Current and future trends in tuberculosis incidence in New York City: a dynamic modelling analysis

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Summary

Background After steady decline since the 1990s, tuberculosis incidence in New York City and throughout the USA has plateaued. We aimed to explore the major drivers of the flattening of tuberculosis incidence in New York City and to project the future trajectory of the tuberculosis epidemic in the absence of any additional intervention.

Methods We developed a compartmental transmission model of tuberculosis in New York City. The model was parameterised with detailed epidemiological data and stratified by age and nativity (US-born *vs* foreign-born). We ran the model under five alternative scenarios representing different explanations for recent declines in tuberculosis incidence. We evaluated the relative likelihood of each scenario by comparing its output with available data. We used the most likely scenarios to explore potential mechanisms underlying the recent declines in tuberculosis in New York City and to describe the reasonable range of future epidemic trajectories. Our primary outcome was the projected rate of decline in tuberculosis incidence from 2015 to 2025. Model calibration yielded estimates of future disease incidence and reductions in incidence with 95% credible intervals (CrIs).

Findings Demographic changes and declining tuberculosis transmission alone were insufficient to explain recent trends in tuberculosis incidence in New York City. Only scenarios that assumed contemporary changes in tuberculosis dynamics among foreign-born individuals—a declining rate of reactivation or a decrease in imported subclinical tuberculosis—could accurately describe the trajectory of disease incidence since 2007. In those scenarios, the projected decline in incidence from 2015 to 2025 varied from minimal (2·0% per year [95% CrI 0·4–3·5]) to similar to 2005 to 2009 trends (4·4% per year [2·5–6·4]). The primary factor differentiating optimistic from pessimistic projections was the degree to which improvements in tuberculosis dynamics among the foreign-born population continued into the coming decade.

Interpretation Further progress towards elimination of tuberculosis in New York City requires additional focus on the foreign-born population. Without additional intervention in this group, tuberculosis incidence might not decline further.

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Introduction

After steady decline since the 1990s, tuberculosis incidence in the USA remained relatively flat between 2013 and 2015.[1] This plateau was presaged by a slowing decline of tuberculosis incidence in New York City since 2010.[2] New York City has long been an important locus of tuberculosis in the USA,[3] and changes in incidence of the disease in this city often anticipate national trends.[4] The reasons for the abrupt plateau in tuberculosis incidence in New York City and the USA more broadly, and whether incidence will decline further in the future, remain unclear.

As incidence has declined, tuberculosis budgets have contracted,[5] and the finite resources must be allocated efficiently to continue progress toward elimination of the disease. Declines in tuberculosis in the last half of the 20th century have been driven by antibiotic chemotherapy, decreasing tuberculosis transmission,[6] lower prevalence of latent tuberculosis infection (LTBI) among younger generations,[7] and an aggressive public health response since a surge of the disease in the 1980s.[4] If these factors are also the key drivers of recent declines, the downward trajectory of tuberculosis incidence might be expected to resume. However, if the more recent declines in disease incidence reflect processes that will not inevitably continue, then additional steps, such as increased screening for and treatment of LTBI,[8] might be necessary to resume seemingly stalled progress in the ongoing fight against tuberculosis.

Mathematical models can be useful for understanding the dynamics of infectious disease epidemics[9,10] and could be applied to forecast the trajectory of the tuberculosis epidemic in the USA. Relatively few models exist of tuberculosis in the USA[10] or other low-burden settings,[11,12] and the data informing these models have been insufficient to address detailed mechanistic questions. New York City collects detailed clinical and epidemiological data on tuberculosis dynamics (including LTBI prevalence estimates[13] and routine genotyping[14]), demography, and immigration. The quality and breadth of this information offers a unique opportunity to examine in detail the effects of changing demographics and immigration on tuberculosis

Research in context

Evidence before this study

We searched PubMed and Embase for articles published in any language from Jan 1, 1980, to Jan 1, 2017, with the term "tuberculosis", in addition to "New York City", "United States", or "low-burden". Several studies note that after steady decline since the 1990s, the incidence of tuberculosis in New York City and the USA has remained relatively flat since 2013. Although studies suggest that declines in tuberculosis incidence in the second half of the 20th century were driven by various factors, including antibiotic chemotherapy, decreasing tuberculosis transmission, lower prevalence of latent tuberculosis infection among younger generations, and an aggressive public health response since a surge of tuberculosis in the 1980s and 1990s, the reasons for more recent declines and for the current plateau in incidence remain unclear. Trends in tuberculosis among foreign-born residents have been identified in previous modelling studies as a major driver of the disease in low-burden settings.

Added value of this study

This study uses rich epidemiological data for tuberculosis in New York City to inform a model of tuberculosis transmission and explore the drivers of recent trends in incidence. Our results suggest that recent declines in tuberculosis incidence cannot be explained by demographic trends alone and instead are likely to reflect contemporary changes in reactivation of latent tuberculosis infection among foreign-born individuals or a decreasing amount of imported tuberculosis. We provide numerical estimates of declines in tuberculosis incidence over the coming decade and show that, without additional efforts to further reduce tuberculosis in the foreign-born population, ongoing declines in incidence of the disease might not materialise.

Implications of all the available evidence

The primary determinant of future declines in tuberculosis incidence in settings such as New York City is the ability to further reduce importation and reactivation of the disease among foreign-born residents. This finding argues for interventions such as increased investment in tuberculosis control for countries from which large numbers of foreign-born residents originate, or increased testing for latent tuberculosis infection. Further study into the reasons for declining tuberculosis incidence in this subpopulation could help to prioritise the allocation of finite tuberculosis control budgets. Without additional interventions, tuberculosis incidence in New York City might remain flat.

incidence. We therefore incorporated these data into a model designed to explore the major drivers of the recent flattening of tuberculosis incidence in New York City and to project the future trajectory of the tuberculosis epidemic in the absence of any additional intervention.

For the **DOHMH** see http://www1.nyc.gov/site/doh/index.page

Methods

Model design

We developed a compartmental transmission model of tuberculosis in New York City stratified by age and nativity: US-born (born within the USA or a US territory) or foreign-born (appendix p 3). Compartmental models are widely used in tuberculosis modelling because their computational efficiency allows for many simulations to be run; our model uses compartments similar to other studies.[10] Susceptible populations in our model become infected with tuberculosis at a rate proportional to the prevalence of active disease. Upon infection, people are categorised as having recently acquired LTBI and have a specified rate of progression to active tuberculosis. As time passes since the initial infection, LTBI advances through stages of declining progression rates, but the rate of progression (reactivation) never falls to zero. Active tuberculosis is identified and treated at a given rate; people with active disease also have competing rates of spontaneous resolution and death. Reinfection among people with LTBI or those who have completed treatment is allowed, but their rate of reinfection is reduced compared with never-infected individuals, reflecting partial immunity to reinfection. We chose our age strata to match strata for which mortality rates and tuberculosis incidence have been recorded by the New York City Department of Health and Mental Hygiene (DOHMH). We initiated the model in 1950, and ran simulations up to 2025. The appendix describes the full model in detail.

See Online for appendix

Model calibration

We sought to capture the state of tuberculosis in 2015, and the trends in tuberculosis incidence up to 2015. Because our model is only an approximation of reality and depends on various parameters that are not known exactly, we used a Bayesian approach (as in previous modelling studies[15]) to handle uncertainty. In this approach, we ran 20 000 simulations, each with slightly different model parameters chosen from ranges of likely values. We then used a likelihood function to weight the simulations according to how well they corresponded to tuberculosis incidence from 2010 to 2015. This calibration yielded estimates of future disease incidence and reductions in incidence with 95% credible intervals (CrIs)—intervals within which a prediction will fall with 95% certainty, assuming the model appropriately reflects tuberculosis transmission in New York City.

We estimated model parameters from three sources: epidemiological data from the DOHMH, the scientific literature, and exploratory simulations with the model (appendix). To reflect uncertainty in the model parameters that were not directly estimated from New York City data, for each simulation we sampled

parameters from uniform distributions over the ranges of possible values given in the appendix (p 11). For parameters with minimal supporting data available, we selected median values consistent with the published literature or based on initial simulations and sampled from a range of possible values around that median. We incorporated uncertainty about LTBI prevalence in incoming immigrants and in the population of New York City in 1950 by allowing them to vary randomly from 0·5 to 1·5 times our estimated values.

We designed our likelihood function to match the case notification of tuberculosis among US-born and foreign-born residents in both 2010 and 2015. The likelihood weighted each simulation according to a product binomial likelihood that multiplied the probability of observing the reported number of tuberculosis cases in 2010 and 2015 separately among US-born and foreign-born individuals of all ages, on the basis of the simulation results. Because LTBI prevalence reflects tuberculosis dynamics from the preceding 50–60 years, we excluded simulations that projected a decline in overall tuberculosis incidence from 1950 to 1960 that was more than 50% above or below the estimated historical decline. Similarly, among simulations that sought to reproduce the increase in tuberculosis incidence in the 1980–90s, we excluded those that projected an overall incidence in 1992 of more than 50% above or below the observed incidence at that time. This approach ensured that simulations reflected the 1980–90s trend to an approximate (plus or minus 50%) degree, since a simulation could match well in 2015, while matching poorly in 1992. We fit the model to tuberculosis notifications as a proxy for underlying incidence, because tuberculosis is a reportable disease and most epidemiologically relevant cases in the USA are notified.

Model outcomes and scenarios

Our research objectives were to explore potential mechanisms underlying the recent declines in tuberculosis in New York City and to describe the reasonable range of future epidemic trajectories. Our primary outcome was the projected rate of decline in tuberculosis incidence from 2015 to 2025.

To explore different possible mechanisms for recent tuberculosis trends in New York City, we generated simulations under five different sets of assumptions (table). We evaluated whether trends in tuberculosis incidence in New York City from 2010 to 2015 could be replicated under each set of assumptions, and how each assumption affected projections of future incidence. These five scenarios differed in allowing rates of progression of LTBI to decline with time since infection (beyond 5 years), attempting to recapitulate the increase in tuberculosis incidence in the 1980s and 1990s, allowing rates of LTBI progression to differ between US-born and foreign-born populations, or allowing for a reduction in the amount of subclinical tuberculosis (ie, active tuberculosis after it can be transmitted and diagnosed microbiologically, but before it would be diagnosed based on symptoms[17]) in incoming immigrants. All five scenarios allowed transmission rates to fall over the 75 year period (appendix) and assumed that prevalence of LTBI among incoming immigrants is constant.

We note that our scenarios (particularly differential progression and reduced importation) are broad paradigms that highlight the general mechanisms by which tuberculosis incidence might be changing.

Model analyses and sensitivity analyses

We compared the five scenarios on the basis of their fit to the observed trends; qualitatively by plotting model projections and quantitatively using Bayes factors—the ratio of the overall likelihood of one model versus another (the greater the ratio, the more the data [tuberculosis incidence in 2010 and 2015] support one scenario over the other).[18] Additionally, we examined the ability of simulations in each scenario to recapitulate the age distribution in the population, fraction of incident tuberculosis due to recent (within 2 years) transmission (estimated based on the proportion of cases clustered by IS*6110* restriction fragment length polymorphism and spoligotyping[14]), age distribution of active cases, and age distribution of LTBI in both US-born and foreign-born populations.

We analysed the sensitivity of our primary outcome to each individual parameter value, with adjustment for all other parameters in the model, by calculating partial

	Brief description	Comments
Baseline	Demographic changes only	Constant rate of LTBI reactivation beyond 5 years after infection; no change in tuberculosis dynamics in 1980–90s
Declining progression	Allows declining rate of LTBI reactivation	As in the baseline scenario, but allows for linear decline in the rate of LTBI reactivation with time since infection
1980s increase	Increased tuberculosis incidence from 1984 to 1992	As in the declining progression scenario, but allows for higher rates of transmission and reactivation as observed from 1984 to 1992, without specifying a specific mechanism (eg, HIV or worsening tuberculosis control infrastructure)
Differential progression	Different reactivation rates in US-born *vs* foreign-born individuals	As in the 1980s increase scenario, but allows for different rates of progression from LTBI to active tuberculosis in US-born and foreign born individuals, as well as allowing the rate of progression in foreign-born individuals with LTBI to decline by 1·5% to 5·25% per year after 2007, without specifying a specific mechanism (eg, due to improved nutritional or immune status)*
Reduced importation	Reduced importation of subclinical tuberculosis from 2007 to 2012	As in the 1980s increase scenario, but models a decrease in imported subclinical tuberculosis without specifying a specific mechanism (eg, changing patterns of immigration or use of tuberculosis culture rather than sputum smear microscopy to screen some foreign-born people seeking permanent residence in the US before entry[16]). We represent this decrease as a linear reduction in the risk of incident active tuberculosis among immigrants in their first year after arrival; we assume that in 2007, immigrants have a normal risk, but by 2012 (and after) that first-year risk is halved

LTBI=latent tuberculosis infection. *Rates of decline were selected based on preliminary simulations. Our primary analysis of this scenario assumed that LTBI progression rates among the foreign-born population continued to decline through 2025. Because it is not clear that such a decline would continue year after year, we did a secondary analysis, which assumed that LTBI progression rates did not decline further after 2015. The appendix provides further details.

***Table*: The five scenarios under which simulations were run**

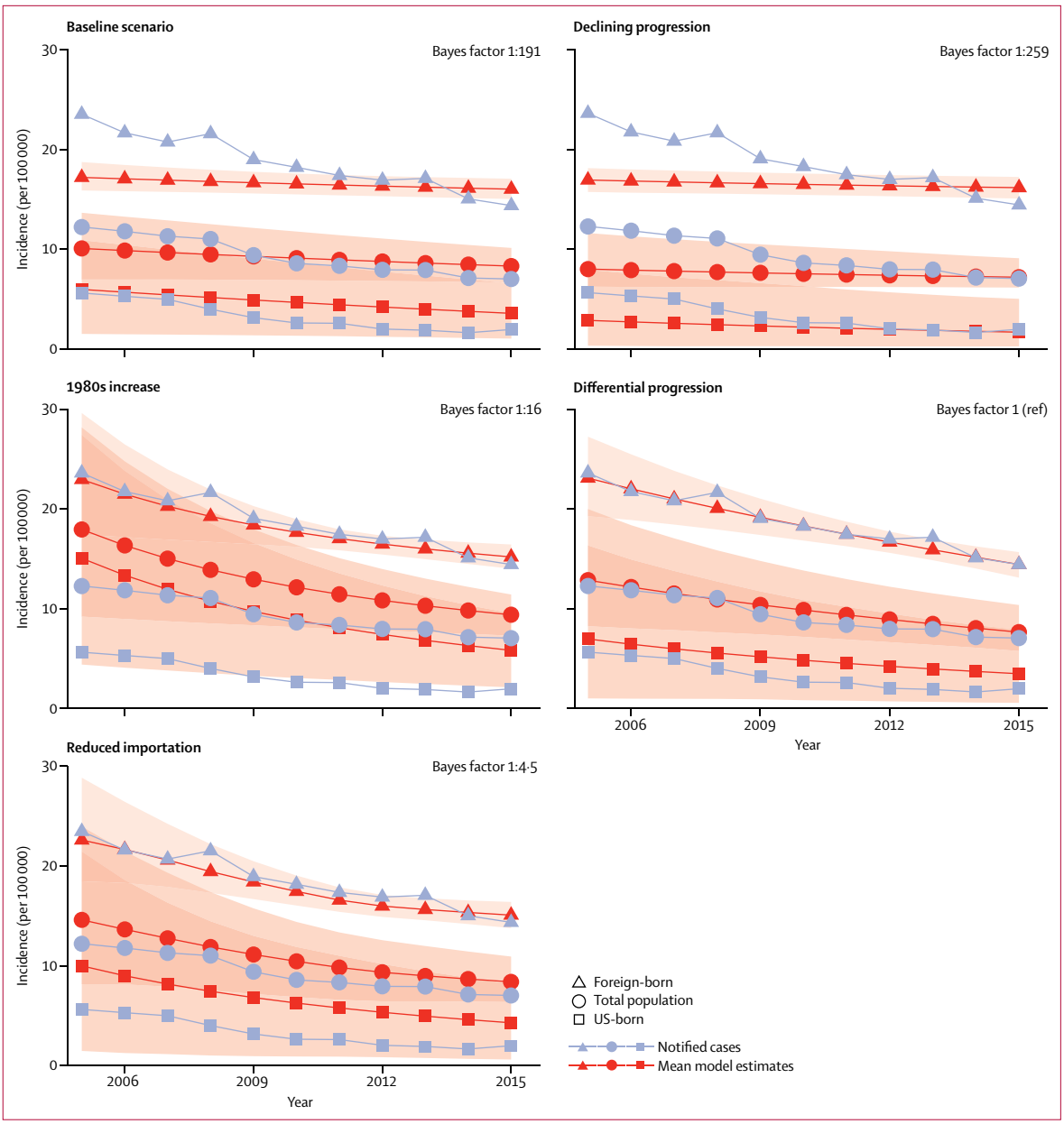

Figure 1: **Estimated versus actual tuberculosis incidence in the foreign-born, US-born, and total populations of New York City under five scenarios**
Shaded areas represent 95% credible intervals. Bayes factors are with respect to the differential progression scenario. A Bayes factor is the ratio of the overall likelihood of one scenario versus another—the greater the ratio, the more the data (tuberculosis incidence in 2010 and 2015) support one scenario over the other. A Bayes factor of 1:10 or less indicates strong evidence in favor of the differential progression scenario.[18]

rank correlation coefficients between the parameter value and the projected decline in tuberculosis from 2015 to 2025 (ie, the correlation between the ranked value of the outcome and the ranked value of each individual parameter, adjusted for all other parameters). We also compared the primary outcome in simulations with the parameter values in the highest quintile to the outcome in simulations with parameter values in the lowest quintile for each parameter. We did sensitivity analyses to identify how much the specification of the likelihood function and previous distributions for model parameters influenced our primary outcome.

Simulations were run with R (version 3.3.1) and the deSolve package.

Role of the funding source

There was no funding source for this study. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

We determined which model assumptions were necessary to replicate recent trends in tuberculosis incidence. Scenarios resting on demographic changes and historical changes in transmission alone (the baseline, declining progression, and 1980s increase scenarios) fit the data poorly (figure 1). To accurately replicate the recent decline in incidence in New York City, it was important to incorporate a more recent (since 2007) change in the dynamics of tuberculosis within the foreign-born population. Examples of such changes included ongoing declines in LTBI progression among foreign-born individuals (the differential progression scenario) or more recent reductions in imported subclinical tuberculosis in this population (the reduced importation scenario). The data did not strongly support either of these mechanisms (figure 1); rather, a recent change in the dynamics of tuberculosis among the foreign-born population was required to replicate the observed data, regardless of the mechanism of that change. Our subsequent analyses focus on the differential progression and reduced importation scenarios.

Both the differential progression and the reduced importation scenarios estimated that slight declines in the transmission rate (3·3% and 3·8% relative reduction per year, respectively) underpinned part of the recent decline in tuberculosis incidence for US-born and foreign-born populations. The differential progression scenario suggested that, if the recent decline in tuberculosis incidence among foreign-born individuals was due to a decrease in foreign-born reactivation rates starting in 2007, the rate of that decline was 2·8% per year (95% CrI 1·5–4·1).

Although both of these scenarios fit historical data well and provided a mechanism for recent declines in incidence among the foreign-born population, the two scenarios differed markedly in projections of tuberculosis over the next decade because of their different assumptions about whether the modeled mechanisms can be maintained (figure 2). The reduced importation scenario, in which imported subclinical tuberculosis was not reduced further after 2012, projected a flattening of tuberculosis incidence beyond 2015, with an estimated decline of only 2·0% per year (95% CrI 0·4–3·5) from 2015 to 2025 (figure 2). By contrast, the differential progression scenario, which assumed that LTBI progression rates among foreign-born individuals would continue to fall in the coming decade, projected ongoing declines in tuberculosis incidence similar to those observed in the past decade—4·4% per year (95% CrI 2·5–6·4%; figure 2). When we instead assumed that rates of LTBI progression among the foreign-born population remained constant beyond 2015, the decline in tuberculosis incidence over the coming decade flattened to 1·3% per year (95% CrI 0·2–2·6).

Sensitivity analyses showed that the projected decline in incidence from 2015 to 2025 under the differential progression scenario was driven primarily by the rate of decline of LTBI progression in the foreign-born population (partial rank correlation coefficient 0·95, indicating that the greatest estimated reductions in tuberculosis were strongly correlated with the highest rates of decline in LTBI progression in foreign-born individuals). The projected yearly decline in tuberculosis incidence from 2015 to 2025 was 3·4% greater (6·7% *vs* 3·3%) in the simulations assuming the highest quintile of values for the decline in LTBI progression compared with the lowest quintile (figure 3). By contrast, under the reduced

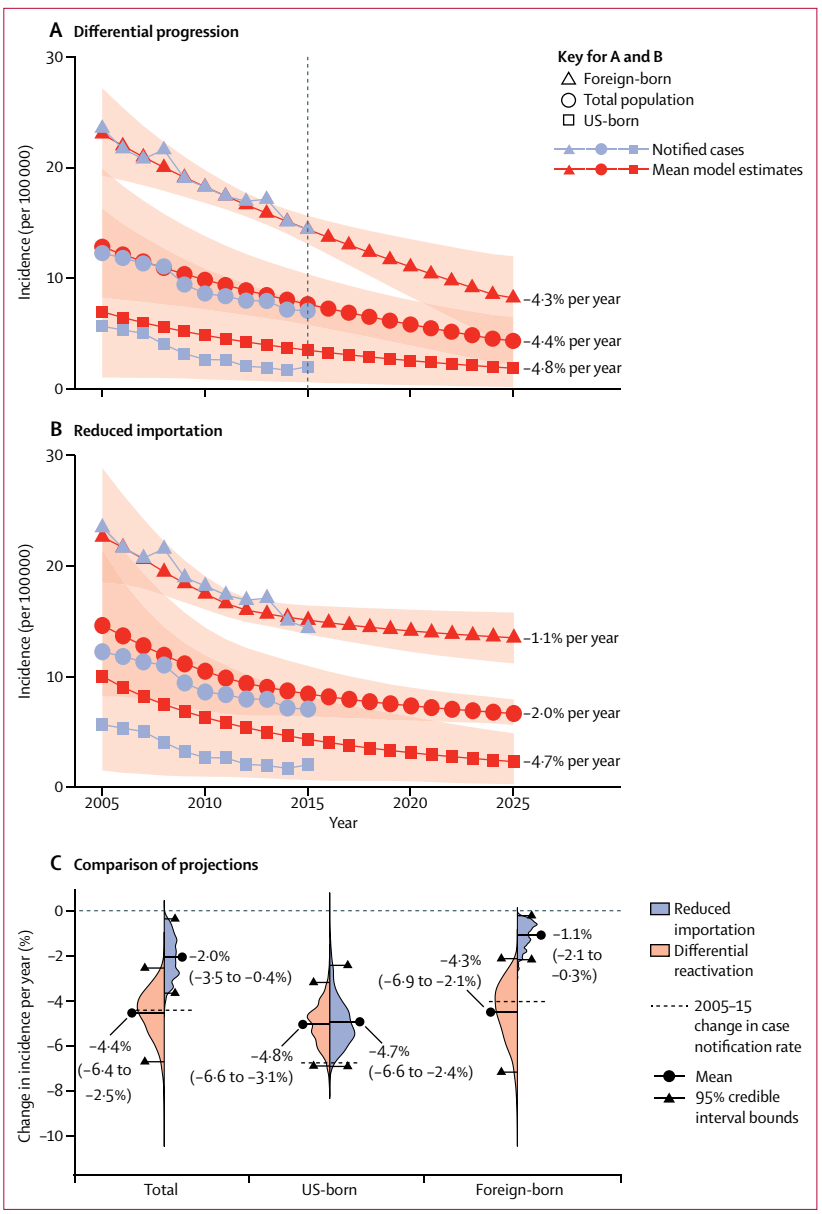

***Figure 2*: Estimated change in total tuberculosis incidence from 2015 to 2025**
Projected incidence for foreign-born, US-born, and total populations in New York City under the differential progression (A) and reduced importation (B) scenarios. (C) Violin plots comparing projected distributions of the yearly decline in tuberculosis incidence from 2015 to 2025 in foreign-born, US-born, and total populations.

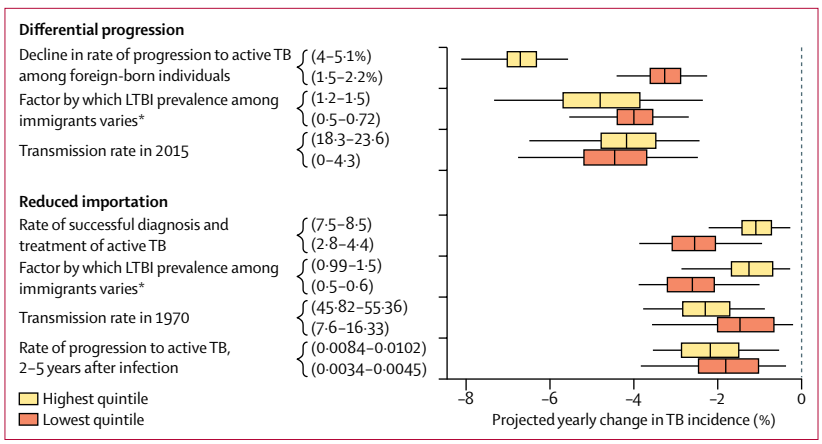

***Figure 3*: Projected annual change in TB incidence in simulations with the highest versus lowest quintiles of selected model parameters**

Vertical lines represent the mean estimated yearly decline in TB incidence, Shaded boxes represent IQRs; whiskers represent 95% credible intervals. The relation of projected yearly change in incidence to an individual model parameter is shown if the projections of yearly decline in incidence from 2015 to 2025, based on the highest quintile of the parameter (the highest 20% of sampled values for the parameter), differed by more than 0·3% per year in absolute terms from projections based on the lowest quintile of the parameter. TB=tuberculosis. LTBI=latent tuberculosis infection. *A parameter that allows the LTBI prevalence among immigrants to vary up or down from estimates generated by prevalence surveys[13] (a value of 1·0 indicates no change from the baseline estimate).

importation scenario, several parameters had mild effects on the primary outcome, but none shifted the projected yearly decline in tuberculosis incidence by more than 1·5% when comparing simulations in the highest quintile to those in the lowest quintile of values for that parameter (figure 3). Sensitivity analyses also showed that our results changed little if we calibrated to years other than 2010 and 2015, or used non-uniform prior distributions for model parameters (appendix).

Discussion

Declines in tuberculosis since the 1990s, both in New York City and throughout the USA, have been driven at least partly by decreasing transmission,[6] the lower prevalence of LTBI among younger generations,[7] and public health measures (such as expansion of directly observed therapy and improved infection control in hospitals, correctional facilities, and homeless shelters) in place since the surge of tuberculosis in the 1980s.[3,4] Although budgetary considerations depend on various competing priorities, the implicit assumption that such factors are driving current trends and will continue to drive down incidence is reflected in cuts to tuberculosis control budgets. However, our results suggest that reduced transmission, changes in demography, and historical trends are not enough to explain the declines in tuberculosis incidence since 2005. In the context of our model, these declines can only be explained by assuming contemporary changes in tuberculosis epidemiology among the foreign-born population, such as a decrease in imported subclinical tuberculosis or declining risk of progression to active disease. If efforts are not made to further reduce reactivation or importation of tuberculosis among foreign-born individuals in the next decade, the flattening of tuberculosis incidence observed over the past 2 years could easily continue into the next decade.

Our models suggest that existing data are consistent with either declining risk of reactivation or reduced importation as the dominant driver of recent tuberculosis trends; they do not elucidate a specific mechanism for either process. We also considered that decreasing prevalence of LTBI among incoming immigrants might partly explain the greater decline in tuberculosis incidence among the foreign-born population, but LTBI notifications among legal immigrants have increased and serial surveys of LTBI in clinics in New York City show that LTBI prevalence among foreign-born individuals rose from 2009 to 2011.[13] Although these observations were not deduced from random population samples, they suggest that LTBI prevalence is unlikely to be falling substantially among new immigrants. Decreasing reactivation rates among foreign-born individuals could result from improved nutritional or socioeconomic status, better access to health care, or increasing treatment of LTBI. For example, patients with LTBI were more likely to complete treatment after switching from the tuberculin skin test to interferon-γ release assays for LTBI testing in DOHMH chest clinics in 2006, particularly if foreign-born.[19] Some degree of reduced importation of subclinical tuberculosis is suggested by internal data from the DOHMH from 2007 to 2011, which show a slightly decreasing incidence of tuberculosis among immigrants in their first year after arrival, although there is substantial variation from year to year. These trends could reflect improved global tuberculosis control efforts or enhanced screening of immigrants and refugees beyond US borders. After nationwide augmentation of pre-immigration screening with tuberculosis culture in 2007, incident tuberculosis in the first 6 months after arrival fell from 4·2% to 1·5% among individuals eligible for screening in California.[16] However, many immigrants are not covered by the extended screening, and the effect of this change in New York City is unclear. A combination of factors probably underpins recent declines in tuberculosis, none of which are likely to fully account for trends on their own.

Regardless of the specific mechanisms, our study suggests that the future trajectory of tuberculosis incidence is linked strongly to the mix of underlying factors that have driven declines in incidence among the foreign-born population since 2005, and the degree to which that mix changes in the future. To the extent that future dynamics are driven by mechanisms that can be further improved, sustained reductions in incidence could be feasible. This notion is consistent with findings from other studies that have found rapidly decreasing incidence among foreign-born individuals over the past decade[20] and identified tuberculosis among the foreign-born population as a major driver of the overall epidemic,[10,12] and has several important implications.

First, it suggests that tuberculosis control programmes should focus on surveillance data by country of origin and time since arrival to identify the primary underlying mechanisms underpinning incidence in the foreign-born population. Second, interventions that can sustain those declines should be a priority. To decrease progression from LTBI to active tuberculosis among the foreign-born population, attention should focus on improving health-care access for foreign-born populations or broadening testing and treatment of LTBI, as recommended by the US Preventive Services Task Force.[8] In terms of reducing imported tuberculosis, a pilot of a pre-screening programme for immigrants to the UK from high-burden countries that diagnosed immigrants in their country of origin highlights the role that innovations in screening of migrants can play.[21] However, greater reductions in imported disease might be difficult to sustain unless patterns of immigration or the global burden of tuberculosis shift substantially. Consequently, our results argue for increased investment in tuberculosis control for countries from which large numbers of foreign-born individuals currently originate.

As with all models, we make a number of simplifying assumptions. First, we assume homogeneous respiratory mixing among all New Yorkers. This assumption is commonly made in compartmental models of tuberculosis in view of the airborne nature of transmission,[15] and is likely to reflect the population-average transmission in our model. Although there might be subpopulations with preferential mixing in New York City, no single social or geographic group is likely to account for a large proportion of transmission. Only 17% of tuberculosis cases with genotype data available from 2001 to 2015 were part of a cluster of ten or more cases, and none of the 42 United Hospital Fund neighborhoods in New York City have an incidence of more than 2·5 times the citywide average.[2] Second, we treat the foreign-born population as homogenous and do not consider migration internal to the USA. This approach allowed us to use New York City-specific estimates of LTBI prevalence and age-stratified immigration patterns. Because internal migration is not a strong driver of tuberculosis transmission, and countries of origin have not changed greatly among immigrants in New York City from 2000 to 2011,[22] our modeled population accurately reflects the population-average patterns (most tuberculosis cases in New York City come from China, Mexico, the Dominican Republic, and the Philippines[2]). However, our projections up to 2025 depend on the composition of incoming immigrants remaining broadly similar; future work could examine the effects if immigration patterns were to shift as a result of national policy or economic pressures. Third, we do not explicitly model HIV. Although people living with HIV are more susceptible to tuberculosis infection, studies suggest that they are no more likely to transmit tuberculosis infections;[23] coupled with the low and decreasing prevalence of HIV co-infection (currently 6% of all tuberculosis cases in New York City[2]), this finding makes it unlikely that HIV would strongly influence current trends. Fourth, we assume that rates of diagnosis, treatment, and mortality are constant over time, and we do not explicitly model drug resistance. Because tuberculosis treatment outcomes, tuberculosis-specific mortality, and overall mortality have not changed appreciably from 2006 to 2015, and the prevalence of multidrug resistant tuberculosis was 2% in New York City in 2015, none of these factors are likely to greatly affect current tuberculosis trends.[2]

In summary, our results highlight that demographic changes, decreasing transmission, and the robust public health measures in place since the 1990s are not enough to explain recent trends in tuberculosis incidence in New York City. The declines in tuberculosis in the past decade are likely to reflect more recent changes in tuberculosis among the foreign-born population: a decrease in imported subclinical tuberculosis or ongoing declines in progression to active disease. Whether tuberculosis incidence continues to decline in the coming decade depends on the ability to sustain these mechanisms. In the absence of additional interventions, ongoing reductions in tuberculosis incidence are far from certain. Further study can help to refine predictions and focus finite tuberculosis control resources. In the meantime, the results of our model argue for redoubled public health efforts and corresponding financial support if the successes against tuberculosis of the past decades are to be continued in the years to come.

Contributors

ATF, DWD, NLS, ASA, and SDA conceived the study. All authors contributed to the study design. ATF, NLS, and ASA developed the model. NLS and SDA collected and synthesised the data from New York City records. ATF did the data analysis and wrote the first draft of the manuscript. All authors contributed to the data interpretation and critical review of the manuscript.

Declaration of interests

We declare no competing interests.

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