Appendix 2: Supplemental methods and results for
"Under-immunization during the 2025 Texas measles outbreak"

Erin N. Hulland, MPH, PhD[1,2], Marie-Laure Charpignon, MSc, PhD[1,2], Thomas Berkane, MSc[1,2], Maimuna S. Majumder, MPH, PhD[1,2]

[1] Computational Health Informatics Program, Boston Children's Hospital & Harvard Medical School, Boston, MA, United States

[2] Comp Epi Dispersed Volunteer Research Network, Boston, MA, United States

Table of Contents

Section 1: Abbreviations

MMR	Measles, Mumps, Rubella
SD	Standard Deviation
SI	Serial Interval
UI	Uncertainty Interval
VC	Vaccination Coverage
VE	Vaccine Effectiveness

Section 2: Extended Methods

Section 2.1: Sourcing data

Below, we provide an overview of the approaches used to source the data underlying our study: (1) reported measles cases, (2) information about the serial interval for measles, (3) plausible values of the basic reproduction number for measles, and (4) the range of estimates for the effectiveness of the MMR vaccine. Additionally, we compile links to useful web portals or pages and cite the relevant literature.

<u>Reported measles cases</u>

Case data among adults and children by date of report were acquired from various sources (see Table S1 below) using web search functionalities via ChatGPT (https://chatgpt.com) and Perplexity (https://www.perplexity.ai/), supplemented by manual searches. The Wayback Machine (https://web.archive.org/) provided access to archived versions of sources that were no longer available live. In addition, we manually extracted data about the geographical distribution of reported cases—both within and beyond Texas—from the following CBS News webpage (https://www.cbsnews.com/us/) on four distinct dates, when updates were made available by the Centers for Disease Control and Prevention (CDC) or the Texas Department of State Health Services (DSHS): March 3, March 6, March 7, and March 11 of 2025. Importantly, while this analysis focuses on cases reported within northwest Texas, in reality, the exposed population is not constrained within these geographical boundaries. Caution should be used when interpreting the results as they are not representative of all transmission events that may have occurred throughout the outbreak; however, our results do represent all reported cases in Texas at the time of analysis (with a last day of data on March 11, 2025). Conversely, the measles-exposed population in northwest Texas is not representative of the entire population living in northwest Texas. Moreover, only some counties have been affected by the outbreak. As such, only a portion of the population is captured in our analysis, likely resulting in lower vaccination coverage estimates than those derived when entire counties, the whole northwest region, or Texas as a whole are surveyed.

Serial interval (SI)
Plausible values for the serial interval (SI) were obtained from a review of the literature. In Table S2 below, we summarize the different literature sources and values considered. In our work, we prioritized values gleaned from recent, local analyses[1,2] and from systematic reviews.[3] Following guidance from other publications of measles, we assume that the SI follows a Gamma distribution.[2,4,5]

Basic reproduction number (R_0)
The range of plausible values considered for the basic reproduction number (R_0) was determined from several publications on measles infectivity and vaccination coverage.[1,4,6] For our primary analysis, we used the most commonly reported values. Specifically, in our main manuscript, we considered a minimum of 11 and a maximum of 18, as well as the median of this interval, i.e., 14.5.

MMR vaccine effectiveness
Lastly, we considered different data sources about the effectiveness of the measles vaccine, particularly in young children. Specifically, a meta-analysis by Di Pietrantonj et al. (2020)[7] focused on children aged 15 or younger estimated the effectiveness of the MMR vaccine in preventing confirmed measles infection to be 95% after one dose and 96% after two doses. In addition, an observational study by Franconeri et al. (2023)[8] based on French data estimated two-dose MMR vaccination effectiveness against confirmed measles infection at 99.6% (95% CI: 99.3–99.8) among children aged 2–5 years old and at 91.4% (95% CI: 85.1–95.0) among individuals aged 26–31 years old. In our study, we used a conservative estimate of 95%, in line with estimates used by existing analyses.[1,9]

Section 2.2: Delays in reporting and under-reporting

This work capitalizes on measles cases that are reported in the news and on public health websites. While we extract measles data as they are reported, early outbreak case reports are frequently an underrepresentation of the true magnitude of an outbreak due to reporting delays.[10] Current CDC guidance recommends reporting probable cases of measles even while awaiting laboratory confirmation. However, this recommendation is not always observed in practice, resulting in case reporting delays and time series that undergo revisions.[11–13] Studies have identified substantial reporting delays, contributing to onward transmission.[14,15] In this analysis, we make every effort to stay up-to-date with the current reporting, but encourage caution in interpreting our results in light of the limitations noted here. In an effort to employ the most vetted, high-quality data, we focus on the period of time after which routine, bi-weekly reporting began by the Texas DSHS: February 25, 2025 through March 11, 2025.[16]

In addition, the reporting of cases relies on linkage with the health system for diagnosis and notification to the health department. Given that the burden of this outbreak has affected mostly unvaccinated individuals,[17] and knowing that mistrust in healthcare professionals is highly correlated with vaccine hesitancy,[18] there are likely many more measles cases circulating that have not been reported and documented. As such, these results should be interpreted in light of this truth, and in reality, the situation may be more dire than our analyses suggest.

Section 2.3: Estimating vaccine coverage over time

Using the posterior estimates of the effective reproduction number (R_t), the range of considered values for R_0, and the conservative estimate of vaccine effectiveness (VE) at 95%, we employed the relationship between these three values (Equation 1) to estimate two-dose MMR coverage over the duration of the study period (VC_t).

Equation 1: $$VC_t = [1-(R_t/R_0)] / VE$$

Section 2.4: Sharing data and code scripts to facilitate replication
All analyses were conducted using R version 4.4.0.[19] Effective reproduction numbers were estimated using the EpiEstim package[5,20,21] and all figures were generated using ggplot2.[22] All compiled data, relevant codes, and supplemental analyses are available on our GitHub repository: https://github.com/ehulland/measles_TX

Section 2.5: Sensitivity analyses

While our main manuscript considered primarily two values of the serial interval (9 and 14.5 days, corresponding respectively to the minimum and maximum plausible values as compiled from the literature), we also explored a larger range of values between 6 and 21 days in this supplementary material (see Table S1). Similarly, for R_0, we investigated primarily the minimum (11), median (14.5), and maximum (18) plausible values compiled from the literature. However, in this supplement we additionally consider all values between 10 and 27 to assess the impact of our results outlying values of R_0, as identified by a systematic review and meta-analysis of measles studies conducted in the Americas.[6]

Section 3: Additional Tables

Table S1: Reported measles case data and sources

Table S1 below summarizes the multiple data sources we have used to derive the time series of reported measles cases in Texas between January and March 2025, including news media articles and updates from the Texas DSHS. All articles have been archived and shared for reproducibility; in many cases, we are archiving the web pages ourselves to preserve temporaneous information at the time of extraction. In addition to source links, we capture the date, number of new incident measles cases (i), and cumulative number of measles cases in the state (n).

Date	**New incident cases (i)**	**Cumulative number of cases (n)**	**Archived article link**	**Source**
1/17/2025	2	2	https://web.archive.org/web/20250313114915/https://www.houstonpublicmedia.org/articles/news/health-science/2025/01/17/511273/houston-measles-cases-first-seven-years/	Houston Public Media
2/5/2025	4	6	https://web.archive.org/web/20250214070833/https://www.dshs.texas.gov/news-alerts/health-alert-measles-outbreak-gaines-county-texas	Texas DSHS

2/7/2025	4	10	https://web.archive.org/web/20250208180824/https://www.dshs.texas.gov/news-alerts/measles-outbreak	Texas DSHS
2/11/2025	18	24	https://web.archive.org/web/20250214070128/https://www.dshs.texas.gov/news-alerts/measles-outbreak	Texas DSHS
2/14/2025	24	48	https://web.archive.org/web/20250217142137/https://www.dshs.texas.gov/news-alerts/measles-outbreak-feb-14-2025	Texas DSHS
2/18/2025	10	58	https://web.archive.org/web/20250313115233/https://www.fox4news.com/news/texas-measles-outbreak-2025-58-cases-across-5-counties-3-weeks	Fox 4 News
2/21/2025	32	90	https://web.archive.org/web/20250222114914/https://www.dshs.texas.gov/news-alerts/measles-outbreak-feb-21-2025	Texas DSHS
2/25/2025	34	124	https://web.archive.org/web/20250313115835/https://spectrumlocalnews.com/tx/austin/news/2025/02/25/measles-cases-in-texas-rise-to-124-as-disease-continues-to-spread	Spectrum Local News
2/28/2025	22	146	https://web.archive.org/web/20250228204402/https://www.dshs.texas.gov/news-alerts/measles-outbreak-feb-28-2025	Texas DSHS
3/3/2025	12	158	https://web.archive.org/web/20250313121346/https://www.fox4news.com/news/texas-measles-outbreak-2025-update-march-3	Fox 4 News
3/4/2025	1	159	https://web.archive.org/web/20250313121950/https://www.reuters.com/business/healthcare-pharmaceuticals/measles-cases-rise-159-texas-state-health-department-says-2025-03-04/	Reuters
3/7/2025	39	198	https://web.archive.org/web/20250308223919/https://www.kxxv.com/news/texas-news/west-texas-measles-cases-rise-to-198-here-is-what-you-need-to-know	KXXV News Texas
3/11/2025	25	223	https://web.archive.org/web/20250313122154/https://www.reuters.com/business/healthcare-pharmaceuticals/measles-cases-rise-223-texas-state-health-department-says-2025-03-11/	Reuters

Table S2: Sources of data for parameterizing the measles SI

Table S2 below summarizes the different studies we used to determine a range of plausible values for the serial interval (SI) associated with measles infection. In addition to the source, we indicate the SI range and the mean value, along with the corresponding standard deviation (SD), where available.

Range	**Mean (SD)**	**Source**
10-14 days	-	Majumder et. al. (2015)[1]
7-21 days	14.5 (3.25)	Worden et. al. (2020)[2]
9-13 days	11.7	Vink et. al. (2014)[3]
-	11.1 - 12.2 (2.47 - 3.26)	Klinkenberg, D. & Nishiura, H. (2011)[23]
6-18 days	11.1 (2.47)	Martoma et. al. (2023)[4]

Table S3: Estimated values of the effective reproduction number R_t, MMR vaccination VC_t, and MMR vaccination coverage gap for six primary scenarios, March 11, 2025

Table S3 below summarizes the estimated effective reproduction number R_t, MMR vaccination coverage VC_t, and gap in MMR vaccination coverage (relative to the median herd immunity threshold of 93%), for three distinct values of the basic reproduction number R_0 (i.e., 11, 14.5, and 18 – corresponding to the minimum, maximum, and median of estimates previously reported in the literature, respectively) and two distinct values of the serial interval or SI (i.e., 9 and 14.5), resulting in six plausible scenarios. Median estimates are provided, along with the corresponding 95% uncertainty interval (UI).

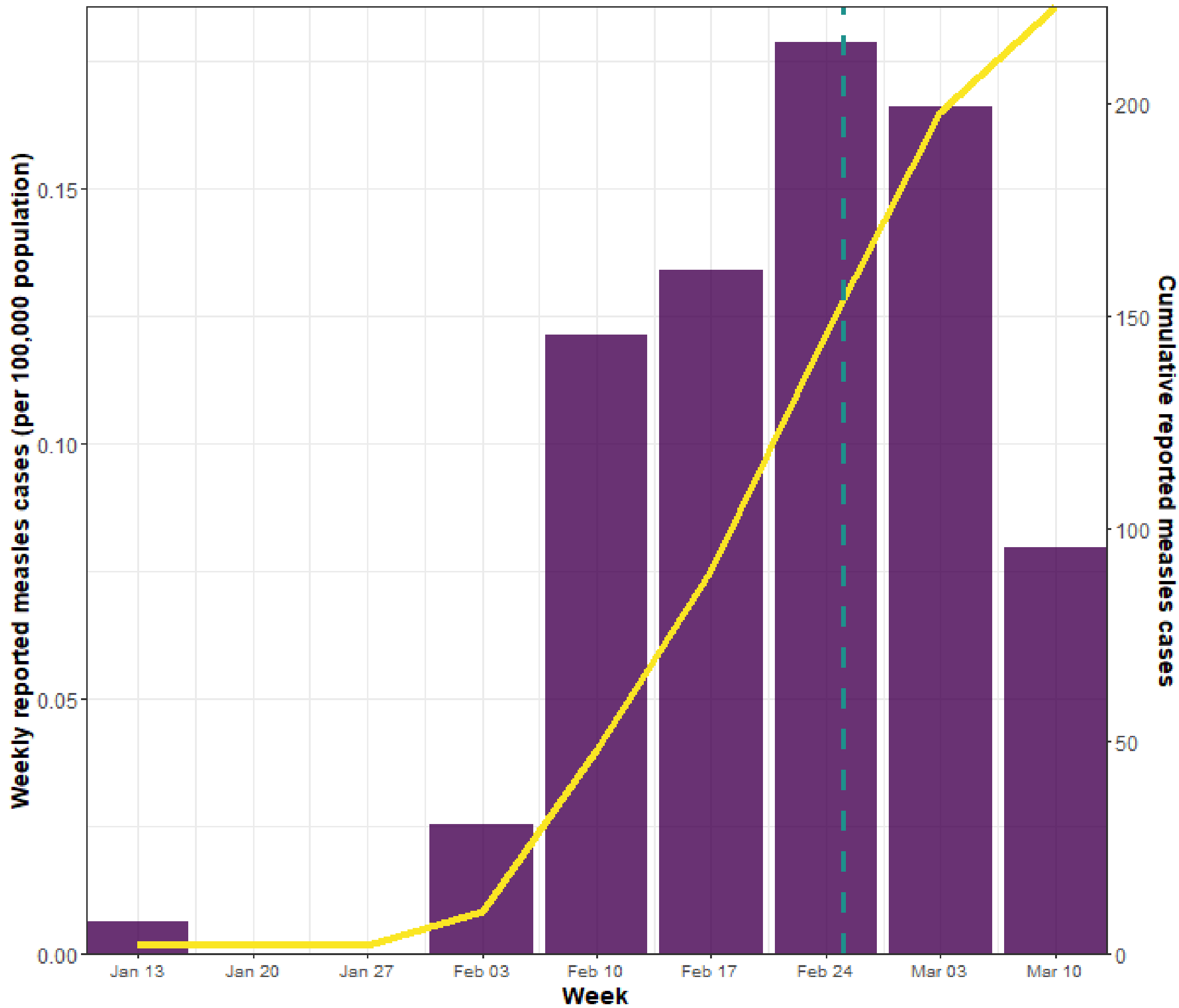
Vaccination Coverage for most recent R(t) values by Serial Interval and R(0)

Using a prior R(0) value 14.5 (SD = 1.5) and vaccine efficacy estimated at 95%

R(0)	Estimated Median R(t)	95% UI R(t)	Estimated Median Vaccination Coverage	95% UI Vaccination Coverage	Median gap in coverage to reach 93%	95% UI gap in coverage
SI 9						
11.0	2.7	2.3 - 3.2	79.2	75.0 - 83.1	13.8	9.9 - 18.0
14.5	2.7	2.3 - 3.2	85.5	82.3 - 88.4	7.5	4.6 - 10.7
18.0	2.7	2.3 - 3.2	89.4	86.7 - 91.7	3.6	1.3 - 6.3
SI 14.5						
11.0	2.7	2.3 - 3.1	79.6	75.4 - 83.4	13.4	9.6 - 17.6
14.5	2.7	2.3 - 3.1	85.8	82.6 - 88.7	7.2	4.3 - 10.4
18.0	2.7	2.3 - 3.1	89.6	87.0 - 91.9	3.4	1.1 - 6.0

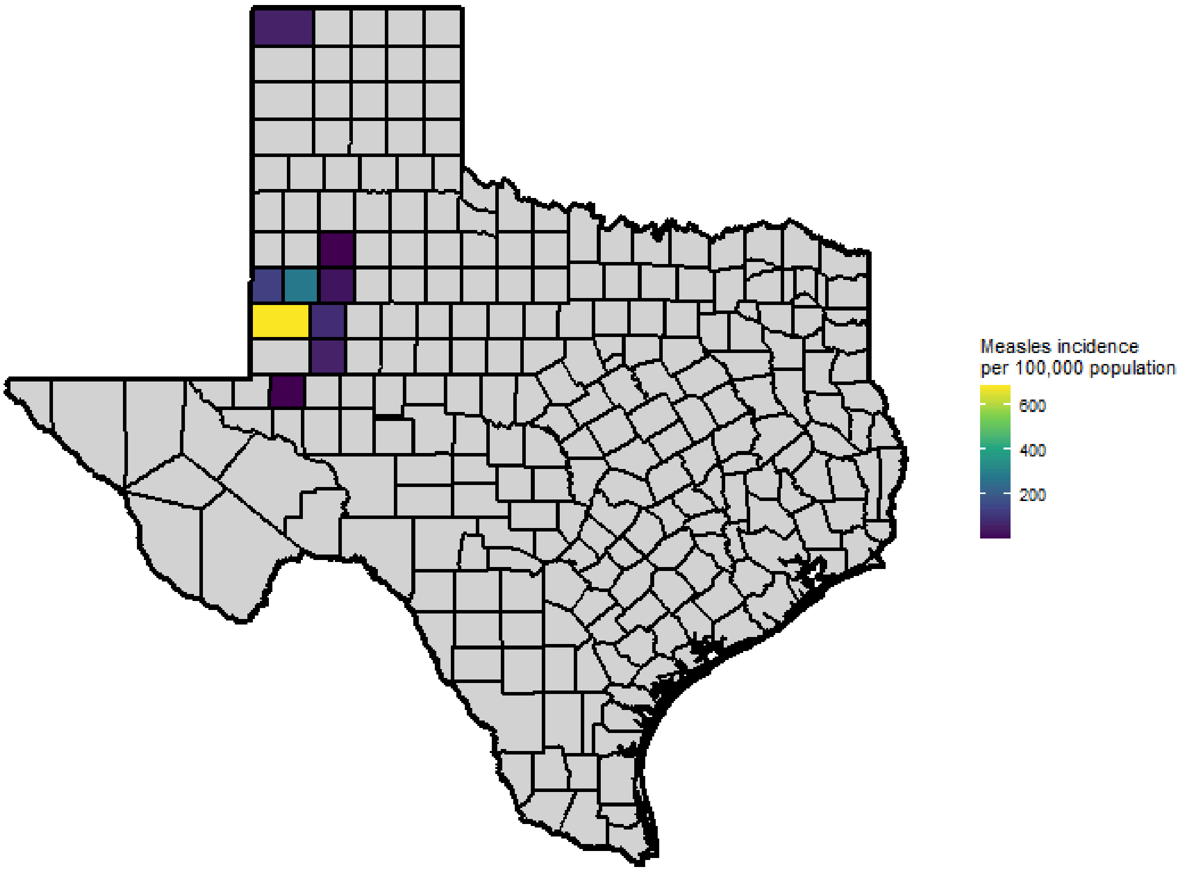
Section 4: Additional Figures

Figure S1: Weekly incident and cumulative reported measles cases, January to March 2025



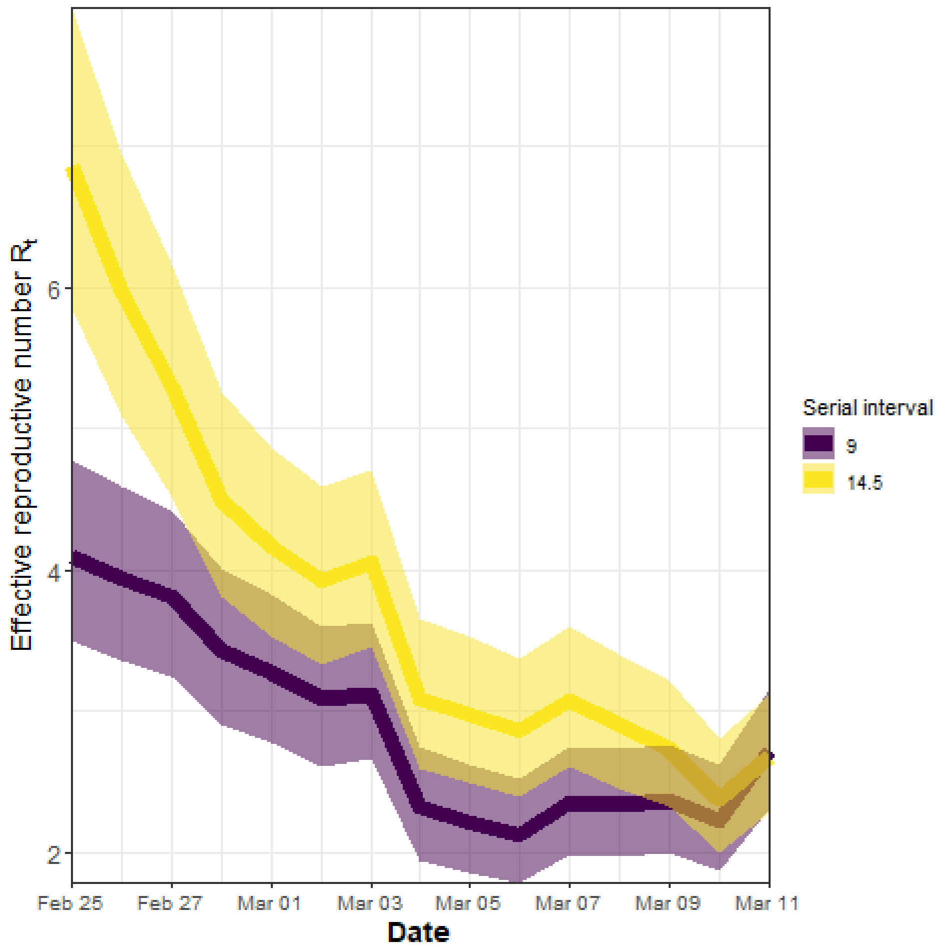
Weekly reported measles cases between January 17 and March 11, 2025 in northwest Texas, as derived from multiple internet sources (see Table S1); all weeks begin on Monday. Purple bars represent weekly incident measles cases per 100,000 population using 2024 population estimates for the state of Texas,[24] while the yellow line represents cumulative cases since the start of the outbreak on January 17, 2025. The teal dashed line represents the date on which routine, bi-weekly reporting began: February 25, 2025; prior to this date, reports were less frequent and not routine.

Figure S2: Measles incidence by Texas county, March 11, 2025



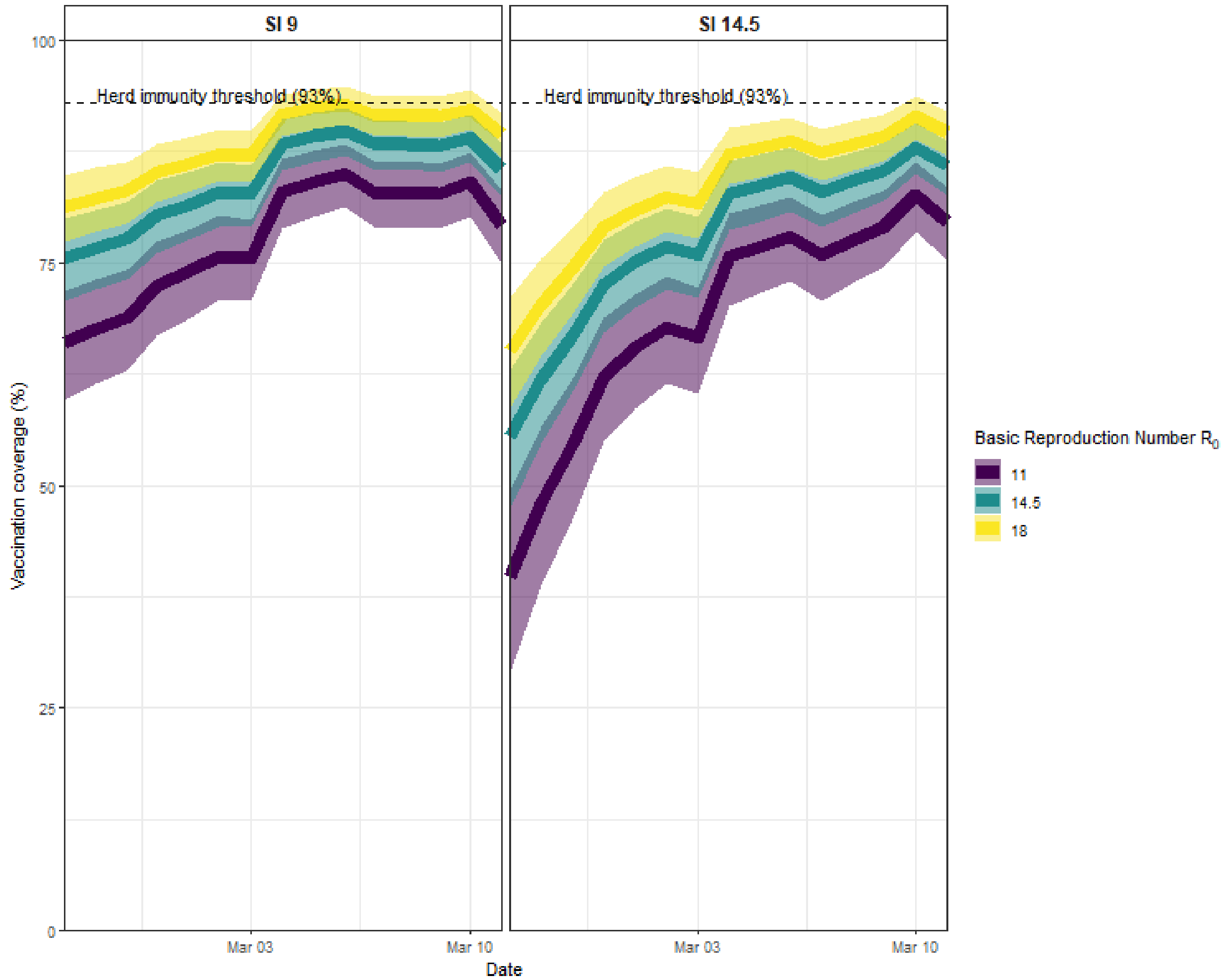
Measles incidence per 100,000 population on March 11, 2025. Counties in grey are those without any reported measles cases as of March 11. 2024 population estimates taken from Census.gov.[24] Texas county shapefile from the Texas Department of Transportation (https://gis-txdot.opendata.arcgis.com/datasets/TXDOT::texas-county-boundaries-detailed/explore?location=30.775999%2C-100.049436%2C5.55).

Figure S3: Median (95% UI) R_t values for SI 9 and 14.5



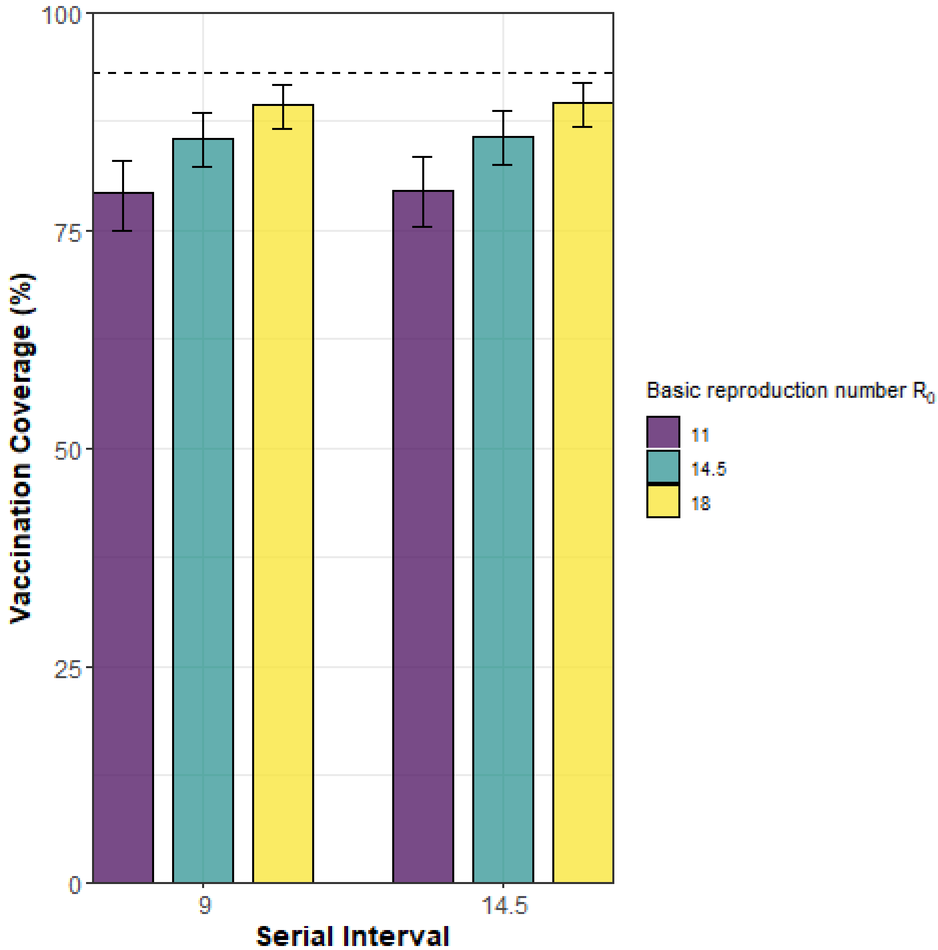
Estimated effective reproduction number R_t over time (February 25 to March 11, 2025). Median estimates are provided, along with the corresponding 95% uncertainty interval (UI).

Figure S4: Estimates of the median (95% UI) MMR vaccination coverage by R_0 values for SI 9 and 14.5



Estimated MMR vaccination coverage over time (February 25 to March 11, 2025). Median estimates are provided, along with the corresponding 95% uncertainty interval (UI). Three distinct values of the basic reproduction number R_0 (11, 14.5, 18) were considered and two distinct SI, resulting in 6 primary plausible scenarios. The dashed horizontal line at 93% represents the MMR vaccination coverage needed to achieve herd immunity (defined as 1- $1/R_0$ and calculated to be 93% using the median R_0 value of 14.5).

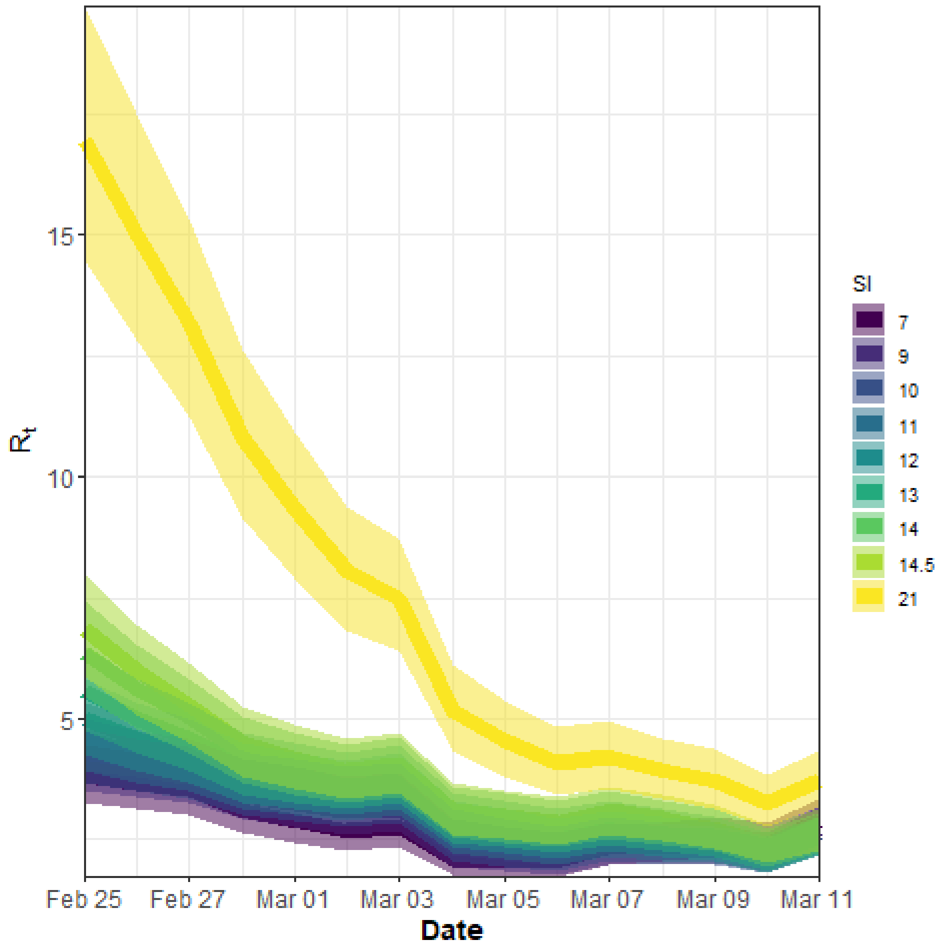
Figure S5: Estimates of the median (95% UI) MMR vaccination coverage by SI and R_0 values on March 11, 2025



Estimated MMR vaccination coverage on March 11, 2025. Median estimates are provided, along with the corresponding 95% uncertainty interval (UI), presented here as error bars. Three distinct values of the basic reproduction number R_0 (11, 14.5, 18) were considered and two distinct SI, resulting in 6 primary plausible scenarios. The dashed horizontal line at 93% represents the MMR vaccination coverage needed to achieve herd immunity (defined as 1- 1/R_0 and calculated to be 93% using the median R_0 value of 14.5).

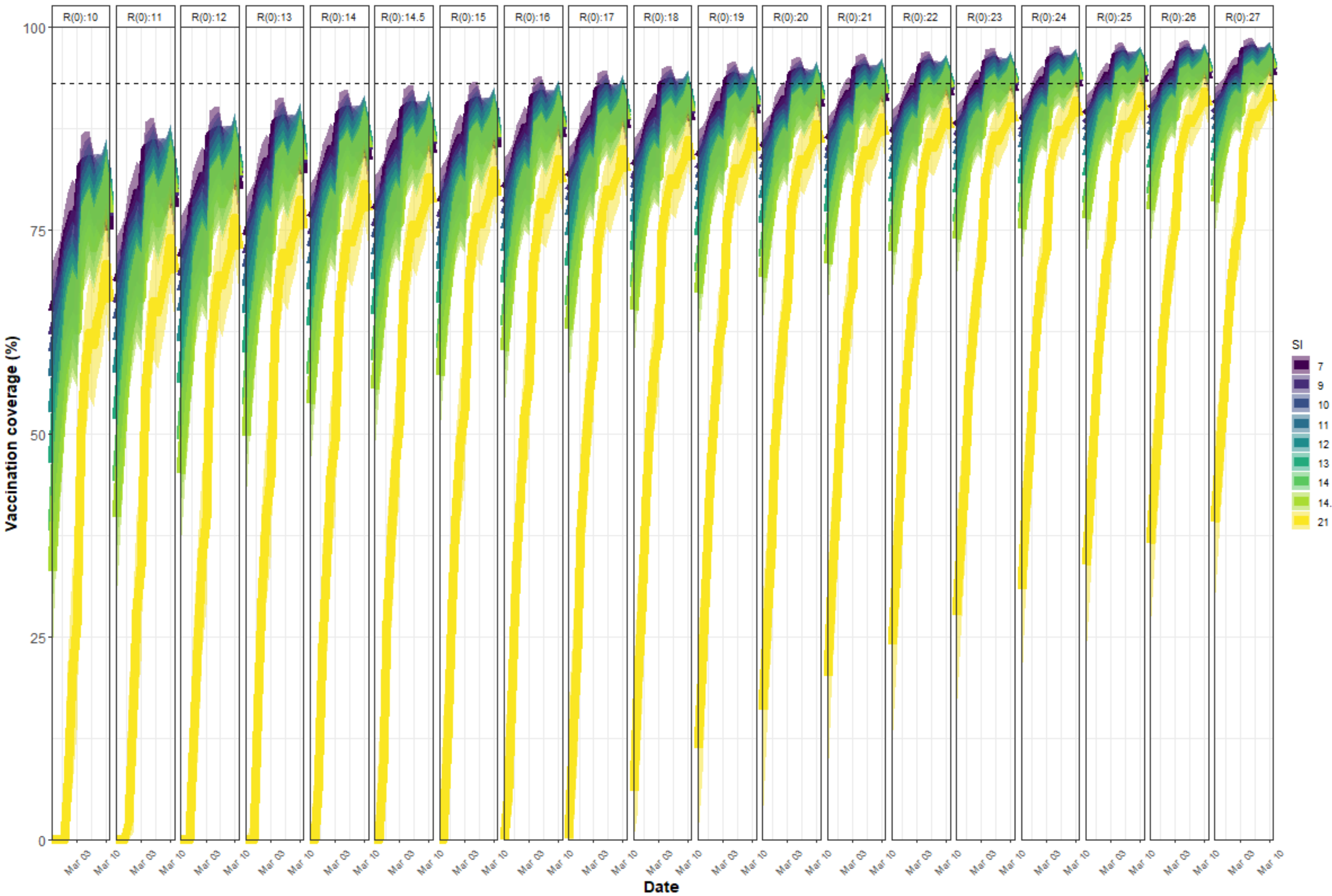
Section 5: Sensitivity Analyses

Figure S6: Median (95% UI) R_t values by SI value



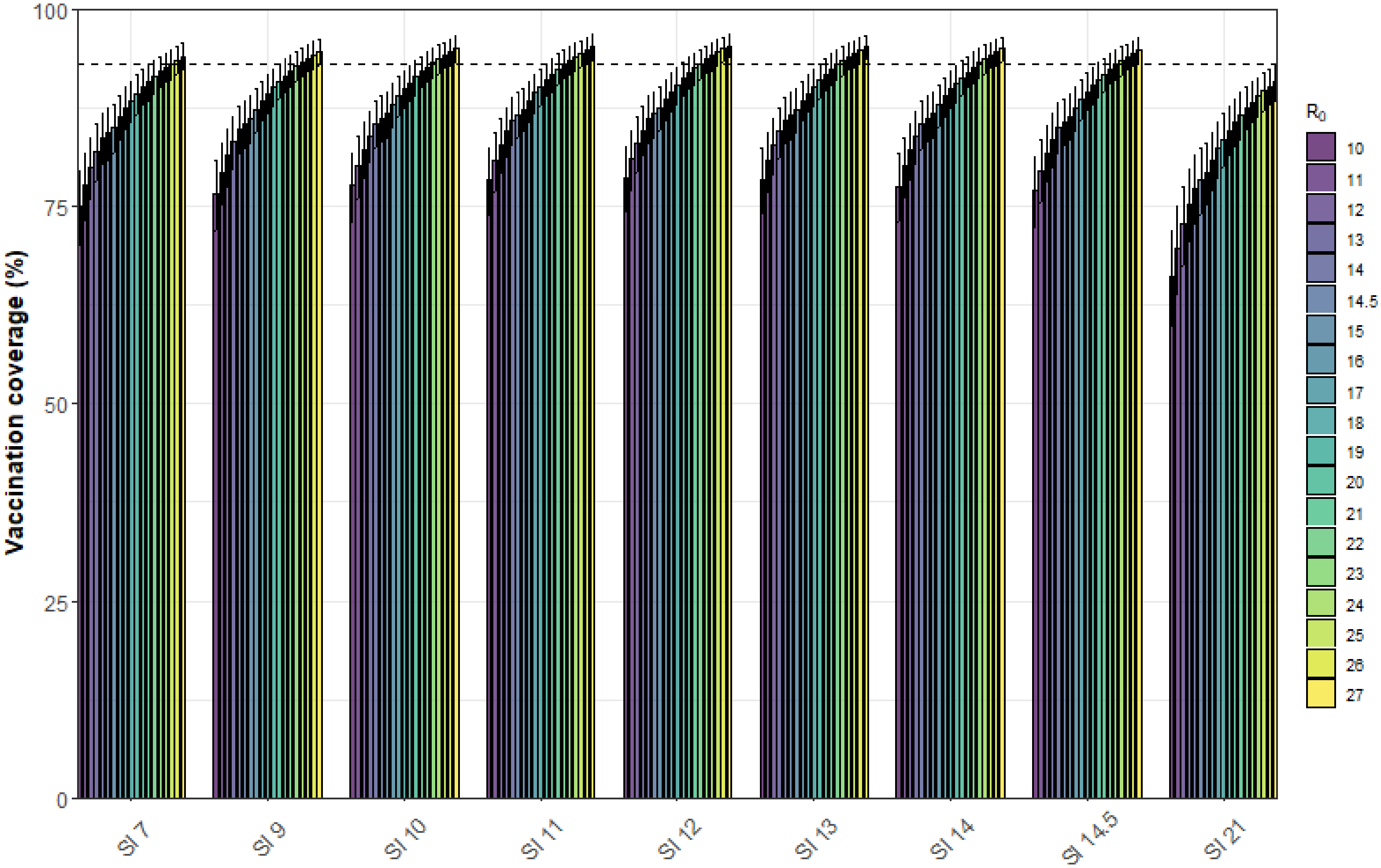
Estimated effective reproduction number R_t over time (February 25 to March 11, 2025). Median estimates are provided, along with the corresponding 95% uncertainty interval (UI). Nine distinct values of the serial interval or SI, ranging from 7 to 21, were considered.

Figure S7: Estimates of the median (95% UI) MMR vaccination coverage by SI and R_0 values



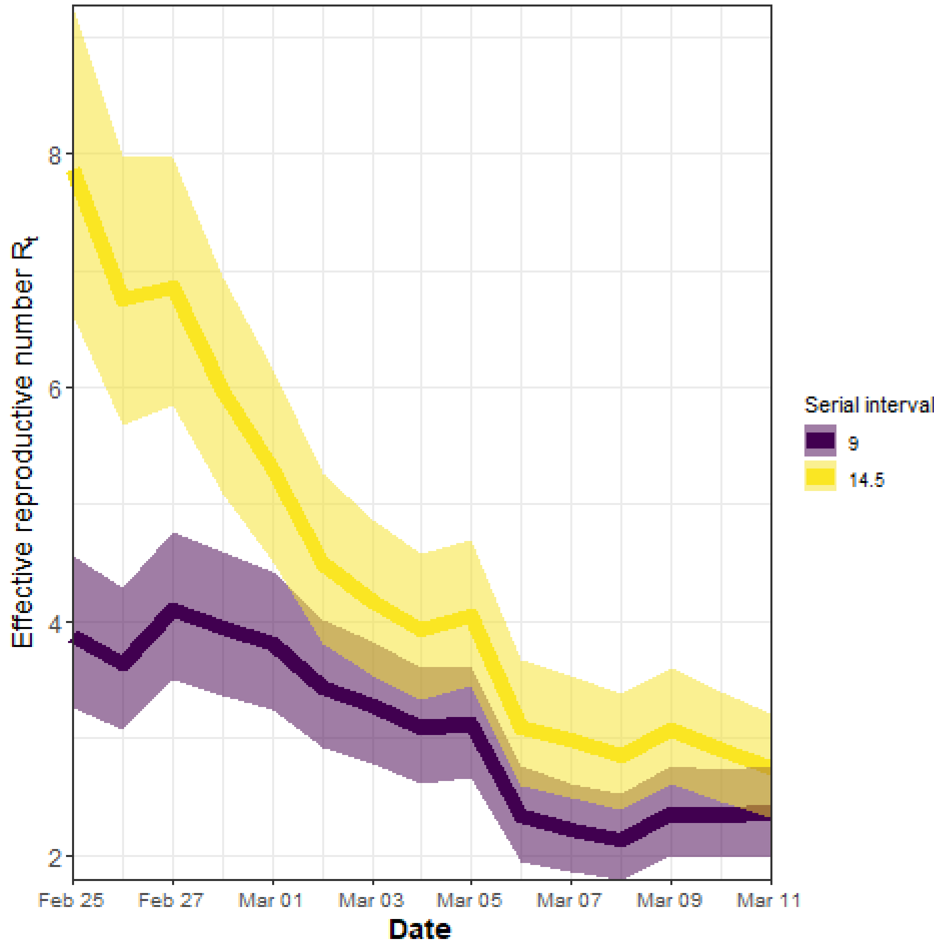
Estimated MMR vaccination coverage over time (February 25 to March 11, 2025). Median estimates are provided, along with the corresponding 95% uncertainty interval (UI). Nineteen distinct values of the basic reproduction number R_0 (ranging from 10 to 27 - here considered as facets) and nine distinct values of the serial interval or SI, ranging from 7 to 21, were considered, resulting in 171 plausible scenarios. Note that estimated values below 0% were removed before plotting. The dashed horizontal line at 93% represents the MMR vaccination coverage needed to achieve herd immunity (defined as 1- 1/R_0 and calculated to be 93% using the median R_0 value of 14.5).

Figure S8: Estimates of the median (95% UI) MMR vaccination coverage by SI and R_0 values on March 11, 2025



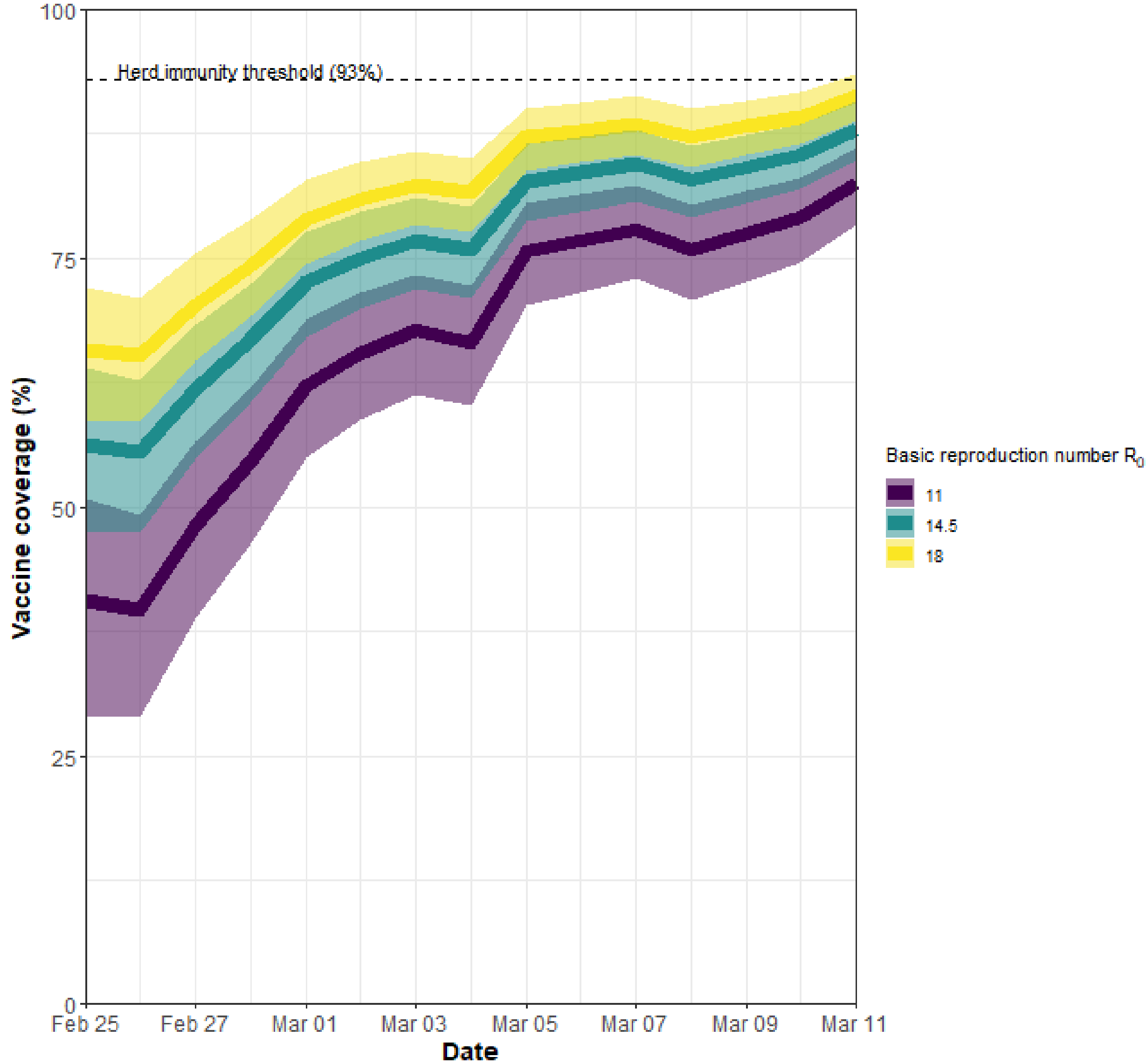
Estimated MMR vaccination coverage on March 11, 2025. Median estimates are provided, along with the corresponding 95% uncertainty interval (UI), presented here as error bars. Nineteen distinct values of the basic reproduction number R_0 (ranging from 10 to 27) and nine distinct values of the serial interval or SI, ranging from 7 to 21, were considered, resulting in 171 plausible scenarios. The dashed horizontal line at 93% represents the MMR vaccination coverage needed to achieve herd immunity (defined as 1- 1/R_0 and calculated to be 93% using the median R_0 value of 14.5).

Figure S9: Median (95% UI) R_t values for SI 9 and 14.5, reporting delayed by 24 hours



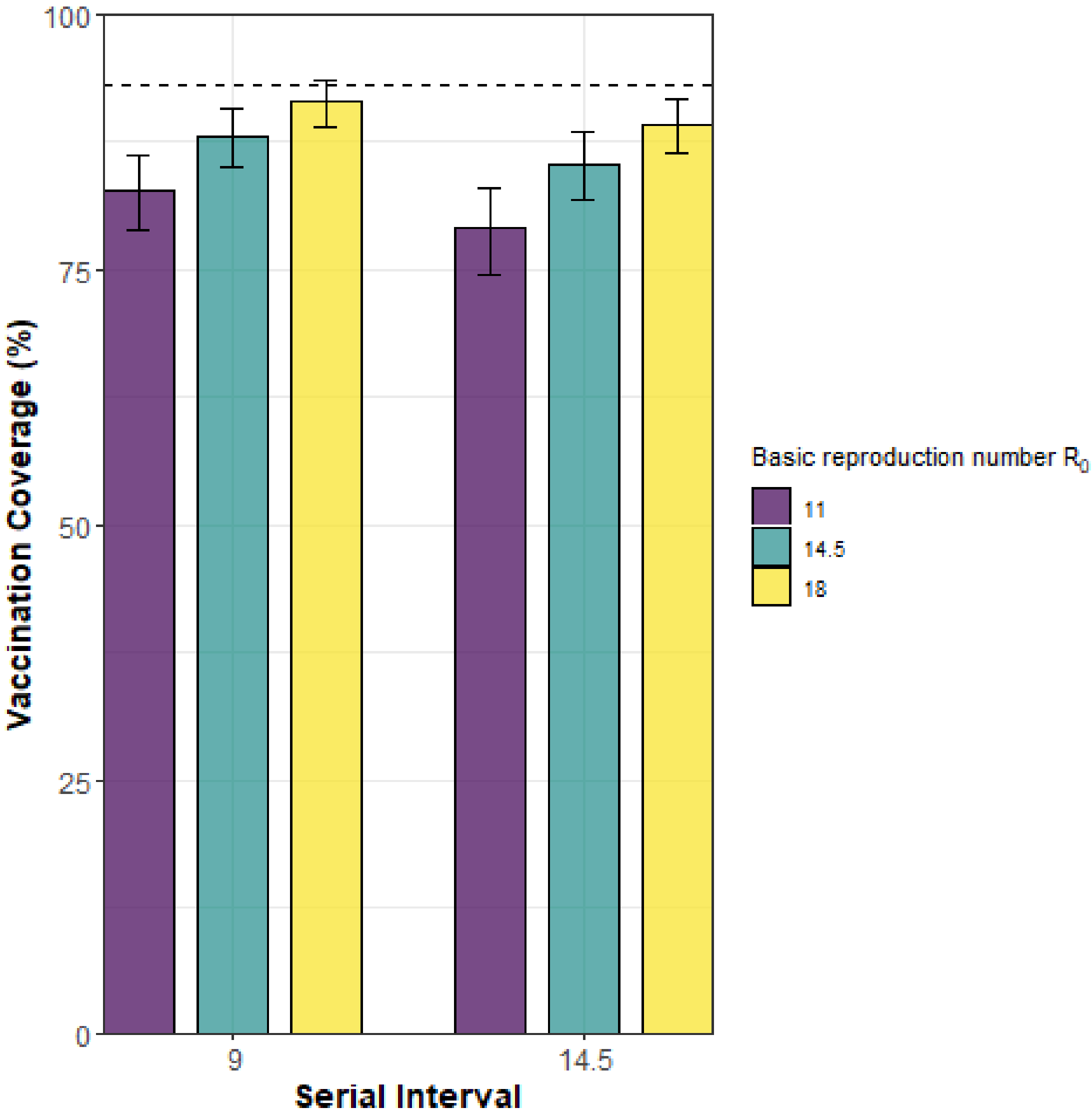
Estimated effective reproduction number R_t over time (February 25 to March 11, 2025), assuming a 24-hour delay from the true day of report. Median estimates are provided, along with the corresponding 95% uncertainty interval (UI).

Figure S10: Estimates of the median (95% UI) MMR vaccination coverage by R_0 values for SI 9 and 14.5, reporting delayed by 24 hours



Estimated MMR vaccination coverage over time (February 25 to March 11, 2025), assuming a 24-hour delay from the true day of report.. Median estimates are provided, along with the corresponding 95% uncertainty interval (UI). Three distinct values of the basic reproduction number R_0 (11, 14.5, 18) were considered and two distinct SI, resulting in 6 primary plausible scenarios. The dashed horizontal line at 93% represents the MMR vaccination coverage needed to achieve herd immunity (defined as 1- $1/R_0$ and calculated to be 93% using the median R_0 value of 14.5).

Figure S11: Estimates of the median (95% UI) MMR vaccination coverage by SI and R_0 values on March 11, 2025, delayed by 24 hours



Estimated MMR vaccination coverage on March 11, 2025, assuming a 24-hour delay from the true day of report. Median estimates are provided, along with the corresponding 95% uncertainty interval (UI), presented here as error bars. Three distinct values of the basic reproduction number R_0 (11, 14.5, 18) were considered and two distinct SI, resulting in 6 primary plausible scenarios. The dashed horizontal line at 93% represents the MMR vaccination coverage needed to achieve herd immunity (defined as 1-1/R_0 and calculated to be 93% using the median R_0 value of 14.5).

Section 6: References

1. Majumder MS, Cohn EL, Mekaru SR, Huston JE, Brownstein JS. Substandard Vaccination Compliance and the 2015 Measles Outbreak. *JAMA Pediatr*. 2015;169(5):494-495.

doi:10.1001/jamapediatrics.2015.0384
2. Worden L, Ackley SF, Zipprich J, et al. Measles transmission during a large outbreak in California. *Epidemics*. 2020;30:100375. doi:10.1016/j.epidem.2019.100375
3. Vink MA, Bootsma MCJ, Wallinga J. Serial Intervals of Respiratory Infectious Diseases: A Systematic Review and Analysis. *Am J Epidemiol*. 2014;180(9):865-875. doi:10.1093/aje/kwu209
4. Martoma RA, Washam M, Martoma JC, Cori A, Majumder MS. Modeling vaccination coverage during the 2022 central Ohio measles outbreak: a cross-sectional study. *Lancet Reg Health – Am*. 2023;23. doi:10.1016/j.lana.2023.100533
5. Cori A, Ferguson NM, Fraser C, Cauchemez S. A New Framework and Software to Estimate Time-Varying Reproduction Numbers During Epidemics. *Am J Epidemiol*. 2013;178(9):1505-1512. doi:10.1093/aje/kwt133
6. Guerra FM, Bolotin S, Lim G, et al. The basic reproduction number (R0) of measles: a systematic review. *Lancet Infect Dis*. 2017;17(12):e420-e428. doi:10.1016/S1473-3099(17)30307-9
7. Di Pietrantonj C, Rivetti A, Marchione P, Debalini MG, Demicheli V. Vaccines for measles, mumps, rubella, and varicella in children. *Cochrane Database Syst Rev*. 2021;(11). doi:10.1002/14651858.CD004407.pub5
8. Franconeri L, Antona D, Cauchemez S, Lévy-Bruhl D, Paireau J. Two-dose measles vaccine effectiveness remains high over time: A French observational study, 2017-2019. *Vaccine*. 2023;41(39):5797-5804. doi:10.1016/j.vaccine.2023.08.018
9. Plans-Rubió P. Evaluation of the establishment of herd immunity in the population by means of serological surveys and vaccination coverage. *Hum Vaccines Immunother*. 2012;8(2):184-188. doi:10.4161/hv.18444
10. Noufaily A, Ghebremichael-Weldeselassie Y, Enki DG, et al. Modelling Reporting Delays for Outbreak Detection in Infectious Disease Data. *J R Stat Soc Ser A Stat Soc*. 2015;178(1):205-222. doi:10.1111/rssa.12055
11. Güris D, Harpaz R, Redd SB, Smith NJ. Measles Surveillance in the United States: An Overview. *J Infect Dis*. 2004;189(Supplement_1):S177-S184. doi:10.1086/374606
12. CDC. Chapter 7: Measles. Manual for the Surveillance of Vaccine-Preventable Diseases. February 5, 2025. Accessed March 11, 2025. https://www.cdc.gov/surv-manual/php/table-of-contents/chapter-7-measles.html
13. Johns Hopkins University. Global landscape of measles and rubella surveillance. Published online 2025. https://publichealth.jhu.edu/sites/default/files/2025-02/Measles-Risk-Assessment-2.21.25_1.pdf
14. Swaan C, Broek A van den, Kretzschmar M, Richardus JH. Timeliness of notification systems for infectious diseases: A systematic literature review. *PLOS ONE*. 2018;13(6):e0198845. doi:10.1371/journal.pone.0198845
15. Marinović AB, Swaan C, van Steenbergen J, Kretzschmar M. Quantifying Reporting Timeliness to Improve Outbreak Control. *Emerg Infect Dis*. 2015;21(2):209-216. doi:10.3201/eid2102.130504
16. Texas Department of State Health Services. Texas Department of State Health Services - Update February 25, 2025. Facebook. February 25, 2025. Accessed March 12, 2025. https://www.facebook.com/photo?fbid=1049772957186727&set=a.246433067520724
17. World Health Organization. Measles - United States of America. Disease Outbreak News. March 27, 2025. Accessed April 1, 2025. https://www.who.int/emergencies/disease-outbreak-news/item/2025-DON561
18. Silver D, Kim Y, McNeill E, Piltch-Loeb R, Wang V, Abramson D. Association between COVID-19 vaccine hesitancy and trust in the medical profession and public health officials. *Prev Med*.

2022;164:107311. doi:10.1016/j.ypmed.2022.107311

19. R Core Team. R: A Language and Environment for Statistical Computing. Published online 2024. https://www.R-project.org/

20. Gostic KM, McGough L, Baskerville EB, et al. Practical considerations for measuring the effective reproductive number, Rt. *PLOS Comput Biol*. 2020;16(12):e1008409. doi:10.1371/journal.pcbi.1008409

21. Cori A, Cauchemez S, Ferguson NM, et al. EpiEstim: Estimate Time Varying Reproduction Numbers from Epidemic Curves. Published online January 7, 2021. Accessed October 18, 2023. https://cran.r-project.org/web/packages/EpiEstim/index.html

22. Wickham H. ggplot2: Elegant Graphics for Data Analysis. Published online 2016.

23. Klinkenberg D, Nishiura H. The correlation between infectivity and incubation period of measles, estimated from households with two cases. *J Theor Biol*. 2011;284(1):52-60. doi:10.1016/j.jtbi.2011.06.015

24. Bureau UC. County Population Totals and Components of Change: 2020-2024. Census.gov. March 2025. Accessed April 3, 2025. https://www.census.gov/data/tables/time-series/demo/popest/2020s-counties-total.html