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MAJOR ARTICLE

Getting Personal: How Childhood Vaccination Policies Shape the Landscape of Vaccine Exemptions

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Background. State-mandated school entry immunization requirements in the United States play an important role in achieving high vaccine coverage, but variations in vaccine exemption policies result in a patchwork of vaccine coverage across the country.

Methods. In this study, we evaluate epidemiological effects and spatial variations in nonmedical exemption (NME) rates in the context of vaccine policies. We first analyze the correlation between NME rates and vaccine coverage for 3 significant childhood vaccinations. Furthermore, we assess the effects of policy changes in a subset of states, using a correlative approach at the state level and performing a clustering analysis at the county level.

Results. We find that higher rates of exemptions are associated with lower vaccination rates of school-aged children in all cases. In a subset of states where exemption policy has recently changed, we show that the effects on statewide NME rates vary widely and that decreases in NMEs can lead to an increase in other types of exemptions. Finally, our clustering analysis in California, Illinois, and Connecticut shows that policy changes affect the spatial distribution of NMEs.

Conclusions. Our work suggests that vaccination policies have significant impacts on patterns of herd immunity. Our findings can be used to develop evidence-based vaccine legislation.

Keywords. disease ecology; herd immunity; immunization.

Immunization requirements for school entry play a key role in achieving high levels of vaccine coverage against communicable diseases in the United States [1]. However, this patchwork of childhood immune protection is punctured by heterogeneous, state-specific vaccination exemption rules. Medical exemptions to mandated vaccinations are available in all 50 states, and 47 offer nonmedical exemptions (NMEs) in some form. Eighteen states offer personal belief exemptions for those who object to vaccinations for philosophical or moral reasons, and in the remaining states they are limited to religious beliefs. Finally, California, Mississippi, and West Virginia only offer medical exemptions. Although this has been the policy in Mississippi and West Virginia for decades [2], the ban on NMEs in California (enacted by California Senate Bill 277 [SB277] in January 2016) was motivated by the 2015 measles outbreak in the state [3] in which suboptimal vaccination rates in school-aged children were an important factor [4].

The ease of obtaining NMEs varies widely depending on state public health policies, from requiring a simple signature from the parents to obtaining a notarized document [5]. In general, higher rates of NMEs are found in states where policies are more permissive [1, 6, 7]. In addition, states that allow only religious exemptions have low NME rates [8], although they tend to increase faster over time [7]. Policy efforts to slow down NMEs may also have less predictable results. For instance, adopting a standardized form for exemption requests to better track exemptions may result in an increase in NME rates [8], because it may inadvertently allow the emergence of resources facilitating the filing of exemptions by parents.

The impact of exemption policies on vaccination rates is also important to consider. Childhood vaccination rates tend to be lower in states with more permissive exemption policies [9], and, in states allowing personal belief exemptions, higher levels of exemptions are associated with lower levels of measles, mumps, and rubella (MMR) vaccination [10]. The positive impacts on vaccination rates of increasing the difficulty of obtaining NMEs have also been observed in Washington in 2011 [11] and California from the 2012–2013 school year [12]. Some of these impacts on vaccination rates may be limited because children may enter school without being fully vaccinated through other means such as conditional admission or continued noncompliance. However, assessing the association between policy changes and NME rates remains necessary in other states and policy contexts. California's success in eliminating

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NMEs comes in contrast with several failed legislative attempts in other states [9]. Because the success of legislative actions in reducing NME rates varies, we need to assess variations in rates over consecutive years in different policy and epidemiological contexts.

In this study, we focus on the epidemiological effects and spatial variations in NME rates, and we place it in the context of public health policies. We first assess the association between state-level NMEs and vaccination rates for 3 common childhood diseases. We expect that increased levels of exemptions result in decreased levels of immunization. If this association exists, policy changes effectively reducing NMEs would likely increase immunization levels. We thus focus next on the state-level dynamics of NME rates over several school years in a subset of states with recent vaccination policy changes. Policy changes may affect NME rates in a spatially inhomogeneous manner. To assess changes in spatial structure, we examine 4 instances of vaccination policy changes at the county scale. Our analysis highlights how weak vaccination policies result in high NME and low vaccination rates, producing hotspots of susceptible school-aged children for a number of vaccine-preventable immunizations.

MATERIAL AND METHODS

We assessed the association between NME rates and vaccination rates for school years 2016–2017 and 2017–2018 using data in kindergarten from 48 states and the District of Columbia [13, 14]. No vaccination data were available for Oklahoma in 2016–2017, and neither vaccination nor NME rates were reported for Wyoming in both years. Diphteria, tetanus, and acellular pertussis (DTaP) coverage was also not available for Pennsylvania in 2016–2017. To test the associations between the proportion of NME and vaccination rates, we used a beta regression approach [15]. This analysis was run in R version 3.5.0 [16].

A subset of 6 states have made it harder to obtain NMEs between 2012 and 2016 [5]: Alaska (2013), Oregon (2014), Illinois (2015), Connecticut (2015), Missouri (2015), and Michigan (2015). In addition, in 2016, Vermont disallowed philosophical exemptions to only allow religious exemptions [17]. Finally, the state of California has strengthened its school immunization policies twice in the past decade: NMEs were made harder to obtain from the beginning of school year 2014–2015, and in 2015 new NMEs were barred from the beginning of the 2016–2017 school year [18]. For these states, we compiled data on NMEs in kindergartens from the Centers for Disease Control and Prevention (CDC) annual school report results between 2003–2004 and 2010–2011. We note that these reports were accessed online in July 2018 [19], but are no longer accessible, and that the data provided by the CDC may have been unverified. Starting in school year 2011–2012 and up to school year 2017–2018, we obtained data from published annual surveys [13, 14, 20–24]. Because of inconsistencies in data reporting for Illinois and Missouri for the period around the policy change, we did not include these 2 states in our analysis. In addition, less than 10% of enrolled students were sampled in 2010–2011 and 2011–2012 in Alaska, and these 2 years were not included in the dataset. We used a linear regression on years before the policy change to forecast NME rates in the absence of that change. In Vermont, we fitted the regression starting from school year 2008–2009, because of the sudden increase in NMEs during the school year 2007–2008. We expect an effective policy change to lead to the data diverging from the forecasted trend.

Finally, we collected county-level data on NMEs from state health departments in 3 states, including 4 instances of policy changes. In California, we obtained data on NMEs in kindergarten covering the period 2013–2014 up to 2016–2017, covering policy changes at the beginning of the 2014–2015 and 2016–2017 school years, respectively. In Connecticut, we included data on NMEs in kindergarten for the school years surrounding a policy change in 2015. Finally, in Illinois, we compiled data on MMR-specific NMEs in all school-aged children for the 2 years surrounding a policy change in 2015. To analyze variations in the spatial structure at the county level after policy changes for each state and year, we computed Moran's I adjusted for rate variables, using queen contiguity spatial weights [25]. We also calculated the mean and variance in relative risk of NMEs at the county level by dividing the number of NMEs in a county by the expected number of exemptions in the absence of spatial variability. The expected number was calculated by multiplying the number of enrolled students by the state average rate of NMEs. To better capture the direct effects of the policy change on the relative risk, we used the year before the policy change as the baseline in the calculation in both the year prior and the year immediately after the change. Finally, we performed a spatial clustering analysis for each state before and after the change in policy using local Moran's I [26] adjusted for rate variables [25], to detect clusters of high and low rates of NMEs. Spatial weights based on contiguity were used for this calculation as well. We focus on how high and low clusters are determined surrounded by similar values (ie, HH and LL for high and low values, respectively). Moran's I and local Moran's I calculations were performed using the PySAL 2.0 module [27] in Python 3.6.3. We note that alternative techniques, such as for instance SaTScan [28, 29], could have been used, but it would be generally expected to provide similar answers [30, 31].

All data used in the manuscript, and codes for the statistical analysis, are available on Github at github.com/BansalLab/NME.

RESULTS

First, we analyzed the association between NME rates and MMR vaccination levels for 2016–2017, including all states irrespective of the breadth of the NMEs they allow. We found that higher rates of NMEs are associated with lower vaccination rates for the MMR vaccine (Figure 1A; beta regression estimate = −13.9; *P* = .001), as we expected based on the analysis of Olive et al [10]. Furthermore, similar significant negative associations were present for DTaP (Figure 1B; beta regression estimate = −14.0; *P* = .002) and varicella (Figure 1C; beta regression estimate = −10.0, *P* = .02). We also obtained similar negative associations between NME and vaccination rates for school year 2017–2018 (Figure 1D–F). Full results for the beta regressions can be found in Supplementary Table 1. Because the District of Columbia appeared to be an outlier, we have rerun the analysis without it. We find that all associations remain significant, and that the strength of the relations is largely unaffected (Supplementary Table 2).

We considered how changes in state public health policies affected NME rates between school years 2003–2004 and 2017–2018 (Figures 2 and 3). First, in Vermont in 2008, the levels of NMEs have increased rapidly from the previous year, in relation to a new requirement for immunization against hepatitis B and varicella being enforced at the beginning of the 2008–2009 school year. After this sudden increase, NME rates showed no trend between 2008 and 2015 (linear regression, *P* = .38). In all other states, NME rates increased significantly from school year 2003–2004 until the considered policy change (linear regression, all $P \leq .007$). Differences between the forecasted levels of NMEs and the actual NME rates highlight a number of situations (Figure 2). In some cases (Alaska, Connecticut), rates continued to increase at apparently similar rates after the policy change. In all the other cases, decreases were observed, with most appearing to only have temporary effects (Oregon, Michigan, California in 2014). Finally, eliminating either the philosophical exemption in Vermont or NMEs altogether in California appears to have the strongest effect. However, in Vermont, the loss of philosophical belief exemptions was partly compensated by a sharp increase in religious exemptions, from 0.1% in school year 2014–2015 to 3.7% in 2016–2017 (Figure 3A). The decrease also appeared much slower in the second year after philosophical exemptions were banned. Likewise, in California, the sharp decrease in NME rates was

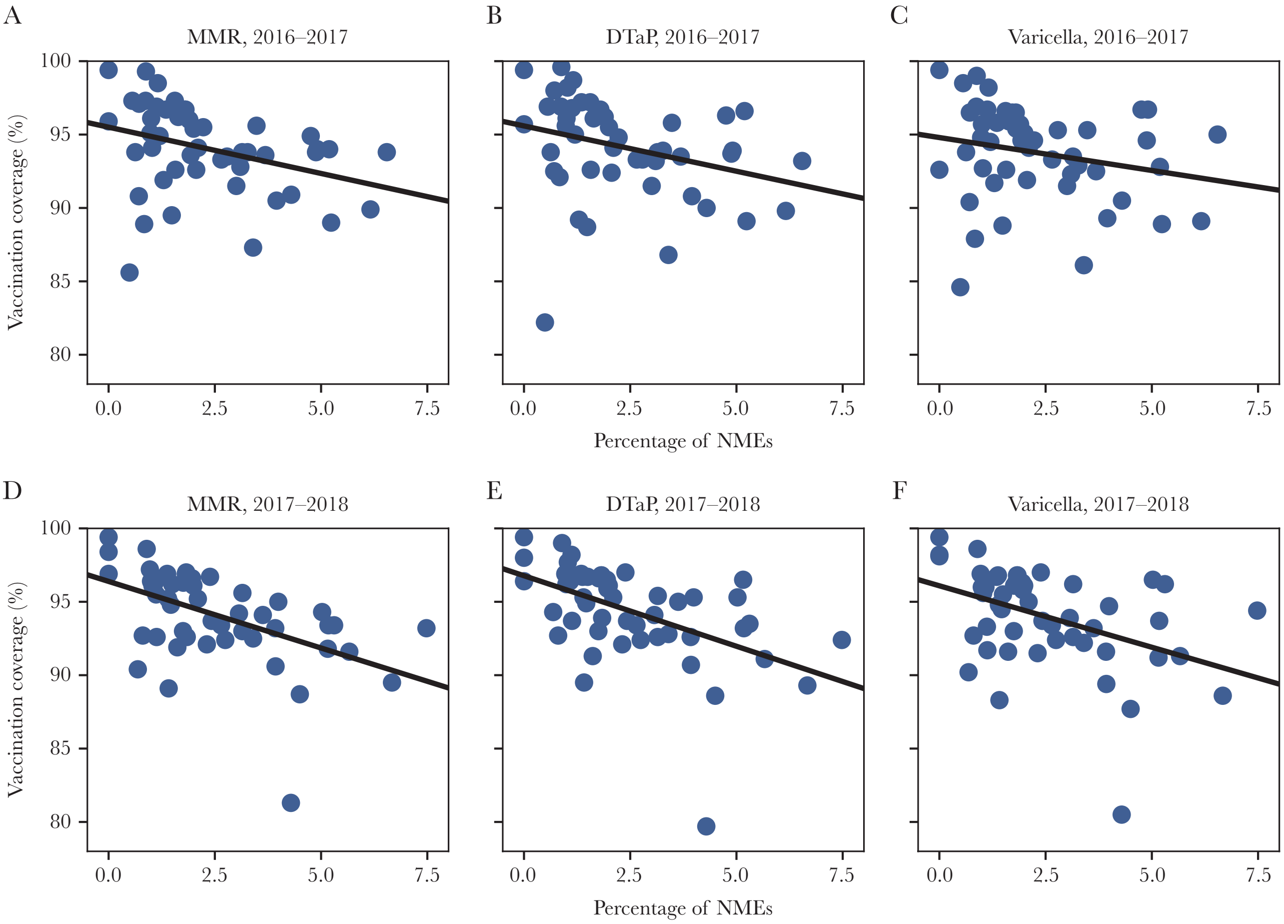

Figure 1. Association between percentages of nonmedical exemptions (NMEs) and vaccination coverage at the state level in school year 2016–2017 (A–C) and school year 2017–2018 (D–F) for 3 common childhood vaccines: (A) measles, mumps, and rubella (MMR); (B) diphtheria, tetanus, and acellular pertussis (DTaP); (C) varicella; (D) MMR; (E) DTaP; (F) varicella.

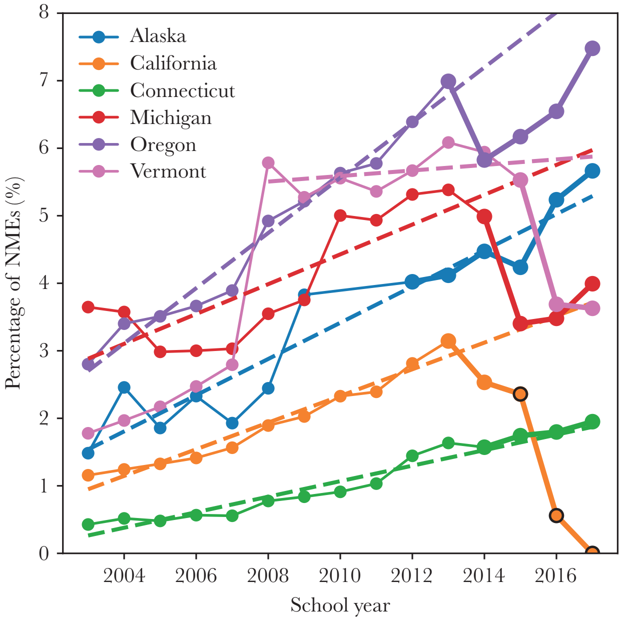

Figure 2. Dynamics of nonmedical exemption (NME) rates between the school years 2003–2004 to 2016–2017 in 6 states with recent exemption policy changes. The solid line presents the data, whereas the dashed line represents the prediction of a linear regression fitted to the years before the first policy change in a state. The model was only fitted starting in 2008–2009 in Vermont. The transition from thinner to thicker lines indicates where the policy change took place. The second policy change in California is further indicated by a change in the marker outline.

partly matched by a concurrent increase of medical exemptions from 0.17% in 2015–2016 to 0.51% in 2016–2017 (Figure 3B), probably in relation to how SB277 has provided for more physician discretion in the assessment of medical exemptions [18]. Reported exemption levels reached near zero as early as 2017–2018. Of note, even though medical exemptions have increased in California, there is still an overall clear decrease in total exemptions, whereas the picture remains comparable in all other analyzed changes (Supplementary Figure S1).

Analyses of Moran's I showed that rates of NMEs showed spatial variability at the county level in all 3 states on which we focused (Table 1). In Illinois, there is significant spatial structure in both years, with limited changes to Moran's I before and after the policy change (2014–2015, Moran's I = 0.177; 2015–2016, Moran's I = 0.222). In California, spatial structure was affected by the first policy change, with Moran's I dropping by more than half in school year 2014–2015 compared to 2013–2014. However, Moran's I values indicated that spatial structure was significant again in school year 2015–2016. This result is in line with the effect of the first policy change being less important in the second year (as shown on Figure 2). Most significantly, the second policy change eliminating NMEs resulted in an important loss of spatial structure with Moran's I dropping to a low nonsignificant value in school year 2016–2017 (Moran's I = 0.01; $P = .297$). We find that there is no significant

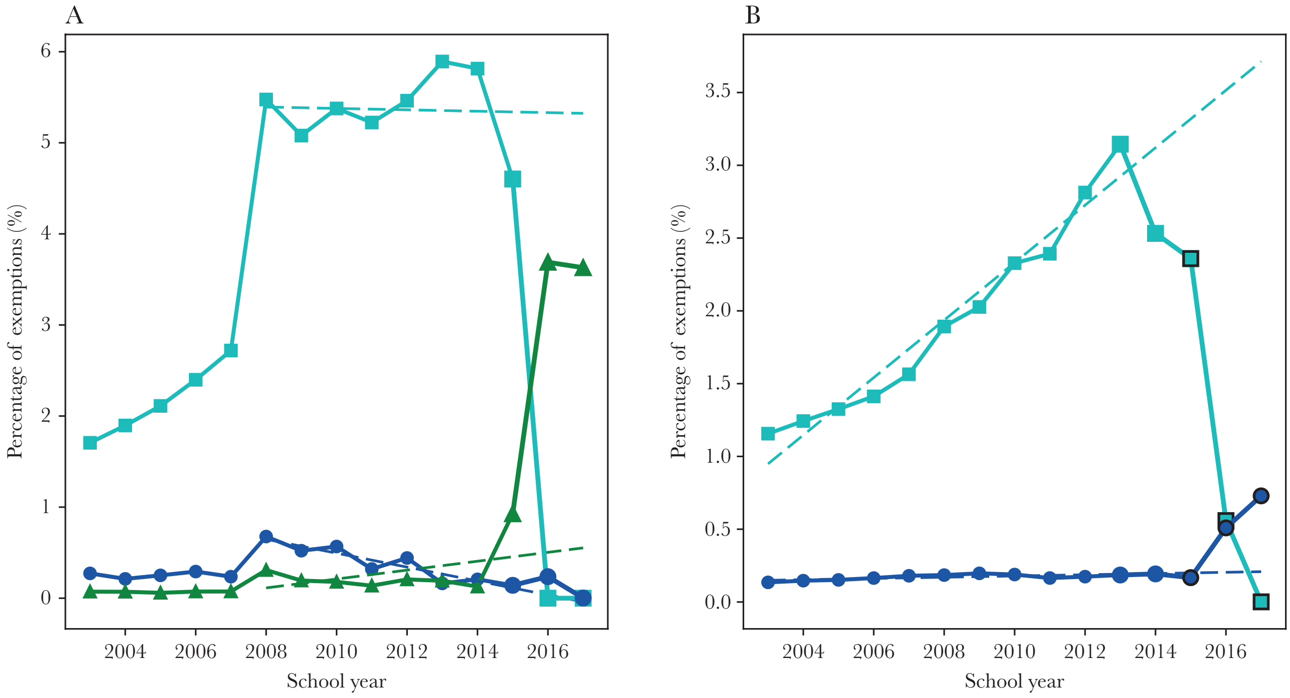

Figure 3. (A) Dynamics of philosophical belief exemptions (light blue), religious exemptions (green), and medical exemptions (dark blue) in the state of Vermont. (B) Details of the dynamics of total nonmedical exemptions (light blue), and medical exemptions (dark blue) in the state of California. In all panels, the solid line presents the data, whereas the dashed line represents the prediction of a linear regression fitted to the years before the first policy change. The model was only fitted starting in 2008–2009 in Vermont. The transition from thinner to thicker lines indicate where the policy change took place. The second policy change in California is further indicated by a change in the marker outline.

Table 1. Moran's I and Significance of Moran's I Computed on NME Rates at With County as the Neighborhood[a]

School Year	State	Moran's I	Moran's I *P* Value	Relative Risk Mean	Relative Risk Variance
2013	California	0.247	0.003	1.738	2.265
2014	California	0.108	0.068	1.913	2.858
2015	California	0.220	0.007	1.832	2.717
2016	California	0.010	0.297	0.154	0.049
2014	Connecticut	−0.192	0.453	1.202	0.156
2015	Connecticut	−0.131	0.448	1.314	0.196
2014	Illinois	0.177	0.003	1.010	0.635
2015	Illinois	0.222	0.001	1.062	0.720

Abbreviations: NME, nonmedical exemption.

[a] Mean and variance of the relative risk of NMEs at the county level. Relative risk is calculated as observed exemptions relative to the expected exemptions based on the mean NME rate in a state and the enrollment in a county in a given year. The year before the relevant policy change is taken as the baseline in both the year before and the year after the change. Three states (California, Connecticut, and Illinois) for which data were available at the county level are included. Policy changes occur at the beginning of school years 2014 and 2016 in California and of school year 2015 in Connecticut and Illinois.

spatial structure in Connecticut both before and after the policy change. However, because Connecticut only has 8 counties, this result needs to be taken with caution.

In addition, we find that most policy changes have no apparent effect on the mean and median relative risk of NMEs at the county level (Table 1). However, a reduction in both the mean and the variance of the relative risk is observed between school years 2015–2016 and 2016–2017 in California, when new NMEs become unavailable. This reduction of both mean and variance of the relative risk in California in school year 2016–2017 indicates that counties tend to have lower risk of NMEs and to be more similar after the policy change.

The spatial clustering analysis further shows how the policies impact the spatial distribution of NMEs (Figure 4 and Supplementary Figures S2 and S3). First, in California, the 2 policy changes had different spatial impacts. The tightening of regulations around NMEs in 2014 had some effects on the spatial clustering of NMEs (Figure 4A), with a large cluster of NMEs almost disappearing in school year 2014–2015. However, levels of NMEs remained high in all of the counties of Northern California (Supplementary Figure S3). This cluster is apparent again in school year 2015–2016 but disappears completely in school year 2016–2017 (Figure 4B), indicating a large effect of Senate Bill 277, the legislation removing NMEs, on the spatial structure of NME rates. In Illinois (Figure 4C), the change in policy does not appear to have impacted the spatial clustering of NMEs. A single large cluster of high NMEs was identified in the northern part of the state both before and after the policy change. Only a cluster of low exemptions in the southern part of the state was slightly increased after the policy change. Finally, in Connecticut (Figure 4D), we could not identify any cluster in either years, indicating that, although spatial variation is present, it does not cluster in any particular way.

DISCUSSION

We have shown that, aggregated at the state level, NME rates are negatively associated with vaccination rates for 3 major childhood vaccinations for which mandates exist. Furthermore, analyzing the dynamics of NMEs in several states with policy change history, we showed that eliminating either a subset of exemptions (in Vermont) or all NMEs (in California) appears most effective in reducing exemption rates overall. Finally, we showed that NMEs are clustered at the county level, and that only the most stringent policy change appeared to modify both the spatial structure and the mean and variance in the relative risk of NME rates in any significant way. In particular, we found that policy changes not only affect the spatial distribution of clusters of high NME rates, but they also increase the size of clusters of low NME rates.

The association between childhood vaccination rates and NMEs has important implications for vaccine-preventable childhood infectious disease risk. The heterogeneous spatial distribution of NMEs is likely to result in spatial variability in vaccination rates, which in turn would create pockets of eroded herd immunity where outbreaks of vaccine-preventable diseases would be more likely [32]. Furthermore, we illustrate that this is true not only for MMR [10] but for a wider range of childhood vaccinations, thus compounding the public health risk posed by NMEs. Individuals with NMEs have an increased risk of contracting vaccine-preventable diseases such as measles, and higher rates of exempted individuals in the population can increase the incidence of the disease in vaccine-protected populations [33]. Intentionally unvaccinated individuals make up large proportions of cases in outbreaks of both measles and pertussis in the United States [34], and they can unwittingly be the starting point of epidemics that may take hold in populations with relatively high vaccination rates [35]. The potential cocirculation of childhood infections also raises concerns of immunological and ecological interference between the diseases [36, 37].

We highlight that policies that reduce the spatial structure of NME rates are key to eliminating pockets of susceptibility and minimizing the risk of childhood disease outbreaks. Our work suggests that making NMEs more difficult to obtain by increasing

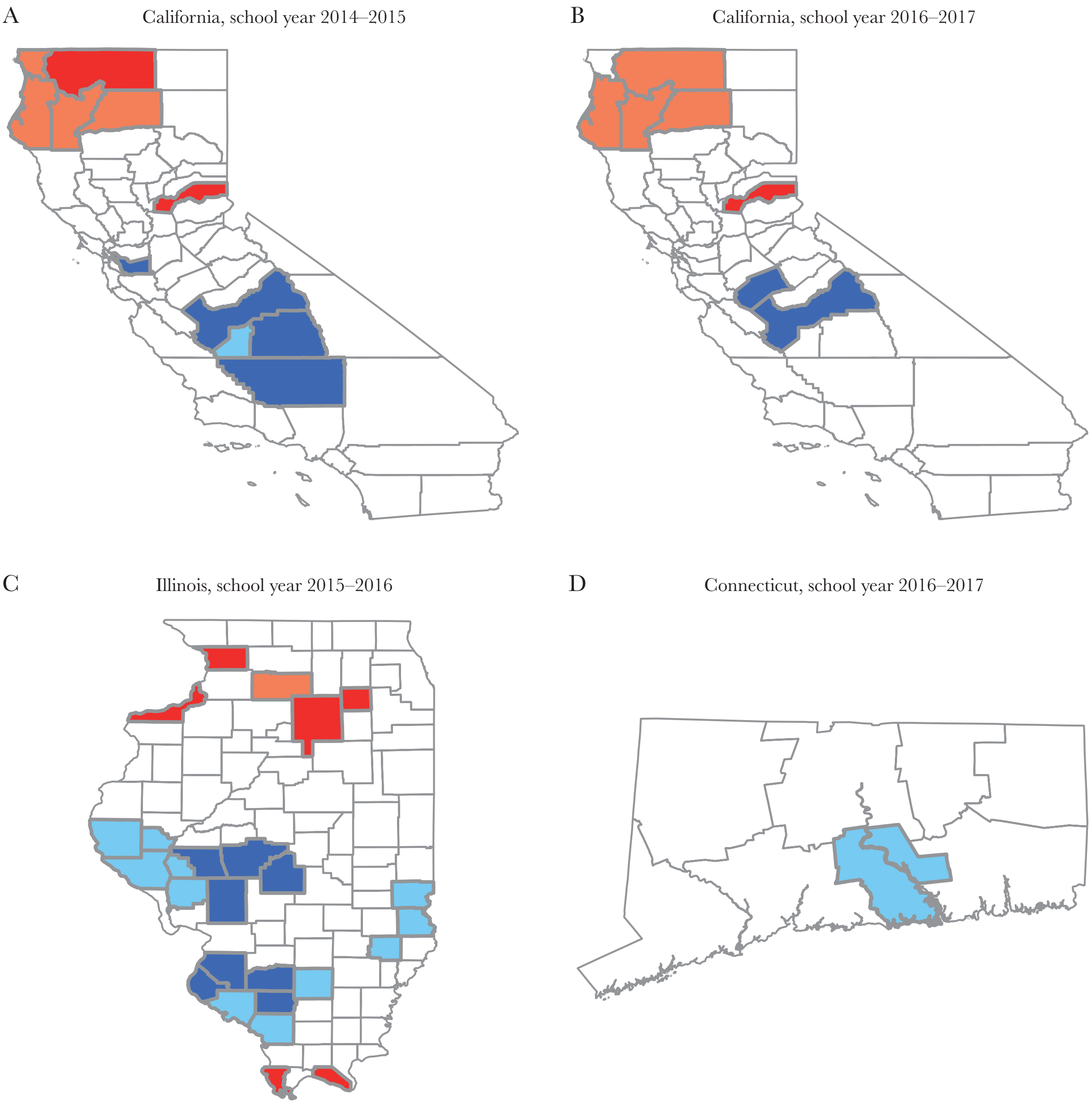

Figure 4. Maps showing the clustering of the proportion of nonmedical exemptions (NMEs) before and after a policy change. Counties belonging to a high cluster in the year preceding and succeeding a policy change are shown in red; counties belonging to a high cluster in the year preceding a policy change only are colored in light red; counties belonging to a low cluster in the year preceding and succeeding a policy change are shown in blue; and counties belonging to a low cluster in the year after a policy change only are colored in light blue. Counties outlined in gray were never included in a high or low NME cluster. (A) California NME proportions with clusters highlighted from school years 2013–2014 and 2014–2015; (B) California NME proportions with clusters highlighted from school years 2015–2016 and 2016–2017; (C) Illinois NME proportions with clusters highlighted from school years 2014–2015 and 2015–2016; (D) Connecticut NME proportions with clusters highlighted for school years 2014–2015 and 2015–2016.

the administrative burden for parents can have spatial effects but is unlikely to achieve this goal. These partial effects are evident in the reduction of conditional entrants after SB277 in California, which may be at least partly attributed to education requirements introduced before this bill [38, 39]. A similar spatial analysis of Vermont would be needed to assess whether the partial removal of NMEs has similar effects. In addition, we highlight that data at finer spatial scales could reveal the presence of these spatial effects below the county scale. It is interesting to note that the high clusters we identified at the county level in California appear to match school-level clusters [40], except in school year 2016–2017 where we could not detect a cluster in Northern California that was found at the school level. Although this may be partly explained by the need to impute school-level data but having readily available county-level data, it may also highlight the importance to consider smaller spatial scales.

The immediate benefits of policy changes may also markedly differ depending on whether NMEs are granted for several years (as was the case in California) or require annual renewal because of state or school policies [41]. Existing exemptions may indeed be grandfathered into the system, and it may take several years for existing NMEs to fully expire. In the case of California, a zero NME rate was estimated to only be achievable by 2022 even though no new NMEs have been granted since the beginning of school year 2016–2017 [42]. This means that a return to optimal herd immunity levels may take several years. The overall decrease in new exemptions and the spatial effects we observed within 1 year of the new law coming into effect indicate that California is on track to achieve that goal. However, the risk of replacement by spatially clustered medical exemptions [18] should not be underestimated.

We also argue that the context of what alternative exemptions are available to parents needs to be taken into account to maximize the increase in vaccination coverage. Both the increase in religious exemptions in Vermont and in medical exemptions in California points towards parents seeking alternative exemptions whenever possible. The positive relationship between an increase in medical exemptions and past rates of NMEs in California also supports this idea [18]. An increase in medical exemption could be expected in response to any increase in the difficult of obtaining NMEs [11]. However, states where NMEs are hard to obtain have only slightly higher medical exemption rates if the procedure to obtain these exemptions remains stringent [43]. The greater discretion afforded to medical professionals in granting medical exemption in California, introduced in SB277 alongside the elimination of NMEs, may thus be partly to blame for the sharp increase in medical exemptions at the start of the 2016–2017 school year [18, 44]. Although the child's healthcare professional is often in the best position to offer relevant counsel on immunization to vaccine-hesitant parents [45], parents may put pressure on providers to obtain medical exemptions and/or turn to more sympathetic providers [11]. In addition, recent studies have shown a rise in conditional admissions after an exemption policy change [11] (which is not something we included in our analysis), thus further consideration of effect of this category of students is also needed [12]. Variable proportions of conditional admissions could, for instance, partly explain the noise in the association between NME rates and vaccination rates. Likewise, we did not analyze the potential impact of the homeschooling and remote schooling of children, whose parents may remain harder to convince with the type of policy change enacted in California [46]. We argue that, to maximize the effects of the elimination of (some) exemptions, efforts should be made to keep other types at least as difficult to obtain as they were before the new policy. Further actions to curb unwarranted medical exemptions, such as that taken by the Medical Board of California [47], represent a step in that direction.

More generally, the question of whether a model with only medical exemptions would be well accepted and/or enforceable in the United States is an open question [2, 48]. Monetary incentives have been suggested to discourage parents from obtaining NMEs, in particular in the form of fees [49]. The rationale is that fees would reduce the convenience of NMEs and result in increase of vaccination rates, whereas any money collected would help alleviate the financial burden that vaccine-exempt individuals place on taxpayers. Another possible option, used for instance in Australia, could be to tie welfare payments to children vaccination records [50]. However, evidence from the Australian model shows that the decision to reconsider vaccination decision in that model is only significant in the fraction of the population that depends on financial aid [51]. In the context of the United States, this policy could thus be misguided: vaccine refusal has been shown to be more prevalent in higher socioeconomic neighborhoods [52] where welfare payments may be uncommon. From an ethical standpoint, which approach is preferable between (1) making NMEs harder to get through administrative or time-consuming hurdles and (2) outright elimination of NMEs is far from settled [39, 53–55]. Vaccination mandates can indeed be effective, but they can also trigger backlash and serve to strengthen groups opposing vaccination [39, 55]. Even though there is a strong legal basis that would allow states to ban NMEs [56], partial elimination targeting diseases whose transmission is primarily school based, such as measles, may be preferable to avoid further strengthening antivaccine sentiments [45]. Communication around the benefits and safety of vaccines should represent a key component of any elimination effort, even though education of vaccine-refusing parents has proven challenging [57]. In any case, although the exploration of models used in other countries around the world provides useful data, understanding the local and national context is likely to be key to the implementation of a successful policy aimed at maximizing vaccination rates and herd immunity [58].

CONCLUSIONS

The benefits of herd immunity for childhood infections cannot be overstated. The reduction of NME rates through NME policies remains a powerful tool in the fight to maintain herd immunity. However, effective policies regarding vaccination exemptions require careful evaluation of the relative costs and benefits in the near and long term.

Supplementary Data

Supplementary materials are available at *Open Forum Infectious Diseases* online. Consisting of data provided by the authors to benefit the reader, the posted materials are not copyedited and are the sole responsibility of the authors, so questions or comments should be addressed to the corresponding author.

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Author contributions. R. G. and S. B. conceived the work. R. G. and E. R. N. compiled the data and performed the analysis. All authors substantially contributed to manuscript draft and approved the final version.

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