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# Enhancing healthcare planning using population data generated from mobile phone networks in Futaba County after the Great East Japan earthquake

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**After the Great East Japan Earthquake, planning appropriate healthcare resource allocation was crucial. However, accurately estimating medical care demand was challenging due to substantial population fluctuations caused by extensive evacuations, compounded by the inaccuracy of conventional Resident Resister data in this context. This study employs population data generated from mobile phone network from 2019 to 2020 to conduct a detailed temporal and spatial population estimation in Futaba County, originally a complete evacuation zone. To enhance the precision of population estimates, population data independently collected by each municipality were used as reference data in the estimation process. Further, the utility of the estimated population data for calculating emergency transport rates was assessed. Our findings revealed discrepancies between daytime and nighttime populations within Okuma and Futaba Town, where median day/night population ratio exceeded three across both weekdays and weekends. Additionally, sex–age-adjusted emergency transport rates calculated using the estimated population demonstrated closer alignment with the national average compared to those calculated based on census data. This study demonstrates the importance of considering dynamic population data, such as that generated from mobile phone networks, in enhancing healthcare planning and ensuring that resources are efficiently allocated to meet communities' evolving needs during recovery periods.**

**Keywords** Population estimation, Disaster medicine, Emergency transport, Medical planning, Mobile spatial statistics, Public health

Estimating the demand for healthcare in a region is important for planning the appropriate allocation of healthcare resources. Attempts have been made to identify a target population and assume appropriate healthcare demand according to the size and risk factors of that population[1–3]. Appropriate population identification of a target area is crucial for such estimation of the prevalence of disease and medical demand[4]. However, following the improvement of transportation, globalization, and economic development worldwide, local populations have become more fluid. In economically active cities, their surrounding areas, and tourist destinations, the statistical resident population deviates from the actual population of the region. The statistical resident and real populations diverge during nighttime and daytime hours and even more significantly on an hourly basis[5,6]. It is difficult to accurately grasp the local population dynamics[7]. Therefore, it has become extremely difficult to estimate the demand for medical care in accordance with the local population. Notably, in the case of emergency

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medical care, which occurs differently during the day and night, understanding the day and night populations is essential for estimating demand. Estimating the true demand for healthcare in a region is a significant public health issue because everyone has the right to access healthcare; it is also important to accurately determine the population of a region to do so.

The displacement of residents after a major disaster is an example of major population change and accelerated population mobility[8,9]. In the case of a major disaster that affects a wide area, the number and composition of the resident population change rapidly, as the local conditions change on a monthly basis from the time of the disaster to the recovery and reconstruction period, and some disaster victims are forced to change their residences[10–12]. Following such population changes, estimating post-disaster medical demand is essential[13]. Additionally, the industrial structure of a region changes along with the reconstruction process, the outgoing and incoming population, and the working population. Although it is necessary to monitor population recovery during the reconstruction process, as well as social and spatial population changes and differences by region[9], it is difficult to accurately survey a dynamically floating population. This, in turn, makes it difficult to estimate the demand for medical care during the recovery period following a major disaster.

Fukushima Prefecture is a prime example of a case in which population disaggregation has been difficult because of significant population changes since the 2011 Great East Japan Earthquake (GEJE) and Fukushima Daiichi Nuclear Power Station (FDNPS) accident, which was accompanied by the evacuation of residents. After the GEJE, in addition to those whose continued residence was made difficult by the tsunami and earthquake, residents in areas designated as evacuation zones (owing to fear of radioactive contamination) were forced to evacuate for extended periods[14]. Notably, in the Futaba area, located within a 30 km radius of the FDNPS, almost all residents were forced to evacuate after the earthquake. Although the evacuation order was gradually lifted, the evacuation zone was still designated 13 years after the disaster[15]. Additionally, in areas where the evacuation order was lifted, which means people were allowed to live and stay overnight, the duration of residence restrictions and the timing of the lifting of restrictions differed by region, and the status of the number of people returning to or relocating varied by region too. The earlier the evacuation is lifted in an area, the more residents return. However, it is difficult to ascertain the actual status of their return[16].

Furthermore, reconstruction projects are still ongoing in these areas, and there is population interaction among decontamination and daytime workers[17,18]. The population dynamics in areas affected by the 2011 GEJE are becoming increasingly complex. In Japan, population statistics are obtained through the Basic Resident Register, tabulation based on resident registration cards, and census, which is based on individual house visits by local government surveyors. The Basic Resident Register accounts only for the population at the registered address, even if the residents are migrants or temporarily out of residence. Although the census is more likely to reflect the actual state of residence at the time of the survey, with surveyors verifying actual residences, it is conducted infrequently, once every five years, with a one-month survey period. Despite the complexity of population dynamics in these affected areas, there is a lack of comprehensive studies applying appropriate demographic methods to understand the population changes over time and in real time. This gap in the research hinders our ability to accurately estimate the demand for medical care and other essential services in these regions. Addressing this issue is crucial for effective planning and resource allocation in the ongoing recovery efforts.

Therefore, this study attempted to estimate the population of Futaba County, Fukushima Prefecture, using a temporal and spatial population estimation technique that utilizes mobile phone location information[10]. It is possible to capture the fluctuation of the population that actually exists, and the changes can be captured in fine time units, such as day and night, to reveal the differences in the population composition and temporal characteristics of each region. Using a similar approach, in a previous study, we examined a single point in time over four years and attempted to analyze changes in the population in areas strongly affected by the disaster[19]. We found that the composition of the population groups in the area differed according to the impact of the disaster and the status of reconstruction in the area.

This study examined eight municipalities in Futaba County that were particularly affected by the evacuation order and attempted to elucidate more comprehensive and detailed population dynamics by analyzing weekly population changes over two years in this area. Furthermore, to analyze the relationship between the characteristics of the population in the affected area and the demand for medical care, we identified the ratio of the number of occurrences per population in emergency medical service transport, for which a more detailed understanding is necessary for future human life. Such an analysis of spatial and temporal population dynamics will clarify the relationship between the current situation in areas most affected by the GEJE and emergency medical care demand.

## Methods

### Study location and evacuation order

This study covered six towns and two villages in Futaba County, which is located within a 30 km radius of the FDNPS (Fig. 1). Evacuation orders were issued to these areas following the nuclear disaster, and the timeline for lifting these orders varied across the county[20]. For parts of Hirono Town, Kawauchi Village, and Naraha Town, located within a 20–30 km radius of the FDNPS, the emergency evacuation order was rescinded six months later, on September 30, 2011. The orders for Kawauchi Village and Hirono Town were subsequently lifted on January 31, 2012, and March 31, 2012, respectively[21]. The evacuation order for a zone in Kawauchi Village, within a 20 km radius of the FDNPS, was revoked on October 1, 2014, whereas for Hirono Town, it was lifted on March 31, 2012. Naraha Town had its evacuation zone lifted on September 5, 2015. For other areas within a 20 km radius of the FDNPS, characterized by high contamination levels and targeted for decontamination, evacuation orders were lifted five- or six-years post-disaster. Evacuation in Katsurao Village, Tomioka Town, and Namie Town was lifted on June 12, 2016[22], on April 1, 2017, and March 31, 2017[23], respectively. Okuma Town and Futaba Town, home

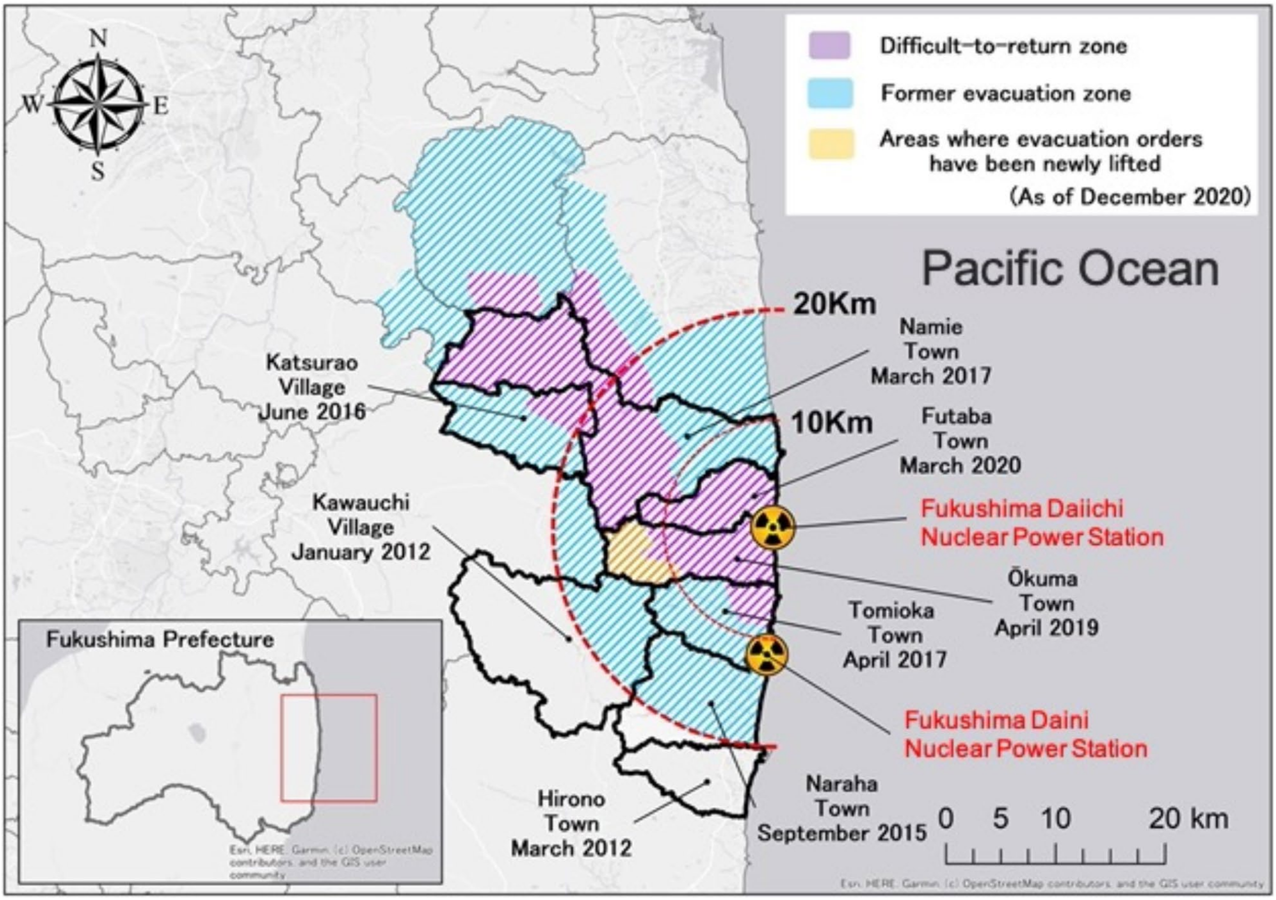


**Fig. 1**. Map of Futaba County. The map illustrates the name of the area and the year and month when the evacuation started to be lifted. Color-coded evacuation-ordered areas as of December 2020. The name of each municipality and the date indicated when the evacuation order was lifted. Purple indicates areas that are difficult to return to, blue indicates areas that were previously under lifted evacuation orders, and orange indicates areas where evacuation orders were lifted in 2019. Most areas in Okuma and Futaba are still under evacuation orders. This map was created with ESRI's Arc GIS pro version 3.1. (https://www.esrij.com/products/arcgis).

to the FDNPS, had their evacuation orders lifted eight years later in April 2019 and nine years later in March 2020, respectively. However, as of 2023, nearly 80% of the area remained under evacuation orders[20].

## Population estimation methods

We used the dynamic estimated population data generated from mobile phone network to grasp the actual population trend and calculated the day/night population ratio for each municipality. We also collected the returnee population data independently investigated by each municipality for the population estimation process.

### *The method for mobile spatial statistics technology*

Population estimates were done using mobile spatial statistics (MSS), a demographic statistic developed by DOCOMO Insight Marketing, Inc[24]. This method leverages the number of cell phones provided by NTT DOCOMO, the largest cellular phone operator in Japan, in each area, periodically recorded by each base station providing cell phone services. After processing to anonymize personal information, user attributes aggregated the data and then statistically analyzed. This process includes adjusting for NTT DOCOMO's market penetration rate to estimate the geographic distribution of the population[25]. The method allows for continuous monitoring of population trends, offering hourly breakdowns of population counts by sex and age within a minimum radius of 500 m. This approach was approved by Japan's Ministry of Internal Affairs and Communications, which issued guidelines for its public and industrial applications. It has been employed to assess urban travel patterns[26], determine the impact of developments in rail and road transport networks[27], and analyze population movements during disasters[28] and pandemics, including the assessment of lockdown measures[29,30]. As it provides a dynamic estimate of the population distribution by tracking the location of mobile terminals, it can be used for a wide range of subjects and target areas, making it an effective method for understanding the population. The census is based on individual visits by surveyors every five years in October and has the disadvantage of not directly reflecting differences between weekdays and weekends. In contrast, the method for MSS have the advantage of being able to calculate population estimates for daytime and nighttime, weekdays, and weekends with high frequency. In this study, DOCOMO Insight Marketing Inc. provided the estimated population for each of the eight municipalities, which we analyzed.

*Reference population data for the population estimation*

The method for MSS use resident population data to estimate the population based on the rate at which cell phones are detected in the area relative to the population. It typically relies on the Basic Resident Register. However, in areas designated as evacuation zones following the nuclear accident, the present target areas, the actual number of residents can significantly differ from those registered in the Basic Resident Register. To address this discrepancy, we used the number of residents based on the population information that each of the eight municipalities investigated, which we requested access to. Municipalities independently tracked the number of people who had returned to the area. This data is more reflective of the actual population in the target area. However, there is no standardized method for compiling the data across municipalities. Some methods rely on population counts by smaller administrative district heads, while others are based on return notifications submitted by the residents. In cases where the population could not be obtained through data collection by local municipalities, data from the Basic Resident Register were used. The survey data covered the monthly number of residents, disaggregated by sex and age, for 24 months, from January 2019 to December 2020. Age groups were categorized as follows: only the 15–19 age group was counted at five-year intervals, the 20–80 age group was counted at 10-year intervals, and those over 80 years of age were grouped into a single category. As a reference population, Okuma Town was assumed to have a population of zero before May 2019, when the evacuation order was lifted. Similarly, the population of Futaba Town, where evacuation orders remained during the survey period, was assumed to be zero. Finally, these data were corrected for deviations from the 2020 census data: the census data are population data obtained through individual residential visits every five years in October; the ratio of the October 2020 Census population to the October 2020 population reported by each municipality was calculated, and the reported monthly population was multiplied by that ratio to obtain the corrected monthly population. Based on the data thus generated by us on the population assumed to live in the area, the DOCOMO insight marketing company calculated dynamic population estimates. As reference information, population estimates based on population information without such census correction and population estimates based only on population information from the Basic Resident Registers were also obtained.

The use of these reference populations in the method for MSS[24] is expressed in a simplified form in the following calculation: The calculated regional reference population ( $P$) is used for population estimates ( $Ep$ ), which are based on cell phone penetration rates that vary by sex, age, and region. Equation (1) that dividing the registered number of mobile phones ( $Mr$) for the entire region by the reference population ( $P$) yields the in-area cell phone coverage rate ( $C$) per population:

$$K = \frac{Mr}{P} \tag{1}$$

By dividing the estimated number of cell phone handsets ( $Mb$), based on data obtained from base stations, by the in-area cell phone coverage rate ( $K$), the estimated population ( $E$) in the observation area can be calculated, as in Eq. (2):

$$Ep = \frac{Mb}{K} \tag{2}$$

The estimated population for the entire area can then be obtained by summing these values across all regions.

*Characteristics of the estimated population*

The estimated population data provided by DOCOMO Insight Marketing Inc. was as an average of the measured weekly values, categorized by region, daytime (2 p.m.) or nighttime (2 a.m.), sex, weekday or weekends, and age group. Population estimates were made for individuals aged 15 years and above, divided by sex and age group in 10-year increments. These estimates were conducted for each of the eight towns and villages over two years, from December 31, 2018, to January 3, 2021. Weekly averages were computed separately for weekdays and weekends. Typically, the average from Monday to Friday was used to determine the weekday average, whereas the average for Saturdays and Sundays was used as the weekend average. The daily population was estimated based on the number of people present in the area at 2:00 a.m. (nighttime population) and 2:00 p.m. (daytime population); these figures were then averaged across the week. The total number of weeks of weekends and weekdays were 105 and 105, respectively. The validity of the chosen timeframes for representing daytime and nighttime populations was confirmed by comparing them with the periods before and after, ensuring that there were no significant discrepancies, thereby confirming these times as appropriate representations of daytime and nighttime intervals.

## Analysis of the population trend by towns and villages and day/night population ratio

Based on the population estimates, we analyzed the change in the daytime and nighttime population by the town/village and calculated the ratio of the nighttime to the daytime population for each area. The ratio of the daytime population to the nighttime population for the day was calculated separately for the weekday and the weekend, respectively. For each area, the median ratio of the daytime population to the nighttime population for the two years was then calculated along with the interquartile range.

### Calculation of the ratio of emergency transports per population

*Emergency transport information*

We used data on post-disaster emergency transport (ET) in eight towns and villages in Futaba County, owned by the Futaba County Fire Headquarters. The period covered spanned January 1, 2019, to December 31, 2020. Data items included the address, date, and time when the emergency call was made, the attributes of the patient transported, the time required for transport, and the name and address of the destination hospital. The region of the emergency medical service transport was defined as belonging to the destination to which the emergency medical team was dispatched.

*Age-adjusted emergency transport rates by demographic method*

To derive the annual ET rates per population for each region in 2019 and 2020, we aggregated the number of ETs. The calculations utilized population estimates for each age group, sex, day/nighttime period, and weekends/weekday to compute the sex- and age-adjusted transport rate, employing the 2015 population model for adjustments[31]. Two age brackets, including individuals aged 15–60 years and those aged 60 years or older, were considered. Emergency occurrences were categorized based on time: daytime was from 8:00 a.m. to 8:00 p.m., and nighttime was from 8:00 p.m. to 8:00 a.m. It is known that the number of emergency call transports varies between daytime and nighttime hours. Moreover, inspired by previous research that identified day/night population distribution as a reliable predictor of disease incidence[32], we believe that segmenting the population according to these periods would enhance the accuracy of transport rate calculations. Because the number of ETs in the neighboring towns of Futaba, Okuma, Katsurao, and Namie were not sufficiently large, they were calculated as a single category each, and the analysis was divided into six areas, including the remaining four towns and villages. The detailed calculation formula is described in Supplementary File 1. To compare the accuracy and utility of different data sources for understanding ET needs, we analyzed the rates of ETs calculated from two distinct sources: estimated populations and census data. Regarding calculations based on census data, we determined sex- and age-adjusted transport rates using the census population figures for each region. Additionally, to facilitate comparisons, age- and sex-adjusted national ET rates for the same period were calculated across Japan. This involved using annual national transport numbers published in the Fire and Disaster Management Agency's White Paper on Emergency and Rescue for 2020[33] and calculating these rates based on population figures from the 2020 Census.

### Ethics committee

An ethical review was not required for the analysis of population information because the company provided no personal information. Regarding the analysis of ET data in this study, the individual consent of the participants was waived by using the opt-out method. Approval for this study was obtained from the Ethics Committees of Minamisoma Municipal General Hospital (Approval No. 105) and Fukushima Medical University (Approval No. 30114). All methods were performed in accordance with the relevant guidelines and regulations.

## Results

### Population estimates

*Weekday and weekend populations*

Table 1 illustrates the estimated population by weekdays and weekends, by day and night, and by attributes for the eight towns and villages in Futaba County. Figure 2 illustrates the estimated population divided by day/night and weekday/weekend over two years on a weekly basis. The estimated population generally indicated that daytime populations were larger than nighttime populations, except for Kawauchi Village and Hirono Town. The weekend nighttime populations in Kawauchi Village and Hirono Town, with figures of 1876 and 5110, respectively, were slightly higher than their respective daytime populations of 1,813 and 4,919. Across all towns and villages, except the nighttime population in Katsurao Village, the estimated weekday population exceeded the weekend population in both the daytime and nighttime zones. The municipalities that exhibited a higher weekday population in the daytime zone than on weekends, in order of magnitude, were Okuma Town with a factor of 3.3, followed by Futaba Town and Tomioka Town at 2.2 times, Namie Town at 1.8 times, and Katsurao Village at 1.7 times (Supplementary Table 1). Regarding the nighttime population, Okuma Town had a weekday population 1.5 times larger than its weekend population, and Tomioka Town had a 1.4 times larger weekday population, with the differences in other municipalities being negligible.

*Composition of the population by sex*

In all the municipalities, the male population was always consistently larger than the female population (Supplementary Table 2): weekdays, weekends, and both day and night. During the weekday daytime, Okuma Town had the highest male-to-female ratio at 5.0 times, followed by Futaba Town at 4.6 times and Tomioka Town at 3.7 times. Regarding nighttime hours on weekdays, the municipalities with the highest male-to-female ratio were Futaba Town at 6.2 times, Okuma Town at 5.5 times, and Tomioka Town at 4.4 times. During daytime hours on weekends, the municipalities with the highest male-to-female ratios were Okuma Town at 4.3 times, Futaba Town at 3.8 times, and Tomioka Town at 2.8 times. The nighttime hours on weekends had even more pronounced male-to-female ratios, with Futaba Town leading at 10.7 times, followed by Okuma Town at 5.3 times, and Tomioka Town at 3.3 times. Kawauchi Village, however, recorded the smallest ratio of men to women on both weekdays and weekends across daytime and nighttime periods.

*Age demographics*

Regarding age demographics, except Hirono during weekday daytime periods, all municipalities reported a larger population of individuals aged 40–69 across all categories. In Hirono Town, on weekdays, the population

| | | | Weekday | | Weekend | |
|---|---|---|---|---|---|---|
| | | | 2 a.m. | 2 p.m. | 2 a.m. | 2 p.m. |
| Estimated population *-n (median [quartile]) | Okuma | | 1081 [910–1192] | 7672 [7365–8009] | 703 [596–867] | 2328 [1927–2744] |
| | Futaba | | 268 [203–335] | 3113 [2759–2683] | 243 [186–316] | 1393 [1037–1617] |
| | Katsurao | | 360 [342–374] | 850 [753–982] | 372 [354–400] | 513 [473–601] |
| | Namie | | 2320 [2208–2462] | 5271 [4951–5442] | 2050 [1931–2176] | 3002 [2733–3294] |
| | Naraha | | 4060 [3979–4159] | 5810 [5655–6204] | 3730 [3651–3818] | 4290 [3921–4290] |
| | Kawauchi | | 1935 [1915–1958] | 2135 [2077–2205] | 1876 [1839–1917] | 1813 [1737–1889] |
| | Tomioka | | 2747 [2560–3040] | 5717 [5461–6082] | 2008 [1846–2198] | 2602 [2393–2825] |
| | Hirono | | 5831 [5443–6014] | 6388 [6074–6723] | 5110 [4896–5349] | 4919 [4655–5130] |
| Sex -n (median [quartile]) | Okuma | Male | 965 [820–1056] | 6396 [6086–6675] | 631 [528–772] | 1924 [1927–2744] |
| | | Female | 175 [143–220] | 1291 [1221–1358] | 120 [74–168] | 451 [341–533] |
| | Futaba | Male | 256 [212–325] | 2557 [2334–3052] | 235 [170–316] | 1105 [838–1306] |
| | | Female | 41 [24–68] | 558 [462–628] | 22 [0–47] | 292 [229–366] |
| | Katsurao | Male | 254 [243–263] | 649 [571–749] | 254 [236–268] | 371 [330–430] |
| | | Female | 108 [98–120] | 211 [189–256] | 123 [111–140] | 158 [142–189] |
| | Namie | Male | 1763 [1685–1862] | 4055 [3807–4219] | 1491 [1363–1608] | 2219 [1982–2430] |
| | | Female | 562 [519–604] | 1210 [1129–1279] | 559 [504–611] | 809 [733–892] |
| | Naraha | Male | 2646 [2568–2738] | 4037 [3906–4400] | 2290 [2207–2388] | 2529 [2397–2722] |
| | | Female | 1431 [1409–1456] | 1784 [1751–1832] | 1434 [1386–1483] | 1539 [1483–1637] |
| | Kawauchi | Male | 1058 [1035–1074] | 1274 [1235–1326] | 996 [971–1026] | 999 [955–1048] |
| | | Female | 884 [868–896] | 862 [844–882] | 883 [866–900] | 817 [786–846] |
| | Tomioka | Male | 2257 [2086 – 241] | 4511 [4242–4870] | 1536 [1389–1687] | 1897 [1749–2084] |
| | | Female | 515 [465–603] | 1212 [1166–1260] | 471 [402–523] | 684 [632–739] |
| | Hirono | Male | 3678 [3463–3835] | 5662 [5331–6003] | 4196 [4023–4363] | 4232 [3972–4455] |
| | | Female | 2147 [2043–2210] | 2193 [2140–2269] | 2075 [1993–2143] | 1936 [1861–2005] |
| Age -n (median [quartile]) | Okuma | 15-39yr† | 331 [280–379] | 2261 [2135–2376] | 215 [177–286] | 675 [533–783] |
| | | 40–69yr | 748 [625–814] | 5058 [4829–5278] | 466 [388–593] | 1544 [1205–1770] |
| | | 70 yr- | 71 [50–91] | 376 [336–415] | 58 [33–85] | 175 [129–207] |
| | Futaba | 15–39yr | 98 [73–123] | 859 [731–1119] | 85 [52–118] | 395 [274–502] |
| | | 40–69yr | 199 [150–255] | 2122 [1885–2388] | 169 [126–228] | 901 [682–1082] |
| | | 70 yr- | 22 [12–30] | 164 [143–198] | 21 [14–40] | 96 [68–127] |
| | Katsurao | 15–39yr | 54 [44–65] | 174 [145–198] | 58 [46–72] | 96 [81–121] |
| | | 40–69yr | 200 [185–211] | 557 [500–655] | 207 [191–220] | 315 [281–374] |
| | | 70 yr- | 106 [99–122] | 125 [112–144] | 112 [102–123] | 115 [103–131] |
| | Namie | 15–39yr | 428 [383–467] | 1230 [1146–1302] | 357 [300–415] | 602 [526–701] |
| | | 40–69yr | 1527 [1443–1647] | 3388 [3211–3562] | 1288 [1212–1400] | 1928 [1731–2120] |
| | | 70 yr- | 366 [336–390] | 609 [555–663] | 379 [361–416] | 479 [425–527] |
| | Naraha | 15–39yr | 779 [747–812] | 1346 [1287–1449] | 709 [678–749] | 820 [762–896] |
| | | 40–69yr | 2314 [2225–2382] | 3435 [3315–3753] | 2038 [1972–2101] | 2257 [2154–2401] |
| | | 70 yr- | 985 [961–1015] | 1032 [1001–1064] | 981 [956–1015] | 999 [953–1031] |
| | Kawauchi | 15–39yr | 306 [292–323] | 381 [358–406] | 290 [270–308] | 285 [264–312] |
| | | 40–69yr | 947 [925–980] | 1112 [1089–1145] | 910 [888–942] | 902 [853–946] |
| | | 70 yr- | 697 [663–709] | 651 [618–676] | 686 [653–701] | 632 [599–664] |
| | Tomioka | 15–39yr | 667 [593–738] | 1574 [1471–1667] | 464 [418–502] | 627 [578–686] |
| | | 40–69yr | 1847 [1703–1995] | 3657 [3477–3947] | 1280 [1138–1423] | 1648 [1501–1789] |
| | | 70 yr- | 273 [218–321] | 448 [422–492] | 258 [218–305] | 335 [299–370] |
| | Hirono | 15–39yr | 1496 [1322–1585] | 2382 [1827–2909] | 1279 [1150–1382] | 1301 [1181–1404] |
| | | 40–69yr | 3230 [3051–3406] | 2254 [1904–3017] | 2790 [2641–2932] | 2614 [2453–2735] |
| | | 70 yr- | 1072 [1031–1098] | 1470 [908–2112] | 1062 [1017–1081] | 1011 [971–1053] |

**Table 1**. Estimated population in eight towns and villages. *Quartile; interquartile range, Q1 to Q3. † *yr* year.

of 40–69-year-olds increased more during the nighttime than during the daytime, while in all other regions, the daytime population of this age group was higher than that at nighttime. Similarly, during weekends, Kawauchi Village and Hirono Town had greater increases in the nighttime population of 40–69-year-olds compared with daytime, whereas in all other areas, the daytime population of this age group increased more than the nighttime population.

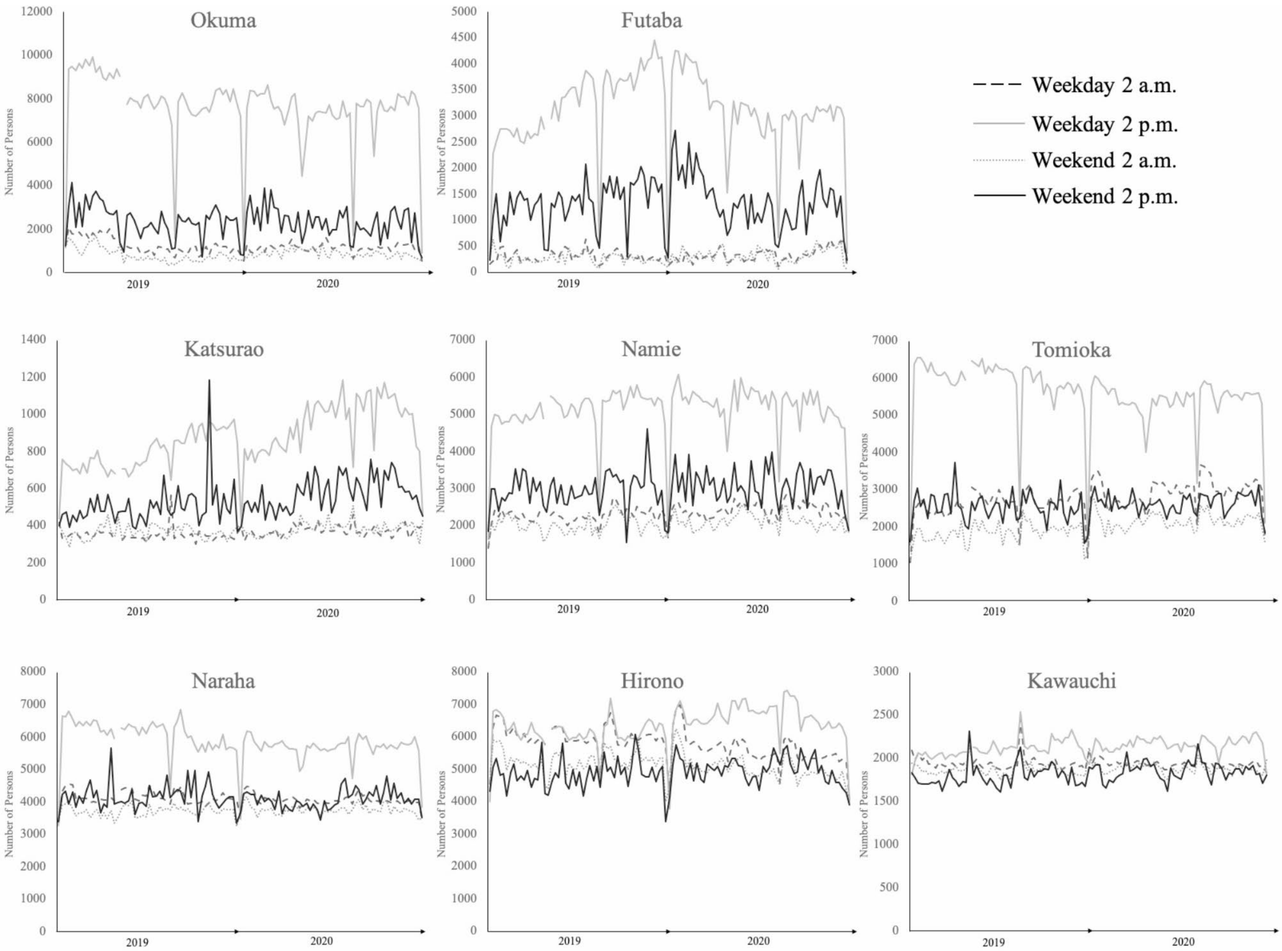


**Fig. 2**. The estimated population trend by day/night and weekday/weekend over the two years. It represents the average number of people in each category per week from 2019 to 2020. The thick line represents the population at 2 p.m. on weekends, the fine wavy line represents the population at 2 a.m. on weekends, the dashed line represents the population at 2 a.m. on weekdays, and the thin line represents the population at 2 p.m. on weekdays.

| | Population ratio day/night (median [quartile]) | |
|---|---|---|
| **Area** | **Weekday** | **Weekend** |
| Okuma | 6.9 [6.1–8.3] | 3.1 [2.4-4.0] |
| Futaba | 11.9 [8.8–14.3] | 5.4 [3.8–6.9] |
| Katsurao | 2.4 [2.1–2.7] | 1.4 [1.3–1.6] |
| Namie | 2.3 [2.1–2.3] | 1.5 [1.3–1.6] |
| Tomioka | 2.0 [1.8–2.2] | 1.3 [1.2–1.4] |
| Naraha | 1.4 [1.4–1.5] | 1.1 [1.0-1.1] |
| Hirono | 1.1 [1.0–1.2] | 0.9 [0.9–1.0] |
| Kawauchi | 1.1 [1.1–1.1] | 1.0 [0.9-1.0] |

**Table 2**. Ratios of daytime and nighttime populations in the eight towns and villages.

*Ratio of day and nighttime population*

Table 2 and Supplementary Fig. 1 present the median ratio of day/night population by municipality for each year. In Okuma Town and Futaba Town, the daytime population was substantially larger than the nighttime population throughout the two years, with the median day/night population ratio being more than three for both weekdays and weekends. In Katsurao Village, Namie Town, and Tomioka Town, the daytime population exceeded the nighttime population to a moderate extent, with the weekday day/night population ratio more than

| Variable | | 2019 | | 2020 | | Total | |
|---|---|---|---|---|---|---|---|
| Number of people-n | | 1056 | | 1008 | | 2064 | |
| Sex-n (%) | Female | 382 | (36) | 314 | (31) | 696 | (34) |
| | Male | 674 | (64) | 694 | (69) | 1368 | (66) |
| Day-n (%) | Weekend | 239 | (23) | 245 | (24) | 484 | (23) |
| | Weekday | 817 | (77) | 763 | (76) | 1580 | (77) |
| Age-n (%) | 15–59yr† | 441 | (42) | 398 | (39) | 839 | (41) |
| | 60 yr-† | 615 | (58) | 610 | (61) | 1225 | (59) |

**Table 3**. Breakdown of emergency transportation in the eight towns and villages in 2019 and 2020. † yr; year.

| | National† | Hirono | Naraha | Tomioka | Kawauchi | Okuma・Futaba | Katsurao・Namie |
|---|---|---|---|---|---|---|---|
| Crude prevalence, % | 4.51 | 3.63 | 5.21 | 5.19 | 7.47 | 2.16 | 3.48 |
| Estimated population-based age-adjusted prevalence (95% CI), %†† | - | 3.77 (3.25–4.28) | 5.05 (4.37–5.73) | 6.41 (5.28–7.54) | 6.42 (5.32–7.53) | 2.08 (1.19–2.98) | 3.43 (2.74–4.11) |
| National population census-based age-adjusted prevalence (95% CI), % *†† | 4.58 (4.57–4.58) | 4.37 (3.78–4.96) | 6.41 (5.58–7.23) | 8.29 (6.97–9.6) | 6.77 (5.59–7.95) | 10.45 (7.11–13.8) | 6.36 (5.21–7.51) |
| Δ Age-adjusted prevalence (95% CI), %** | – | −0.60 (−1.38–0.18) | −1.36 (−2.43–−0.28) | −1.88 (−3.6–−0.15) | −0.35 (−1.96–1.27) | −8.37 (−11.84–−4.91) | −2.93 (−4.27–−1.60) |

**Table 4**. Age-adjusted prevalence of emergency transport cases. Confidence interval (*CI*). †Age-adjusted prevalence of emergency transport cases in Japan was calculated based on the 2020 national emergency transport data. †† Age adjustment was performed using the 2015 model in Japan. * Based on 2020 National Population Census data. ** Difference in age adjusted prevalence between the estimated population-based prevalence and census-based prevalence.

doubling. In Naraha Town, Hirono Town, and Kawauchi Village, the daytime and nighttime populations were similar, with median day/night population ratios ranging between 0.9 and 1.4 times.

## The difference between the estimated population with and without census correction

Supplementary Table 3 illustrates the population estimates based solely on population data from municipalities. The estimates derived from municipal population data without Census corrections generally indicate smaller median population figures on both weekdays and weekends compared to those derived with census corrections. Compared to the estimates with census corrections, Okuma Town's estimated population was 10% smaller at 2 a.m. on weekdays; Namie Town demonstrated a 19% smaller population for weekdays at 2 a.m., 17% smaller for weekends at 2 a.m., and 10% smaller for weekends at 2 p.m.. In Tomioka Town, on the weekends at 2 p.m., the population was also 11% smaller. Hirono Town exhibited the most significant disparities, with a decrease of 22% in the weekdays at 2 a.m. population, 13% in the weekdays at 2 p.m. population, 22% in the weekend at 2 a.m. population, and 16% in the weekend at 2 p.m. population. Supplementary Table 4 presents population estimates based solely on population data from Basic Resident Resister. Overall, these estimates were higher across all municipalities and time periods compared to those incorporating population information from municipalities. The discrepancy was particularly marked in Namie and Tomioka town, with the median estimated population exceeded 10,000 individuals at both 2 a.m. and 2 p.m. on weekdays.

## Differences in the incidence ratio of emergency transports using estimated population and census data

Table 3 illustrates the breakdown of the number of ETs in Futaba County; 2,064 ETs occurred over two years. The number of ETs was 1056 in 2019 and 1008 in 2020. By age, 839 cases were reported by those aged 15–59, and 1,225 cases were reported by those aged 60 years or older, accounting for 60% of the cases. The percentage of each of these attributes changed insignificantly over the two years.

Table 4 displays the age-adjusted transport rates derived from ET numbers and estimated populations. Kawauchi Village reported the highest rate at 6.42% (95% CI 5.32–7.53), closely followed by Tomioka Town at 6.41% (95% CI 5.28–7.54), Naraha Town at 5.05% (95% CI 4.37–5.73), Hirono Town at 3.77% (95% CI 3.25–4.28), Katsurao Village and Namie Town at 3.43% (95% CI 2.74–4.11), and Okuma Town and Futaba Town at the lowest rate of 2.08% (95% CI 1.19–2.98). Rates calculated from population estimates were lower across all regions compared with those based on census data, with the largest discrepancy observed in Okuma Town and Futaba Town, where the estimated rate was 8.37% lower (95% CI 4.91–11.84) than the census-based rate. The national ET incidence rate was 4.58% (95% CI 4.57–4.58).

## Discussion

We estimated the population distributions by day/night and weekday/weekend in Futaba County following the nuclear power plant accident, where precise demographic data were not readily available. Our findings revealed significant variations in the day/night population ratios across the area: some municipalities experienced minimal changes between day and night populations, others saw the daytime population double that of nighttime, while others observed a substantial increase, with daytime populations more than tripling compared with nighttime populations. The extent of these day/night population ratios was notably higher in areas where evacuation orders were lifted later. Additionally, calculating the incidence rate of ET using population estimates yielded a lower incidence rate than relying solely on census data, aligning more closely with the national average for Japan. Employing population estimates that consider temporal changes may offer a more accurate reflection of the population in areas with diverse demographics, thereby enhancing the prediction of medical care demands.

This study highlights the variance in the daytime-to-nighttime population ratios across different areas, underscoring the unique population dynamics in the regions affected by the nuclear disaster. Typically, urban areas exhibit larger daytime populations owing to work-related commuting, leading to smaller nighttime populations. Conversely, bedroom communities tend to have larger night-time populations as residents return from work in urban centers, resulting in smaller daytime populations. The changes observed in our target areas were similar to these patterns, with all areas demonstrating a larger daytime population, indicating a small, settled population and a significant influx of people from outside the region. Notably, the daytime-to-nighttime population ratio was exceptionally high in Okuma Town and Futaba Town, where the FDNPS is located. These areas experienced severe contamination and were designated as difficult-to-return zones for an extended period post-disaster, with restrictions on residence lifted only eight or nine years later, albeit in a limited area. The daytime population ratios in these towns during weekdays are comparable to those in Tokyo's Chiyoda Ward (17.3 times) and Chuo Ward (4.9 times), known for having Japan's highest day/night population ratios[34]. Areas where the evacuation order was lifted late, and the return or migration has not progressed have a smaller nighttime population because there is a smaller permanent population. The day/night population ratio is considered higher because of the large influx of people engaged in decommissioning work at the FDNPS, interim storage facilities, and decontamination work during the daytime.

The areas that have not allowed the residents to return or migrate to the area in this study have a large working population in the 40–69 age group, and the population is extremely low on weekends. Interestingly, there were periodic decreases in the daytime population, particularly in Okuma, Futaba, and Namie towns, which may reflect the customary vacations in August and at year-end in Japan, when work is often closed. In addition to decontamination work and other nuclear-related projects, these areas are thought to have increased their daytime working population through various industries, including civil engineering projects such as road construction and maintenance and the construction of thermal power plants[35]. These areas also allow overnight stays in permitted release areas; however, the lack of many lodging facilities also contributes to the high day/night population ratio. In contrast, municipalities relatively far from the FDNPS, where the abolition of evacuation orders occurred six months to five years after the accident, have a relatively low day/night population ratio. In areas where the evacuation was lifted relatively early, residents were returning or migrating, more people were working in the area, and daytime and nighttime populations were likely to be stable. The target area had a high rate of aging, even before the earthquake, and many of the returnees were elderly and stayed in the area throughout the day. Therefore, demographics and day/night population ratios may indicate the proportion of true permanent residents and differences in the industrial structure of the area. This study reveals that demographic differences exist, especially in areas that are strongly affected by earthquakes. This underscores the importance of using population estimates to discern regional characteristics, industry differences, and the extent of reconstruction in areas where post-disaster demographic data are difficult to obtain. Further analysis of the reasons why the actual day/night population ratios vary so widely from region to region would require more detailed analysis by obtaining more multidimensional population data.

This study underscores the potential of dynamic population estimates using mobile phone network, such as those employed in this study, in accurately determining medical care demand. The age–sex-adjusted ET occurrence rates using population estimates in this study were closer to the national average in most areas than those calculated based on census-based populations. Notably, in Okuma Town, Futaba Town, Katsurao Village, and Namie Town, which are characterized by smaller nighttime populations, the ET occurrence rate tended to be higher when calculated based on the census population. This discrepancy could stem from the census underestimating the actual population in these areas, particularly during the day. ET occurrences were more accurately tied to the hourly population presence in an area. The study reveals that, during the day, 1.5 to 11.3 times more people are present in these areas than at night, representing transient populations not captured by the census. Failure to account for these individuals, who may require ET owing to injury or illness, would inherently skew the ET rate upward when based solely on census figures. Therefore, calculating ET rates using dynamic population estimates, which can discern fluctuating daytime and nighttime, weekday, and weekend populations, offers a more accurate reflection of reality.

These findings indicate that ET rates were notably high in Naraha Town, Tomioka Town, and Kawauchi Village, which are characterized by smaller variations between daytime and night-time populations and earlier evacuation lifts. Particularly, Naraha Town and Kawauchi Village have reported high returnee rates, between 60% and 80% of the pre-disaster population[36]. Correspondingly, the Futaba Medical Center, the primary healthcare facility in Futaba County, observed a higher number of ETs from Naraha Town, Tomioka Town, and Hirono Town in 2019 and 2020[37]. This suggests that areas with a significant number of returnees, where residents are resuming their pre-disaster lifestyles, can anticipate a high demand for ETs[38]. These data imply that ET needs may be greater in regions where recovery is more advanced and residency rates are increasing. Despite adjustments for sex and age, the study found that ET rates were slightly higher than the Japanese average. Particularly after the earthquake, the loss of medical resources in these areas could have hindered access to nearby medical facilities[39,40], potentially leading to an increase in ET rates. Additionally, residents in these areas may not have been able to receive appropriate medical care, which may have exacerbated chronic diseases.

Lifestyle-related diseases are worsening among nuclear power plant workers[35], and the Futaba Medical Center has reported an increase in emergency room visits owing to diabetes[37]. Because the rate of emergency room visits per population can serve as an indicator of the health of residents in an area and of medical resources, it is necessary to accurately predict and evaluate this rate.

Futaba Town and Okuma Town, which have high day/night population ratios, reported lower ET rates than the national average. The predominant demographics in these municipalities include nuclear power stations and reconstruction workers, who are largely young men aged 40–69. This group represents a particularly healthy segment of the working population, which may explain the lower ET rates observed. However, as this study revealed, the absolute number of people staying during the day is 6.9 to 11.9 times greater than that during the night; therefore, diseases arising from this fluid population should be considered. Diseases associated with work-related trauma and recovery processes require particular attention[41,42]. It is also expected that as reconstruction progresses in these areas, the resident population will increase, in which case, the incidence of emergency medical care will also increase. Therefore, continuous assessment of the population is necessary.

This study is unique in that it uses population estimates based on spatial statistics for events, such as a distinct disaster, where it is difficult to determine the resident population. In urban areas, where there is significant interaction between regions, population estimates based on spatial statistics are used to estimate the need for medical care, housing, and other services. Previous studies have often used estimates based on GPS data[43] or alternative indicators such as the number of train users. This study, however, uses estimates based on communications between cell phones and base stations rather than GPS data. This provides a more reliable population estimate than the GPS. This method is particularly useful during times of crisis when the estimated population itself is ambiguous, as was the case in this study. Applying a similar method could be invaluable for managing disasters that necessitate widespread evacuation and reintegration, as well as post-conflict and post-war reconstruction efforts. However, gathering detailed data for population estimates in such contexts can be challenging. In this study, we collected data crucial for estimating regional populations in collaboration with local governments. This dynamic population estimation would not have been feasible without access to such data that closely reflects the actual population. Indeed, as shown in Supplementary Table 2, estimations based solely on Basic Resident Register yielded implausibly high population figures. For instance, in Namie and Tomioka Town, where approximately 2,000 returnees resided[36], the estimated nighttime population was more than five times this figure. Even accounting for temporary inflows from outside the area, this estimate likely significantly overstates the actual resident population. This underscores the importance of local authorities in maintaining a comprehensive understanding of resident demographics as a preparatory measure for disaster response, highlighting the critical role of innovative population estimate methods in disaster readiness and recovery planning.

### Future implications

This study further underscores the importance of understanding demographics when observing an area during the recovery period after a major disaster. This highlights the necessity of comprehensively grasping not only the static population figures within a community but also dynamic aspects such as population fluctuations, age distribution, and male-to-female ratios throughout the day. This depth of demographic insight is pivotal not only for assessing immediate needs, such as ET demands but also for planning long-term requirements for medical resources and urban development. Additionally, as this study illustrates, it is important to continue estimating the current and future status of the population over time, especially during the recovery period, because demographics change rapidly over time.

### Limitations

This study has several limitations inherent to the population estimation method employed. Primarily, the estimated population is just that, an estimate with the potential for deviation from actual figures. Converting data from base station areas to mesh grids introduces errors owing to discrepancies when allocating population figures to administrative boundaries and mesh areas, ranging from a few hundred meters to several kilometers. Furthermore, when the absolute population numbers in the observed area are small, the figures may be omitted or rounded off as a confidentiality measure, thereby affecting the accuracy of the estimates. Additionally, the younger and older generations may be prone to errors. This is because the sampling rate is lower for those aged 14 years and younger and those aged 75 years and older who have fewer subscriptions to cell phone companies. It is necessary to consider errors owing to the characteristics of these population estimation techniques. There can also be errors that must be considered owing to the characteristics and habits of people and firms. If an individual has multiple cellphone subscriptions, it is possible to estimate a larger population. Users of handsets that are habitually turned off may not be counted at the place where they stay for the time they are turned off, which may result in a lower population estimate. The population of returnees collected from each municipality used for statistical processing was expected to have some errors because the collection method was not uniform and was based on the definitions of each municipality. Despite these methodological constraints, the approach used in this study is considered the most accurate method currently available for estimating populations, especially in scenarios involving disaster recovery where traditional methods may fall short.

## Conclusions

Population estimates based on spatial statistics demonstrated that the population of Futaba County had a large day/night population ratio, which was more pronounced in areas where the lifting of evacuation orders was slower. The use of population estimates allowed for a more accurate calculation of the incidence of ET cases in Futaba County. Understanding not only the population at a fixed point in the region but also the population, age structure, and male-to-female ratio by time of day is important in the affected areas during the reconstruction period to efficiently prepare for the demand for medical care, including the demand for ET.

## Data availability

The data that support the findings of this study are available from the corresponding author, A.H., upon reasonable request.

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Conceptualization, A.H and M.M., M.T.,Methodology, A.H, M.M., Formal analysis, H.Y.,Resources, C.Y., T.O., T.S., Y.S., A.O.,Writing—original draft preparation, A.H.Writing—review and editing, H.S., T.A., T.Z., I.A., N.I., C.Y., S.N., T.S., Y.S., A.O., T.O.,Visualization, A.H.Supervision, M.M., M.T.Project administration, M.T.Funding acquisition, M.T. All authors have read and agreed to the published version of the manuscript.


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## Declarations

## Competing interests
The authors declare no competing interests.

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