaks in the future.

1. Introduction

When the Corona Virus Disease of 2019 (COVID-19) outbreak was noticed for the first time by the end of 2019, the majority of cases were linked to the Huanan seafood wholesale market of Wuhan in the Hubei province of China. This market is mainly involved in the sale of the seafood, vegetables, fruits, poultry, snakes, birds, frogs, hedgehogs, and other wildlife animals[1–4]. On June 11, 2020, another outbreak with 335 confirmed cases had emerged in Beijing, which was found to be linked with the Xinfadi wholesale food market; where poultry, chicken, mutton, seafood, fruits, and vegetables were on sale. Further studies involving the whole genome sequence analysis of the Xinfadi strain isolated from the patients revealed that this strain was different from the one that caused the Wuhan outbreak, which was grouped into Branch 1 of L-lineage circulated in Europe[5,6]. It was also revealed that the SARS-CoV-2 was detected in both food processing and environmental samples in Xinfadi wholesale food market, including a cutting board used to slice imported salmon (https://www.caixin-global.com/2020–07-08/101577190.html)[7]. Recently, SARS-CoV-2 has been detected on frozen food packages imported from other countries. These data suggest that the contaminated wholesale food markets with frozen food have played a significant role in the transmission of SARS-COV-2, where the modern food distribution and supply practices accelerated the spread of the virus[8].

2. Materials and methods

2.1. Internet-based investigation of COVID-19 outbreak

We mined information on the Xinfadi outbreak of COVID-19 in Beijing, available on the internet, which was mainly from the

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detailed daily situation reports released by the Beijing Center for Disease Control and Prevention (https://www.bjcdc.org/). A total of 335 cases of infectious diseases were reported from June 11 to July 12, 2020. All confirmed cases were divided into cohorts of sellers, buyers, and contacts.

The data of COVID-19 cases data from the different groups (Seller, Buyer, and Contacts) were georeferenced and aggregated into 500 m-spaced hexagon grids using GPS location data (Fig. 2 A and B). All other geodata and base maps, road networks, and urban points of interest (POI, including locations of all supermarket stores) data were acquired online from OpenStreetMap (OSM) (https://www.openstreetmap.org)[9]. Population distributions and Xinfadi market-related trade activity data in early June 2020 were derived from the Tencent Location Big Data service (https://heat.qq.com) and Dianping (http://www.dianping.com) respectively, using Python crawling scripts. In the population datasets, the city was divided into a grid of cells of approximately 5 × 5 km and then downscaled to 500 m resolution hexagonal grids and assigned an estimated population value. By considering the distance between the grid cells and stores along with road networks, we assigned each cell to a 'local' store; this process generates over 1000 subpopulations to build trade-mobility layers to reflect the trade and shopping patterns for further spatial modeling analysis. The trade-mobility data revealed significant variations in the number of buyers per market (Fig. 2C).

Geostatistical analyses and COVID-19 disease dynamics simulations were completed in QGIS (https://www.qgis.org/en/site/)[10] with the Geoda (http://geodacenter.github.io/) spatial correlation tools and NetLogo (http://ccl.northwestern.edu/netlogo/index.shtml)[11] software for the agent-based model (ABM). The spatial database was compiled by utilizing OSM data layers of residential areas, business areas, markets, roads, as well as the boundary of districts in Beijing City (Fig. 2C), and the population density (Fig. 2D). The spatial network model was built based on the current traffic road network using the distance (time) for service area analysis (Fig. 2C). Daily confirmed cases in the cohorts (buyers, sellers, and contacts) were summarized for each week after the first confirmed case in every grid to establish a Geographic Information System (GIS) based disease characteristic data layer, including the location and density of confirmed cases.

To examine the spatial association of COVID-19, Moran's I statistic was used for each week with different groups (Fig. 3C and 3D)[12]. Moran I's calculation formula is

$$I = \frac{n}{S_0} \frac{\sum_{i-1}^{n}\sum_{j=1}^{n} w_{ij}\left(x_i - \bar{x}\right)\left(x_j - \bar{x}\right)}{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} \quad (1)$$

where w_{ij} is the weight between the observation of i and j, S_0 is the sum of all w_{ij}'s.

$$S_0 = \sum_{i-1}^{n}\sum_{j-=1}^{n} w_{ij}$$

The value range of Moran's I was [−1, 1] (Fig. 4A).

3. Susceptible to the disease, Infectious, and recovered (SIR) coupled Agent based Modelling (SIR-ABM)

Our SIR-coupled ABM model (SIR-ABM) introduced Seller (Se) and Buyer (Bu) subgroup agents within the traditional Susceptible (S) compartment[13]. The states of human agents change under certain conditions over time. It is assumed that the total population

$N = S(t) + I(t) + R(t)$ is fixed.

It follows that $0 = dN/dt = dS/dt + dI/dt + dR/dt, \forall t \geq 0$ (1)

The SIR-ABM model integrates three layers: real-world data on the city population, real-world data on the mobility of this population linked with trade data (Fig. 3A and 3B), and an individual-based stochastic mathematical model of the infection dynamics. For population mobility, road travel networks with origin–destination matrices of trading patterns were used to ensure comparability between and within cells for their models. The disease is transmitted between adjacent grids when people trade (shopping) across the grid cells. A wide range of non-medical interventions, such as restrictions on retails inside the wholesale food market, market closures, and buying local (Fig. 4B) via adding case progress status variables related to market-related trade data, were then modeled and studied in terms of the effectiveness of the contact-tracing regime.

4. Results

4.1. The transmission of SARS-CoV-2 among the sellers and buyers from the Xinfadi market and Beijing outbreak of COVID-19

Up until July 12, 2020, a total of 335 confirmed COVID-19 cases linked with Xinfadi market were reported by the Beijing CDC. Of these, 261 cases had a history of direct exposure to Xinfadi wholesale food market, which were divided into two cohorts: the seller and the buyer with 177 and 83 cases, respectively. The sellers' cohort included all employees of the market, such as managers, vendors, cleaners, and all others who worked in the market. The buyers' cohort included all customers who visited the market (n = 26), such as the buyers for restaurants (n = 8), other food markets (n = 2), for own family (n = 14), and enterprises (n = 3). These 26 of the 83 infected buyers had transmitted the disease, leading to 63 new infections accounting for approximately 3.2-fold increase in the total number of confirmed cases.

4.2. Transmission of SARS-CoV-2 among the buyers in Xinfadi market and COVID-19 outbreak in Beijing

Our internet-based investigation had revealed eight primary COVID-19 cases that included infected staff from seven restaurants in Beijing and one restaurant in Tianjin. These confirmed primary cases then led to 24 and 2 secondary and tertiary transmissions, respectively. Additionally, seven of the eight infected restaurants had resulted in a secondary transmission.

Further investigation had revealed that eight buyers for restaurants in Beijing were diagnosed with COVID-19. They were distributed in three districts: Daxin (n = 3), Haidian (n = 2), and Fengtai (n = 3) (Fig. 1). Two cooks in the barbeque restaurant were virologically diagnosed and had no history of exposure to the Xinfadi market. However, the manager of the barbeque restaurant had an exposure history to the Xinfadi market, but had no evidence of infection (Fig. 1).

It also needs to be specified that a dishwasher in a western food restaurant at C Hotel in Tianjin city was diagnosed on June 17, 2020. He had denied a history of visiting Beijing. In addition, a chef in the same restaurant had tested positive for IgM against SARS-CoV-2 on June 19. The chef had visited Beijing frequently in the preceding two weeks but had denied visiting the Xinfadi market. Phylogenetic grouping of the complete SARS-CoV-2 genome sequence obtained from the infected dishwasher with Xinfadi strains, which had not been previously circulated in this region, further implies that this case was linked to the Xinfadi market.

The staffs infected in restaurants were cooks, food dispensers, or servers. The items purchased from Xinfadi market for restaurants included meat, seafood, vegetables, fruits, and others. The restaurants in Beijing were relatively small, with more than 50

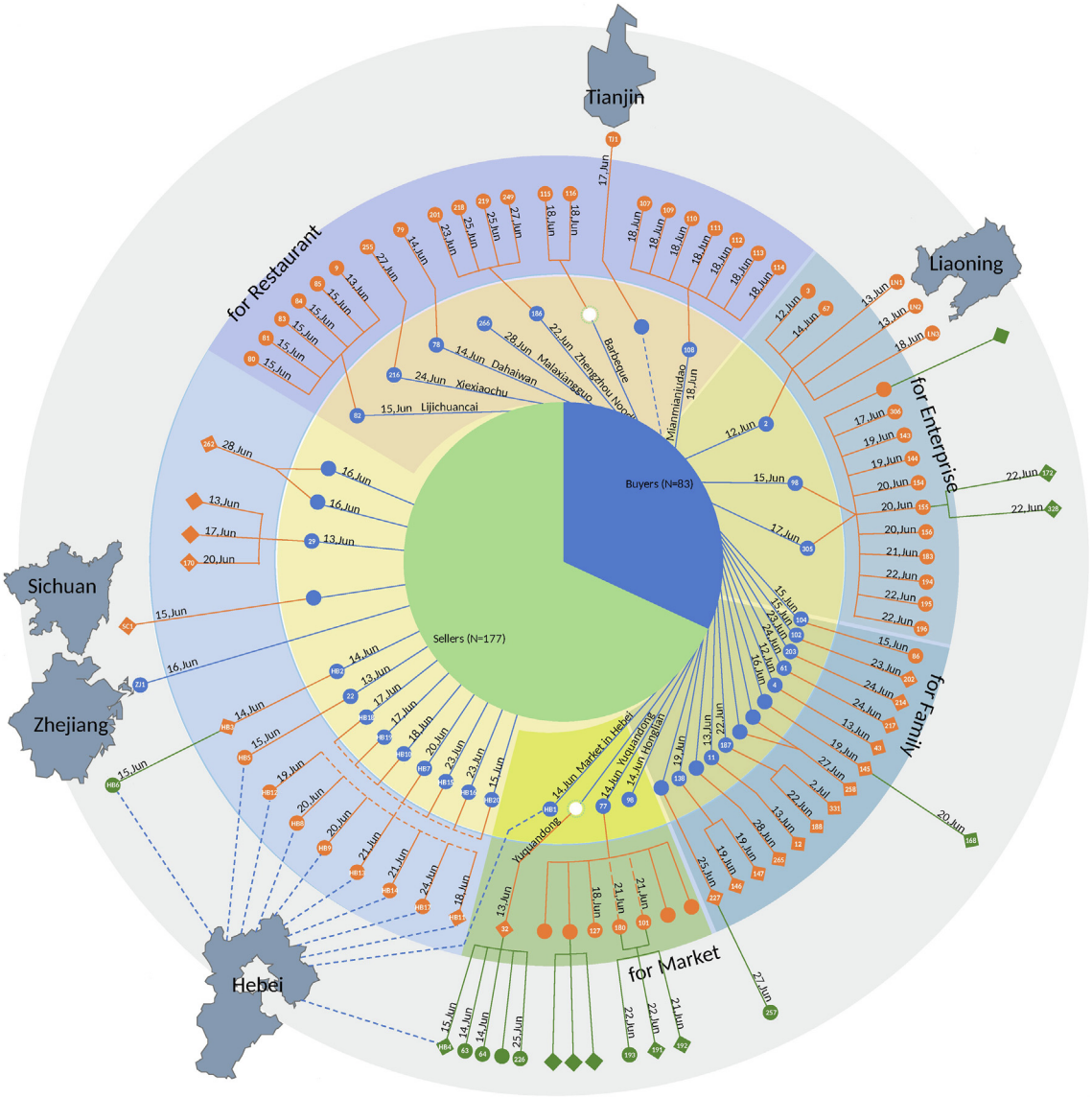

Fig. 1. The transmission of COVID-19 among the sellers and buyers in Xinfadi market.

seats. All of these restaurants had been opened for business before the first employee was diagnosed with the infection. Remarkably, no customer infection from these restaurants was reported.

Additionally, two food markets were confirmed to be infected, with buyers who had purchased items from the Xinfadi wholesale food market. A buyer from Yuquandong food market in Haidian District was diagnosed with COVID-19 and had led to five second-generation and one third-generation transmissions, including one of his family members diagnosed on June 15, 2020. Four vendors in adjacent stalls, about two meters in distance, were also transmitted with SARS-CoV-2 and diagnosed for the same in the period from June 14 to 25, 2020. By sharing the same public toilet in the same building where the infected vendor rented and lived, a staff member from a small restaurant who worked in a nearby food court was also infected, who then further transmitted the disease, leading to four additional cases (Fig. 1).

A buyer from a food market in Xicheng district, who had purchased items from Xinfadi market, was diagnosed with COVID-19 on June 15, 2020. However, no secondary transmission was detected, and all the 62 close contacts of the buyer tested negative for SARS-CoV-2.

Two buyers from an enterprise of food products were diagnosed with SARS-CoV-2 on June 15 and 17, 2020, leading to 11 secondary transmissions and three tertiary transmissions (Fig. 1). A buyer from a food research institution was diagnosed positive for SARS-CoV-2 infection on June 12, 2020, leading to five secondary transmissions, including two cases in Beijing and three cases in Liaoning province (Fig. 1).

Fourteen buyers for their respective families were infected and diagnosed with SARs-CoV-2 during the period from June 12 to 24, 2020, leading to 15 and 3 secondary and tertiary transmissions respectively. It must be noted that 13 of the 14 infected buyers had transmitted the virus to their family members (Fig. 1). One infected buyer had returned to his home town in Hebei province, resulting in a secondary transmission. One of his family members was also infected (Fig. 1).

4.3. Transmission of SARS-CoV-2 among the sellers in Xinfadi market

The retrieved data has revealed that 11 out of 177 (62%) infected sellers in Xinfadi wholesale food market had caused secondary transmissions. Three of the secondary transmission cases

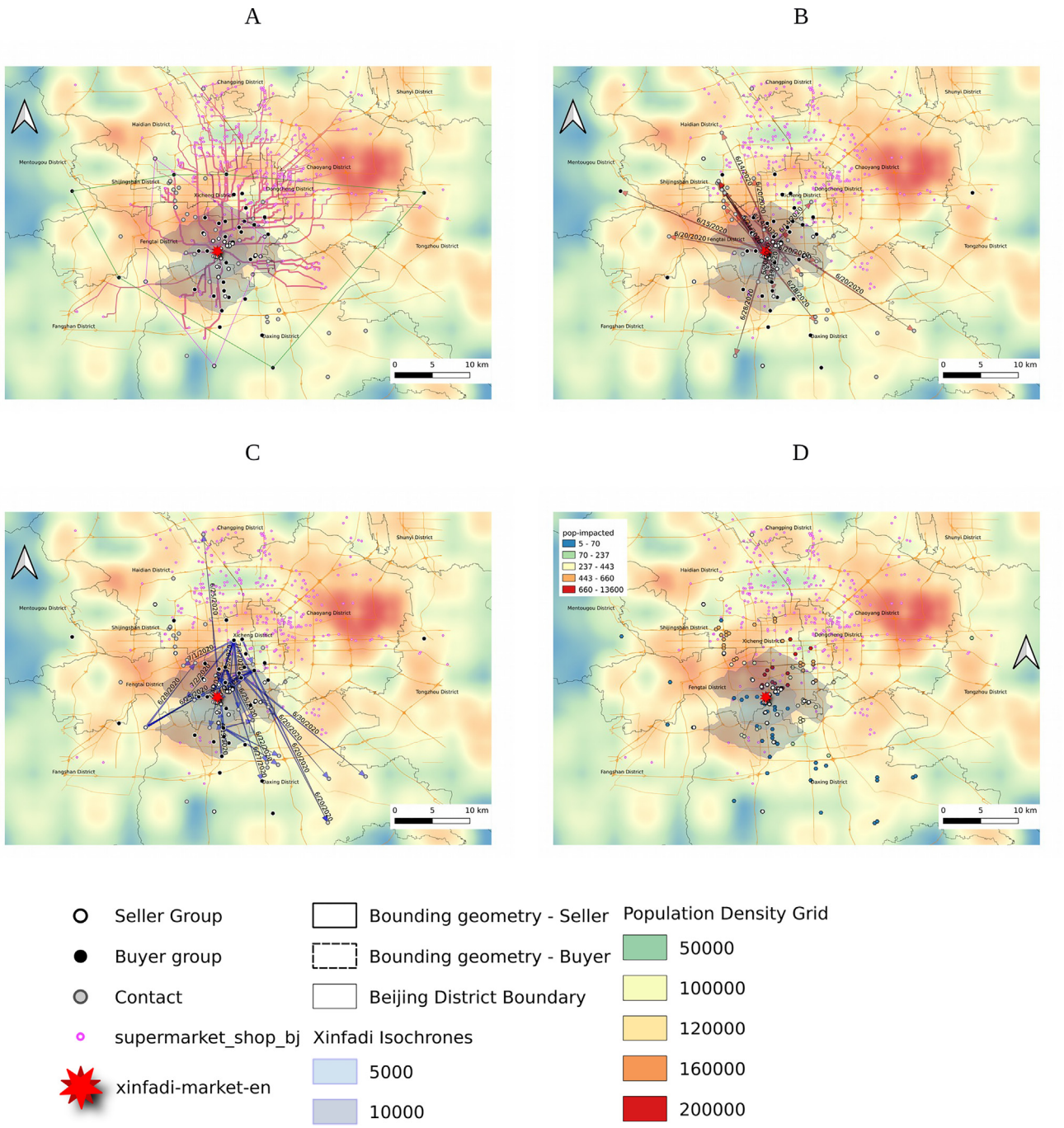

Fig. 2. Spatial epidemiological analysis maps of COVID-19 outbreak in Xinfadi market: White dots represent survey sites with the COVID-19 confirmed cases from the Seller cohort. Black dots represent cases from the Buyer cohort. Grey dots indicate survey sites with the Contacts cohort. Spatial distribution and transmission conducted for A) Xinfadi service area (shown in shade for 5 km and 10 km zone) zoning and trade routing (Pink network links) with other markets; B) Seller epidemiological links; C) Buyer epidemiological links; D) Exposure population grids showing the number of susceptible individuals near case location, warm colors represent high probability of the COVID-19 transmission and cool colors represent low disease transmission probability.

were from Beijing, leading to infection of four family members. It was also revealed that a seller immigrating from Sichuan province had infected his wife, who was diagnosed after returning to the home city. While a seller from Zhejiang province had returned to his hometown and caused no further transmissions.

A total of 21 infections caused in Hebei province were associated with the Xinfadi market. Two infected sellers had caused two secondary and one tertiary transmission. Seven infected sellers had caused nine secondary transmissions in Hebei province; all of whom had contacted the primary cases when they returned from Xinfadi (Fig. 1). However, there was no information to illustrate who was transmitted by whom.

4.4. Food-trade-associated SARS-CoV-2 transmission analysis

Consumers (buyers) who had visited the Xinfadi market and shopped in other places were identified using crawled data from Dianping.com[14]. The actual customer and consumption data with derived store addresses helped to build spatial connections to evaluate the relevance of the Xinfadi market and consumer activities in

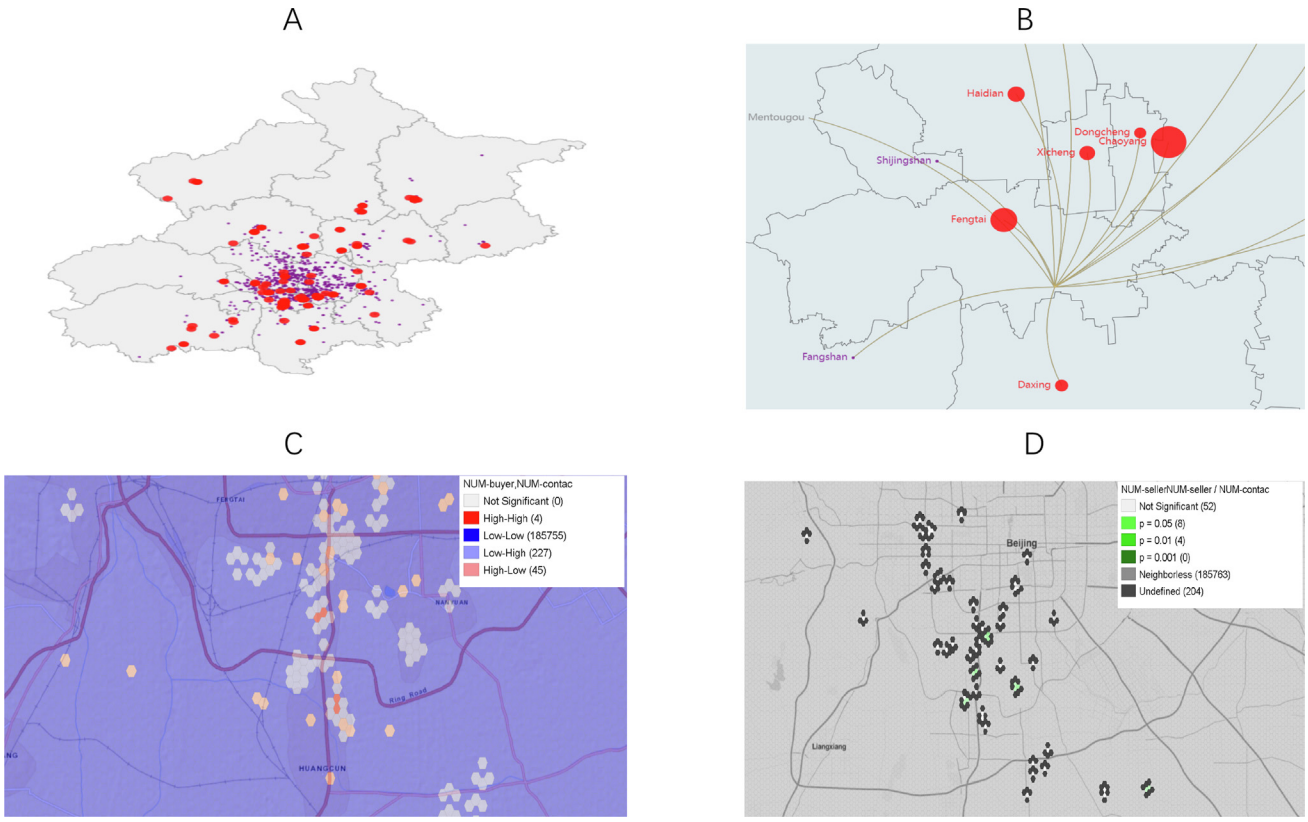

Fig. 3. Simulation of the trade-associated transmission of COVID-19 outbreak using a SIR-ABM model: (A) Map of trade connections with source contaminated wholesale food supermarket in Xinfadi displayed for individual markets and each district; (B) Conditional Map showing the spatial distribution of the total COVID-19 cases with the associated categories of the conditioning distribution of Buyers and Stores. Local Spatial Autocorrelation analysis conducted with Bivariate Local Moran's I examined for Buyer and Contact cohorts with maps of COVID-19 cases (graduated symbol) and statistically significant hotspot locations near Xinfadi clusters; (C) high-high and low-low clusters; (D) Significance Map based on 999 permutations with a *p*-value of 0.05.

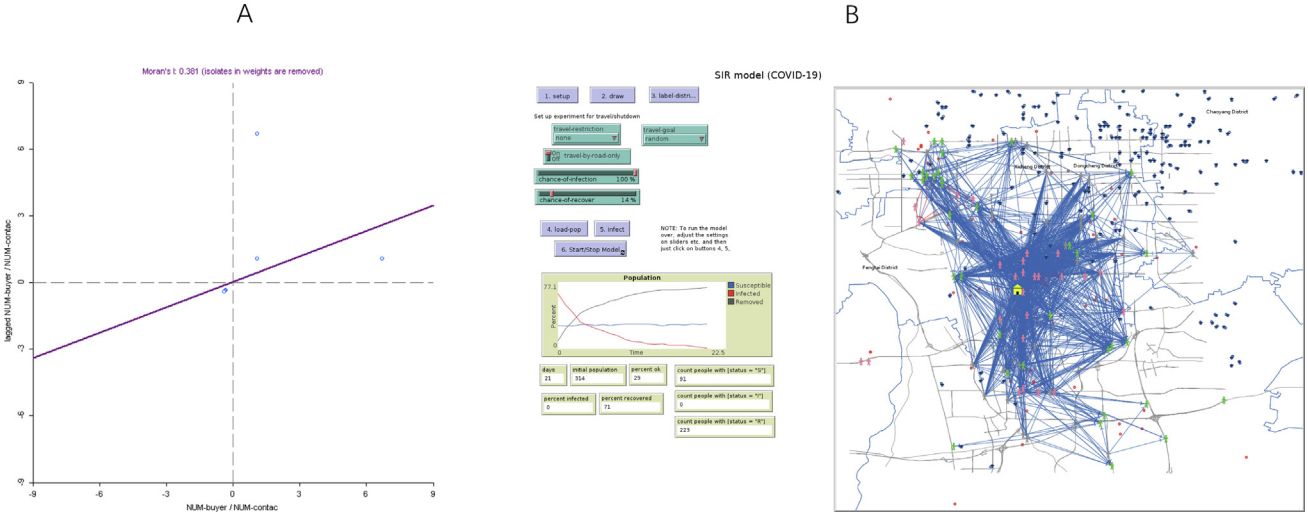

Fig. 4. The trade-associated outbreak simulated with a SIR-ABM model. (A) Moran's I scatter plot showing a positive spatial correlation between Buyers and Contacts groups; (B) Model interface, mitigation options, and exposure population in different groups modeled with linked Seller/Buyer/Contact groups.

other regions. The top-10 districts /regions with Xinfadi trade-related stores based on consumption records are summarized in Table 1. A complete list of stores and other relevant business and spatial data was shared in a dedicated GitLab project site (https://gitlab.com/map4china/xinfadi-COVID.git). It was observed that Xinfadi market attracted customers from across a large region, and most trade-related stores were spatially distributed within the Fifth Ring Road and in the south of Beijing. Among them, approximately 2000 stores were concentrated in the Fengtai and Chaoyang districts, accounting for 46% of the total number of stores in Beijing. The trading stores' coverage was relatively uniformly distributed in the city center. The largest population served by those stores was located in Xicheng, Dongcheng, Haidian, Fengtai district, and several neighborhoods in the Chaoyang district. The

Table 1
Ranking (numbers and percent shares) of trade-related stores with Xinfadi supermarket.

Rank	Districts in Beijing			Province		
1	Chaoyang	1118	25.69%	Tianjin	71	11.36%
2	Fengtai	842	19.35%	Hebei	67	10.72%
3	Haidian	536	12.32%	Shandong	50	8.00%
4	Xicheng	496	11.40%	Guangdong	45	7.20%
5	Daxing	412	9.47%	Sichuan	38	6.08%
6	Dongcheng	377	8.66%	Hunan	31	4.96%
7	Chanping	111	2.55%	Shaanxi	29	4.64%
8	Shijingshan	102	2.34%	Shanxi	28	4.48%
9	Fangshan	93	2.14%	Hainan	27	4.32%
10	Tongzhou	84	1.93%	Jiangsu	26	4.16%

map shown in Fig. 2C illustrates the drive times to Xinfadi market from the connected stores (Table 2), which provides a useful method for determining trade connections based on travel time and road networks. It uses distances along actual streets and highways, and combines with their respective travel speeds, to calculate travel time for food shopping. The map also displays the geographic distribution of other trade-based stores linked to Xinfadi market. By tapping into such trade-based store network/ location data in ABM, our model tracked the transmission of the infection and estimated the number of people who may have been exposed.

4.5. Spatial-temporal analysis of SARS-CoV-2 transmission

Our spatio-temporal analysis has generated maps of the spatial cumulative case distribution in Beijing from June 11 to July 12, 2020 (Fig. 2). The maps revealed a few COVID-19 transmission clusters in two neighborhoods of the Fengtai and Daxing districts (Fig. 2A, 2B), with a much larger buyer bounding area (Fig. 2C). The highest numbers of seller transmission hubs were located in the Xinfadi neighborhood, while the buyer transmission hubs extended to cover more than three different districts. The analysis of the exposure population density for the affected grid cells reveals that Fengtai district had the highest number of cases, whereas the northern districts had reported fewer or no cases (Fig. 2D). It also revealed that the areas with a high incidence of COVID-19 were concentrated across neighborhoods in the southwest of Beijing's Fifth Ring Road and the western section of the Fourth Ring of southwestern Beijing, and the west portion of Fuxing Road. The spread of COVID-19 within the Sixth Ring Road was centered on the intersection of the South Fourth Ring Road and Beijing-Kaifeng Expressway and extended along the northwest-southeast direction (south-north direction).

Following the intuitive description of the spatial–temporal distribution of COVID-19 transmission, a global/local spatial autocorrelation analysis was conducted with the epidemiological data to interpret the quantitative distribution characteristics of the spatial aggregation. The bivariate Moran's I of 0·38 (Fig. 4A) for the numbers of Buyers and Contacts cases indicates that there is a strong positive correlation for transmission of SARS-CoV-2 between them. In addition, the study of the global Moran's I of new COVID-19 cases every week reveals that there is spatial clustering mainly in the first and third weeks, and the new cases in the second and fourth weeks show a relatively unstable random distribution. A transmission risk analysis further revealed that the high-risk (hotspot area) of COVID-19 infection located in the upper right (HH) quadrant is mainly concentrated in the southwest (South Third Ring Road) region of Beijing. The risk of COVID-19 transmission in suburban areas (LH and HL quadrants) in the northeast of Beijing is not only comparatively low but relatively safe as well. High-low clustering refers to the transition from a high-risk transmission area to a low-risk transmission area, and low–high clustering refers to a transition from a low-risk transmission area to a high-risk transmission area. Our analyses reveal that some cases near the Southwest Fourth Ring Road and Southwest Fifth Ring Road in Beijing do not belong to this category.

The SIR model output (Fig. 4A) also supports the results from the space–time statistic. Our modelling analyses reveal that the outbreak originated in the south by June 2020 and then expanded to the west–central and southern districts of Beijing after June 2020. In July 2020, the transmission extended to the surrounding region. It is well known that higher the density and degree of urban space gathering the more severe is the spread of an epidemic. We had implemented all mitigation strategies in order to simulate the transmission of COVID-19 between human agents based on the SIR-ABM analysis (Fig. 4B).

In the SIR-ABM analysis, two COVID-19 mitigation strategies were applied and investigated. The key epidemic control parameters, such as R0, in the model were set differently using the R0 parameter. The mitigation strategies related to the so-called trade-off in our model effectively reduces R0. To model the dynamic process of outbreaks, our ABM model was initialized with collected historical case numbers for the first four weeks and then continued to run for another four weeks to present different adaptation scenarios. The main causes of the COVID-19 outbreak are people's movements for trade as well as their interactions with each other during trade events. Thus, one of the strategies that can help control the COVID-19 outbreak is retail closures (using the travel-goal switch as shown in Fig. 4B) inside the wholesale food markets. The ABM was implemented in two modes: retail shops were open and completely shut down. In the latter case, the number of visitors to the food market dropped by nearly half. The other mitigation measure introduced a buy-local policy that guides consumers to visit nearby markets to access food supply. The results of the simulation indicated that the buy-local option in the Xinfadi market is capable of reducing the number of infected people by 60% each week on an average and more than 70% in total from June 21 to July 20, 2020. Overall, the results suggest that trade-related travel of people is the main factor responsible for the transmission of COVID-19. Thus, the closure of retail outlets as well as the buy-local policy can serve as potential strategies to radically reduce the number of infected people.

5. Discussion

Both the Wuhan and Beijing outbreaks were linked to a contaminated wholesale food supermarket with seafood[1,6]. At the initial stage of the Wuhan outbreak, most cases had a history of exposure to the Huanan seafood wholesale market. Of the first 41 confirmed cases, 27 (66%) had been exposed to the Huanan seafood market[7]. Among the first 425 confirmed cases with onset before January 1, 2020, 55% were linked to the Huanan seafood wholesale market, as compared with 8.6% of the subsequent cases[1], leading to 68 000 cases in total in Hubei province. For the Xinfadi market out-

Table 2
Travel time from Xinfadi supermarket to selected trade-related stores.

ID	Store name	Lon-Lat	Travel time (h)
5084892121	7 11	116.4260876, 39.9203105	0.16
286279253	AnNingZhuang Mei Lian Mei Supermarket	116.3186344, 40.0486722	0.25
2653420501	April Gourmet	116.4650825, 39.9438535	0.21
5949236085	April Gourmet	116.44851, 39.931148	0.18
4858657858	April Gourmet - The closest place to home	116.4390726, 39.9350067	0.18
734837929	Carrefour	116.4091105, 40.0575851	0.28
4787685124	Carrefour	116.309415, 39.9782079	0.18
5078954923	Carrefour	116.6502656, 39.8887683	0.29
5349977123	Carrefour	116.4258436, 39.8926043	0.13
2039584328	Carrefour Dazhongsi	116.3364935, 39.9655119	0.00
6759234985	Eon supermarkets	116.2834799, 40.0948269	0.30
5592820921	Ganyu Dele Supermarket	116.4084267, 39.9154817	0.14
4607766099	H + Supermarket	116.5504555, 40.00932	0.30
3011898463	Hua Lian Supermarket	116.4661798, 39.9887498	0.24
4356841690	Huapu	116.4326985, 39.9233175	0.16
5630082221	Jenny Lou's	116.4886988, 39.9388923	0.22
4890761922	Jenny Wang Shop	116.4773422, 39.974959	0.23
5421820602	Jingkelong	116.4953008, 39.9377552	0.22
4706051389	JingKeLong JinZhan	116.5724355, 40.0012368	0.32
6842478816	Korean Supermarket	116.8274017, 40.1542585	0.58
5811578954	Local market	116.3986243, 39.8596252	0.09
5811595253	Local market	116.4069923, 39.8686387	0.10
1709527090	Lotte Mart	116.4849686, 39.9744152	0.24
5963394690	Magazin Jura	116.4375932, 39.9174063	0.16
6356133586	Magsin Jura	116.4345947, 39.9165563	0.16
973328223	Meilianmei	116.3789307, 39.9498561	0.16
4486190290	Merry Mart	116.3680372, 39.9212437	0.12
820144091	MetroSuper	116.4555915, 39.9666669	0.21
4966402621	Minimart	116.4110572, 39.9333912	0.16
6052524200	Natural	116.3377602, 39.9242233	0.11
5570615523	New Mart	116.4098313, 40.0389857	0.26
2034233477	New World Department Store	116.4117658, 39.8970656	0.12
6203038185	Nick's Mart	116.4729639, 39.9757867	0.23
5020076125	ShijiHualian	116.3513898, 40.0716736	0.27
4751803422	Smart Air	116.4391971, 39.9351994	0.18
5837667486	SunMart (diverse and cheap), food and supermarket	116.3736532, 39.9246066	0.13
4503942371	Tsinghua University Northwest Supermarket	116.3128114, 40.0096102	0.21
5335960521	U center	116.3085101, 39.9945849	0.20
1305021210	Vanguard Supermarket	116.4840365, 39.9839974	0.24
4581719836	Walmart	116.3264218, 40.0289732	0.23
4711123690	Walmart	116.2747578, 39.9524165	0.17
6052523998	Wu Mart	116.3310814, 39.8966254	0.09
2948819433	WuMart	116.405532, 39.993857	0.22
4459857289	Wumart	116.3002526, 39.9881062	0.19
2482406776	WUMART Hypermarket	116.4369302, 39.8040625	0.09
2010091934	Wumart Supermarket	116.4244122, 39.9225959	0.16
4826732999	Wumart Supermarket	116.5357584, 40.0979942	0.38
1253420852	WuMei Super Martket of Miyun	116.8394726, 40.3737251	0.58
6572173085	Youhui Wanja Supermarket	116.4057959, 39.9351906	0.16
1030342288	Your Goal Supermarket	116.3387505, 39.9805127	0.18

break, a total of 335 confirmed cases were reported from June 11 to July 8, 2020[5].

Upon considering the size, trade volume, and density of the visitors, the influence of Xinfadi market was very high, as it covers an area of 1,20,000 m^2, which is 21 times larger than the Huanan seafood market in Wuhan[15]. The Xinfadi market has 4500 employees and approximately 2000 fixed booths comprising of management personnel and tenants. Each day, over 2,00,000 visitors were estimated to visit the Xinfadi market between May 30 to June 12, 2020, when the first case of COVID-19 was identified, and the market was closed to stop the rapid transmission of the virus[15]. The Huanan seafood wholesale market is the largest aquatic product wholesale market in central China, integrating seafood, frozen fresh food, aquatic products, and dry goods; with a size of approximately 50,000 m^2 and more than 1000 stalls.

The susceptible-exposed-infectious-recovered (SEIR) dynamics model analysis suggests that the outbreak probably started between May 22 and May 28. 2020. The cumulative number of COVID-19 cases would have reached 65,090 (95%*CI*: 39 068–105 037) at July 1, 2020[15]. Since the population size and density at Beijing is much higher than that in Wuhan city, and the size of Xinfadi wholesale food market is much larger than Huanan seafood wholesale market; the size of Xinfadi outbreak could have been much bigger, if no prevention and control measures was immediately and effectively implemented[5].

According to current information, the contaminated seafood market was responsible for the re-emergence of the COVID-19 outbreak in Beijing[7,16]. The virus was isolated and detected from environmental samples (chopping board and floor drain) from the Xinfadi wholesale market[6]. The environmental samples from the market were also tested and found to be positive for SARS-CoV-2, including a cutting board in a booth handling imported salmon[7]. However, how the Xinfadi wholesale market was contaminated by the virus still remains unclear. Recently, SARS-CoV-2 has been frequently tested positive in seafood samples imported from several cities in China. These facts suggest that SARS-CoV-2 is evidently associated with food processing and distribution system[17].

We report here for the first time that SARS-CoV-2 could be spread and transmitted by modern food distribution networks, such as the Xinfadi outbreak in Beijing. Out of a total of 335 confirmed cases reported in this Xinfadi outbreak, 177 (52.8%) were employees in the market and termed as sellers, and 83 (24.8%) were customers who shopped there and termed as buyers for the purpose of this study. 26 of 83 (31.3%) infected buyers were responsible for the transmission of 63 new infections (75.9%). Eleven out of 177 (62%) infected sellers caused secondary transmissions, comprising of four infections in Beijing, one infection in Sichuan, and 21 infections in Hebei province.

The highest number of seller transmission hubs were located in the Xinfadi neighborhood where the sellers worked and lived (Fig. 2D). A much larger buyer bounding area (Fig. 2C) was observed in the two neighborhoods in the Fengtai and Daxing districts (Fig. 2A and B). Our analyses further revealed that the Xinfadi market attracted customers from across a large region, and most trade-related stores were spatially distributed within the Fifth Ring Road and in the south of Beijing (Fig. 2C). Moreover, the buyer transmission hubs extended to cover more than three districts (Fig. 2D).

It was found that disease transmission was associated with food-trade activities but not with population density in the Xinfadi market outbreak. The Dongcheng and Chaoyang districts have the highest population density; however, it was the Fengtai district, which had the highest number of cases. The high incidence area of COVID-19 made the Xinfadi food wholesale market as a hot spot that further transmitted along the urban rapid transit line.

The main causes of the Xinfadi market outbreak were the movements of people for the purpose of shopping as well as their interactions with each other during shopping events. Therefore, one of the strategies that can help control the food-associated outbreak is the closure of retail outlets (Fig. 4B) inside the Xinfadi wholesale food market. Our model suggests that when the retail outlets were completely shut down, the number of visitors to the food market would drop by nearly half. When the buy-local policy was implemented, which guides consumers to visit nearby markets to access food supply, the number of infected people could be reduced by 60% each week on an average and more than 70% in total from June 21 to July 20, 2020. According to the results, it is proven that trade-related travel of people is the main factor in spreading the COVID-19 and the Retail closures as well as Buy-local policy can serve as important strategies that can significantly reduce the number of infected people.

The Xinfadi market outbreak of COVID-19 developed uncertainties when the first few cases were confirmed. When the virus was detected in the sealed package of salmon and other seafood during cold storage, we were inspired to consider the possible link with the Huanan seafood market in the Wuhan outbreak. It seems that if the fast, scientific, and strict public health actions were implemented for the Wuhan outbreak at the first time, the massive public infection might have been prevented, as was observed in the case of the Xinfadi market outbreak.

CRediT authorship contribution statement

Shan Lu: Data curation, Writing - original draft. **Weijia Wang:** Software, Visualization. **Yanpeng Cheng:** Data curation, Investigation. **Caixin Yang:** Data curation, Investigation. **Yifan Jiao:** Data curation, Investigation. **Mingchao Xu:** Data curation, Investigation. **Yibo Bai:** Data curation, Investigation. **Jing Yang:** Data curation. **Hongbin Song:** Writing - original draft. **Ligui Wang:** Software, Validation. **Jiaojiao Wang:** Visualization. **Bing Rong:** Software, Validation. **Jianguo Xu:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Shan Lu is a fellow of National Institute for Communicable Disease Control and Prevention, Chinese Center for Disease Control and Prevention. She is currently engaged in the monitoring of infectious diseases and outbreak responses.

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