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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. 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. 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. 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.

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
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 cities 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 retail inside wholesale food markets, 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.

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. 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 cities 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 retail inside wholesale food markets, 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.
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
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. 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. 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.
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
Ranking (numbers and percent shares) of trade-related stores with Xinfadi supermarket.

| Rank | Districts in Beijing | Province | Number | Percent Share |
|------|----------------------|----------|--------|---------------|
| 1    | Chaoyang             | Tianjin  | 1118   | 25.69%        |
| 2    | Fengtai              | Hebei    | 842    | 19.35%        |
| 3    | Haidian              | Shandong | 536    | 12.32%        |
| 4    | Xicheng              | Guangdong| 496    | 11.40%        |
| 5    | Daxing               | Sichuan  | 412    | 9.47%         |
| 6    | Dongcheng           | Hunan    | 377    | 8.66%         |
| 7    | Chaping              | Shaanxi  | 111    | 2.55%         |
| 8    | Shijingshan          | Shanxi   | 102    | 2.34%         |
| 9    | Fangshan            | Hanoi    | 93     | 2.14%         |
| 10   | Tongzhou            | Jiangsu  | 84     | 1.93%         |

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/ locations, 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. 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. 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, leading to 68 000 cases in total in Hubei province. For the Xinfadi market out-
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 effectively implemented\(^1\).

According to current information, the contaminated seafood market was responsible for the re-emergence of the COVID-19 outbreak in Beijing\(^{16}\). 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\(^17\).
Moran PA. Notes on continuous stochastic phenomena. 113490.

The strategies that can help control the food-associated outbreak is actions with each other during shopping events. Therefore, one of 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 uncertainly 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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