Elsevier has created a Monkeypox Information Center in response to the declared public health emergency of international concern, with free information in English on the monkeypox virus. The Monkeypox Information Center is hosted on Elsevier Connect, the company's public news and information website.

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Projecting the global spread of the 2022 monkeypox outbreak considering population mobility

Dear Editor,

Since the first discovery of monkeypox virus (MPXV) in 1970, outbreaks periodically occur in Africa and it has become endemic in West and Central Africa. Since then, only sporadic cases have been occasionally reported in America, Europe and Asia, but all these cases can be traced back to African origins, mostly attributed to travel history to endemic regions [1]. Unexpectedly, the globe is currently facing widespread monkeypox outbreaks across many non-endemic countries. It was sparked in the United Kingdom in May 2022, but rapidly spread to several European and American countries. At the time of the writing, Europe and the United States have emerged as the main epicenters of the current outbreak. The World Health Organization (WHO) has declared it as a Public Health Emergency of International Concern (PHEIC) on 23 July [2]. We recognize that both the epidemic growth and population mobility essentially contribute to the transnational and transcontinental spread. Here, we aim to estimate the transmission dynamics and project the further cross-border spread of monkeypox.

We constructed a multi-regional epidemic dynamical model adopting key parameters related to the current monkeypox outbreak (**Supplementary Fig. S1**). Furthermore, this model considers the impact of international travel on monkeypox spread by incorporating large-scale population flow data (**Supplementary Methods; Table S1**). The reproduction number R_t is a hallmark of the transmission dynamics, representing the average number of secondary infections generated by per infected case. An R value of 1 means that the total number of infections is stable, whereas If R is greater than 1 the epidemic is growing. The larger the value of the reproduction number, the harder it is to control the epidemic. However, R_t can vary subjected to interventions and social contact patterns. We estimated the time-varying R_t values using the R package EpiEstim [3]. We observed a gradual reduction of Rt values from 1.57 in the beginning of June to 1.19 in the middle of August (**Fig. 1A**). Thus, we have incorporated the value of 1.19 (95%CI 1.16–1.22) into our mathematical model for projection.

We first collected international travel flow data of 166 countries outside Africa from the international civil aviation organization (ICAO), where the statistics for air passenger arrivals and departures were recorded. We then integrated these data with the datasets of international arrivals to each country obtained from the World Bank to construct the travel flow network (**Supplementary Methods; Table S1**). By the time of simulation (15 August 2022), 79 countries outside Africa have reported monkeypox cases. We project that monkeypox will reach additional 37 non-endemic countries outside Africa by the end of 2022 (**Fig. 1B**). Thus, in total of 116 countries outside Africa are expected to have monkeypox by the end of this year. The time of the first case introduced into each non-endemic country is corrected to the scale and the pattern of international population flow (**Fig. 1B; Table S1**). For example, in Eastern Mediterranean region, Iran having 8.1 million international arrivals per year is expected to have the first case on 01 November, and Pakistan with 6.9 million international arrivals is expect to import the first case on 16 December. However, in South East Asia region, Viet Nam with 33.7 million arrivals is expect to import the first case on 24 December.

Assuming the reproduction number maintaining as it is in the middle of August, the total number of infections outside Africa would reach nearly 0.2 million by the end of 2022. At regional level, there would be 61.8 (95%CI 59.6–64.3) thousand in Europe, 133.1 (95%CI 127.3–139.4) thousand in America, and 724.5 (95%CI 682.4–769.6) in Western Pacific and Southeast Asia. At national level, there would be 107.2 (95%CI 102.6–112.2) thousand in United States, 15.2 (95%CI 14.6–15.8) thousand in Spain, and 5.8 (95%CI 5.6–5.9) thousand in the United Kingdom (**Fig. 1C**).

The spread of infectious diseases is orchestrated by multiple factors including biological, behavioral, and environmental parameters. Current emphasis mainly focuses on static biological parameters, but factors such as population movement are largely neglected [4]. Mathematical models are valuable tools for understanding epidemic spread and growth, and informing the design, monitoring, and assessment of interventions [5]. In our previous study, we developed a multi-regional, hierarchical-tier mathematical model to recapitulate the early spread of COVID-19 in China. By incorporating the large population flow network data, we were able to reveal insight into how COVID-19 was spread from the epicenter Wuhan to other regions in mainland China [6]. This study employed the similar approach but considers both the scale and the pattern of population mobility. We estimated the transmission dynamics and projected further cross-border spread of monkeypox by the end of 2022. Of note, there are some limitations in this study. First, the methods that were used for estimating population movement likely capture the majority but not all the international travels. Second, as it is highly challenging to predict the varying reproduction number in the coming months, we adopted the R_t value of the middle of August as a static parameter in our model. Third, we did not consider possible interventions which may be taken by some countries to intervene the importation of monkeypox cases. Nevertheless, our projection urges international cooperation to decisively deploy countermeasures for preventing the global spread of monkeypox.

Declaration of competing interest

The authors have no conflicts of interests or disclosures to declare.

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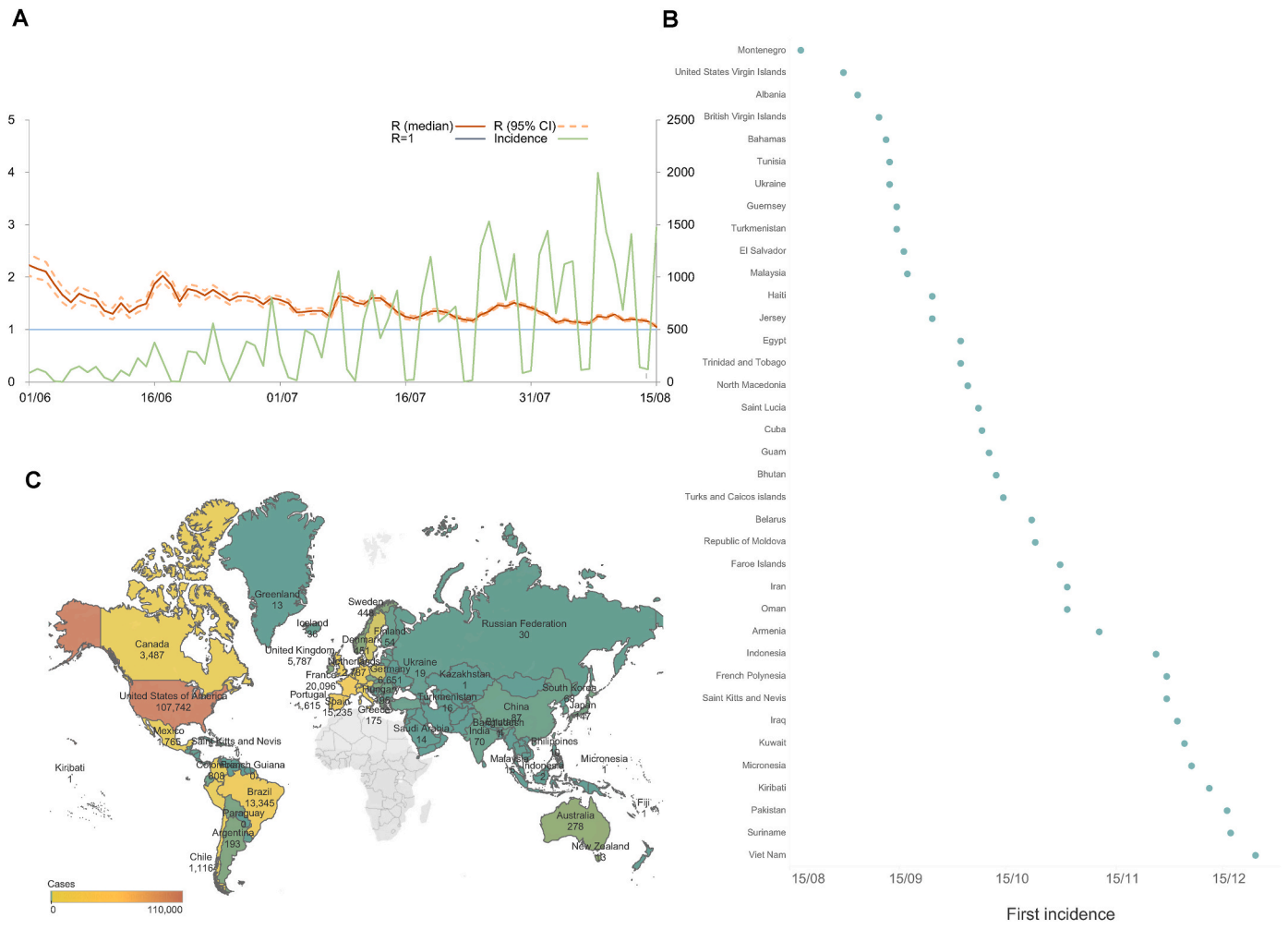

Fig. 1. Estimating the reproduction number and forecasting the global spread of monkeypox. (A) The time-varying reproduction number estimated for the 2022 monkeypox outbreak in non-epidemic countries outside Africa. Incidence curve represents the cumulative number of daily new confirmed cases across global outside Africa retrieved from an open-access database (https://github.com/globaldothealth/monkeypox). **(B)** Forecasting the timeframe of monkeypox reaching each non-epidemic country. This is predicted using an open epidemiological model incorporating international travel flow data and the estimated reproduction number in the middle of August 2022. The reproduction number is estimated as 1.19 (95%CI 1.16–1.22). The corresponding date represents the first incidence occurred in the respective country. **(C)** Visualization the probable geographical distribution of monkeypox cases across the globe outside Africa by the end of 2022.

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Nothing to disclose.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tmaid.2022.102445.

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