Technical Appendix for Individual-based modeling of potential poliovirus transmission in connected religious communities in North America with low uptake of vaccination

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A1. Description of study population districts

A1.1. Initialization of districts

An Amish district constitutes of a cluster of Amish households, the inhabitants of which share church service, send their children to the same school and maintain close contact. Families host church services in their barns on a rotating basis.[27] As illustrated in Figure 1, study population districts distribute throughout the United States (especially the eastern states) and the Canadian province of Ontario. We know the approximate locations of these districts from the address of a district contact person and use estimates of their relative level of conservatism.(Kraybill D.B., personal communication) Detailed information about the structure within districts remains limited, such as the distance between Amish households, the number of non-Amish people living interspersed with the Amish, and the heterogeneity between districts in different regions.

In our model, every district populates with households of people according to the same rules, but with certain stochastic features that make each district slightly different. The first step of the district initialization process determines the number of people in each district. Table A1 shows that the current reported average Amish district sizes differ by state. For example, the average district size in Ohio of 135 (close to the overall average of 136) differs from the average district size in Pennsylvania of 148.[26] For states with relatively very few Amish districts (e.g., those founded relatively recently) reliable estimates do not exist. We estimated the long-term average district size by state from both the reported average by state a_s and the overall average a_o, giving the latter more weight for states with relatively few districts: $a = w * a_s + (1 – w) * a_o$, with w = (number of districts in state)/(highest number of districts in a state). The assumed average district size of Ohio (the state with most districts) thus equals the actual reported average for Ohio, while the assumed average in Florida, with one reported district, falls very close to the overall average. Table A1 lists reported and derived long-term average district sizes by state.

To estimate the actual distribution around the long-term average we must consider the district splitting process already mentioned in the main text. A district splits when its population reaches the state-dependent split size, which we assume relates directly to the long-term average district size. The two newly formed districts (one of which remains at the original location) continue to grow incrementally until they again reach the split size. Given that births and marriages occur in proportion to the district size, districts tend to maintain a relatively low population for a relatively high amount of time. In addition, the splitting cycle ensures that every large district eventually gets replaced by two smaller districts, further increasing the relative number of small districts at a given point in time. When assuming a constant growth rate, these two effects together lead to a theoretical aggregate distribution of district sizes (around the long-term average by state) shown in Figure A1. This implies that the smallest district sizes (i.e. split size/2) occur four times more often than districts approaching their split size. From this distribution it follows that we can calculate the split size by multiplying the average district size by 1.44 such that split size scales directly with the average district size (see Table A1 for the assumed split size by state).

After determining the number of people in each district by sampling from the distribution shown in Figure A1, the model creates a physical layout with fixed boundaries such that each district consists of a grid of 11x11 cells with each cell representing a square area of land of 500x500m. The model then assigns the locations of special places (e.g. school, playground) and households within the district area. First, it creates a school near the center of the district. Then, the district iteratively creates households and locates them according to a stochastic procedure starting from the district center, repeatedly jumping a randomly distributed number of cells in any direction from the center until finding a vacant cell. The procedure leads to district lay-outs that include some realistic distance between households (e.g. allowing for the presence of non-Amish people, infrastructure, natural obstacles), which influences proximity to other household and districts and therefore to some extent selection of contacts during activities and events (see Appendix A2). After assigning the household location, the model composes the people in the household by selecting the number of individuals and their ages and genders from a distribution of possible compositions as described in the next section. The iterative addition of households repeats until the model reaches a population threshold of 7 fewer than the split size, which leads to no expected overshoot of the target population.

A1.2. Household composition

In the absence of data, we sought to develop a realistic initialization method for populating households in the model, consistent with other modeling assumptions. Considering the limited data from a case study in an Amish settlement that reported an average age of marriage for women of approximately 22 years (range 17-31 years)[41] and data from a more recent study[32], we developed the distribution shown in Figure A2 for the age of the wife at the time of marriage. We assumed that Amish men marry women of approximately the same age[41] (i.e., within 0, 1, or 2 years of their age, with husbands 1 year older than their wives on average). This assumption does not affect the model dynamics much, but it allows some flexibility when trying to couple husbands and wives in the model, which keeps the non-marriage rate close to reported numbers.[28] In our calculations we assume that birth rates remained constant since the year 1900, which reflects our assumptions that the Amish do not rely on modern technologies for population control. In our reconstruction of population growth since 1900 (see below) we used the official 2010 mortality rate estimates for white, non-Hispanic Americans as basis for current mortality rates by age.[42] Based on reported birth and growth rates, we calculated a multiplier over the 2010 mortality rates of 1.2, which implies 20% higher mortality rates for the Amish in our analysis compared to aggregate rates for white, non-Hispanic Americans.

We assume that the youngest son of an Amish couple (if any) will continue living in the same household as his parents, even when he gets married (95% of all Amish people eventually get married[28]), in which case his wife moves in as well. This process results in structured households in which family members of several generations may live together for as long as they live. In the model, we consider the most-recently married couple in a household the 'core' couple, or core family when including their children. Non-core families then live in the same household as their married youngest son. Some of their unmarried children may also still live with them, and no one lives alone. We construct the study population in the model using a rigorous iterative statistical algorithm that samples from basic input distributions of individual and household properties, such as birth year, life expectancy, age of marriage, age difference between husband and wife, and final number of children in completed families, which we derived from the literature to the extent possible. We verified the consistency of all input distributions (and output distributions, see below) with reported demographic data in the literature. Based on the input distributions, we derived a joint distribution for all possible household compositions of core and non-core families (conditioned on the age of the (married) youngest son), in terms of year of marriage, age of the wife, age difference between husband and wife, number of children, and husband and wife survival. Assuming birth of the first child (if any) always occurs one year after marriage and each subsequent child after a fixed time interval of 1.5 years,[41] we derive the birth years of all family members.

We assume that all children except the youngest son move out of the household at the moment they get married. For households with a husband and wife, Figure A3 shows the distribution we used for the number of children in Amish households derived from limited available data that suggest an average of 7.1 births per family with 10 or more children in 13% of families[28] and only 4.4% of all families remaining childless.[31] Furthermore, we assumed a maximum childbearing age of 44 years (less than 1 birth per 1000 women in that age group in the US[43]), and no twins or multiple births.[41]

Based on these assumptions, we reconstructed the household composition distribution by propagating the assumptions on all births, marriages, and deaths since 1900. First, we derived a distribution and current status of all married Amish couples since 1900. This involved reconstructing distributions for the number of women born in each year, with the age of the wife and husband determined probabilistically along with the chance of either dying during a prior year. The resulting distribution lists all possible combinations of birth year for women, age of marriage for women, age of death for women and men, and age difference between the spouses. The second step extends this information by adding the assumed distribution of the number of children of each couple constrained by the age of marriage, such that not all couples can reach all possible family sizes. We combined the results of these steps and derived a distribution of household compositions in terms of the year of marriage, age of marriage for women, the current number of children (i.e., at the simulation start day), and the 'sequence' number of the youngest son if already married. Complimentary additional distributions, conditioned on the listed attributes, correctly derive additional information, such as the target number of children, the age difference between husband and wife, and the probability of survival of the family members.

The model uses the distributions to populate households during initialization by first sampling a composition for the core family, then determining the probability (i.e., roughly 32%) that a given Amish person in the core family represents the youngest son of his parents, and then adding non-core family members until complete or until the age of the last added male exceeds 90 years.

The household initialization procedure generates households of 6.7 people on average, which appears consistent with the reported average district size of 135 people[26] and number of households per district of 20.[28] The model uses an age distribution consistent with numbers from highly variable results in case studies from Indiana[31] and Lancaster.[28] Following the generation of a household and its population with people of certain gender and age, the model creates ties between infants and their mother.

<u>A1.3. Practical implications of district splitting in the model</u>

Whenever a modeled district reaches its split size during the simulation, the model randomly picks households (representing approximately half the district population) to split off and then relocates the families to a new location. From the reported growth in the number of settlements and the number of districts over time,[26] it follows that approximately 75% of new districts adjoin their originating settlement, thereby simply increasing the number of districts in that settlement. The model captures this by simply assigning a location within 10 km of the original location. The remaining 25% of new districts moves to an isolated location with respect to other Amish settlements, thereby creating a new settlement. The model repeatedly selects a location at a random distance in a random direction between 50 and 1500 km from the source district until it locates a site within a US or Canadian territory with arable land and low urbanization based on data obtained from open-source GIS projections[44] and processed with ESRI *ArcGIS for Desktop*™[45]. We assume that new districts keep the same mindset as the district from which they originated.

A2. Activities

Table A2 describes each of the more than 30 activities included in the model, the associated locations, and inputs for characterizing contacts and transmission. Table A4 shows the daily activity schedules for each age group for all weekdays and Sundays. Table A3 provides more details about the seasonality of the timing of Amish weddings.

A3. Compatibility of activities and contributions to transmission associated with specific individuals and activities

Table A5 provides our assumptions related to compatibility of activities with respect to generating contacts. Since infections only transmit between infectible and infectious individuals, the model only tracks person-to-person contacts that involve infectible people. When the composition of the individuals in contact with an infectious person changes the model reselects the contacts for that infectious person.

We analyzed the results of iterations on low immunity settings (HIF low, IPV low) to explore the characteristics of the population and the importance of various age groups and activities with respect to transmission. From this analysis, we observe that over 63% of all infections originate from infants and children, while they constitute 47% of the population. In contrast, adult men working in their own business or somewhere outside the district contribute disproportionately little to transmission (i.e., 8% of all transmission despite accounting for 13% of the population). Fully susceptible people account for 83% of all transmissions, with the remainder of transmission occurring as a result of reinfection of partially susceptible individuals (e.g., children with IPV protection exposed to a live poliovirus for the first time, reinfections in individuals with waned immunity).

Approximately 74% of all transmissions occur between people living in the same household, and fewer than 5% of transmissions occur across districts with occasional visits by individual families representing the primary source for inter-district transmission (over 70%). Since we assume lower transmission probabilities for larger congregations of people (e.g. church service, family events, barn raisings, auctions), those events contribute far less to overall transmission, although family events still represent an important source of transmission over longer distances.

A4 Detailed assumptions related to infectiousness and waning curves

Figure A4 shows the assumed curves representing relative infectiousness following a LPV infection for seven immunity states.[11]The curves derive from following infected people in each immunity state through 2 latent and 4 infectious stages in the DEB model[11] and determining the average relative infectiousness according to the proportions residing in each stage using the average duration of infectiousness for each immunity state and the overall relative infectiousness of the immunity state compared to fully susceptible individuals and the relative weights for each infection stage (i.e., 0 for latent stages, and > 0 for infectious stages).[11] The curves represent the combined infectiousness for fecal-oral and oropharyngeal transmission with a relative contribution of oropharyngeal transmission of 0.8, consistent with our prior assumption for the US.[11] Although variability within each immunity state probably exists, we assume that all infected individuals from the same immunity state go through the same infectiousness curve (i.e., we do not include stochastic around the infectiousness curves).

Figure A5 shows the cumulative probability distribution for the total duration between the 'recent' and 'historic' immunity states, as described in the main text and based on prior work.[11] This distribution results from a five-stage process with an average total duration of four years. The resulting distribution represents a gamma distribution. [46]

A5. Details about NetLogo implementation and code

We implemented the model in NetLogo,[38] a platform designed for agent-based modeling. Our NetLogo model uses three root types of agents referred to as patches, turtles, and the observer. Patches represent the two-dimensional squares that together form a grid that constitutes the modeled world. Turtles move over these patches and interact with each other. The observer controls the world and coordinates actions as necessary.

In our model, patches represent squares of land of 500x500 meter. The model constructs districts as a subtype of turtles that cover a fixed grid of 11x11 patches. The districts in turn form a high-level grid in the model, with no relation to real-world geography: X and Y coordinates represent attributes of the districts, with a distance matrix storing the actual distances between them. We use the district data for 2010 (see main text), combined with known aggregated data on the number of districts by state in 2012. The model initializes the map by creating the districts present in the 2010 dataset and then adds districts (or removes them in rare cases) according to the more recent state aggregates. New districts locate according to the district locating process described above. As the population grows, so does the number of districts and thus the number of occupied 'cells' (subdivided into patches) on the district grid. 'Households' (another non-moving turtle subtype) and other locations within districts all cover exactly one patch. Their location within the districts generates stochastically based on some empirical rules (see main text). 'People' constitute the final subtype of turtles in our model, with demographic and disease-related attributes. They move around between patches, based on the generation of activities. Table A6 lists for the 'district' and 'people' agent types the key attributes and the values they can take.

The model uses time steps of 30 minutes, days of 48 time steps and years of 365 days. With regard to school attendance, we assume a summer break between June 1 (day nr 152) and September 30 (day nr 243).

In the 'go' phase, agents perform the following: (1) Evaluate demographic processes (see main text) , (2) change activity based on schedule, (3) given the new activity, move to new location, (4) if infectious: given the new activity and other people present, select contacts and evaluate possible transmission to selected contacts with health state 'susceptible,' and (5) update health state due to becoming exposed, infected, or recovered (see Table 1 for the key model inputs).

A6. Additional details for reported results

Figure A6 provides the results of the simulation for the introduction into Montana. Figure A7 shows the results of our R_0 tests and the implied resulting seasonal R0 curve. We find that the estimated stochastic R_0 values match the expected seasonal curve on average. Figure A8 shows a clear seasonal pattern for a sample of 10 individual runs with significant numbers of cases for HIF low and IPV low, with steep peaks during the (first) summer and troughs during the winter. Although viral transmission decreases somewhat in the fall due to colder weather, during the fall wedding season the large congregations of people (e.g., hundreds of Amish, some travelling a long distance[30,32]) promote long-distance transmission into unaffected settlements during these months, where the large numbers of infectible individuals still allow for new transmission despite the decreased transmission probabilities.

References

For references 1-40 see the main text.
41. Greksa LP. Population growth and fertility patterns in an Old Order Amish settlement. Annals of Human Biology 2002; 29(2):192-201.
42. Murphy SL, Xu J, Kochanek KD. Deaths: Preliminary data for 2010. National vital statistics reports from the Centers for Disease Control and Prevention, National Center for Health Statistics, National Vital Statistics System 2012; 60.
43. Martin JA, Hamilton BE, Ventura SJ, et al. Births: Final data for 2009. National vital statistics reports from the Centers for Disease Control and Prevention, National Center for Health Statistics, National Vital Statistics System 2011; 60:1-70.
44. USDA Natural Resources Conservation Service. USA Soil Survey Map, 2010.
45. (ESRI) ESRI. ArcGISDesktop: Release 10.1. Redlands, CA, 2012.
46. Lloyd AL. Realistic distributions of infectious periods in epidemic models: Changing patterns of persistence and dynamics. Theoretical Population Biology 2001; 60:13.

Table A1: Reported and derived statistics related to district size, by state

State	Number of Amish church districts	Reported current average district size	Assumed long-term average district size	Assumed split size (=1.44 * average district size)
Arkansas	2	75	136	196
Colorado	6	135	136	196
Delaware	10	150	137	197
Florida	1	75	136	196
Idaho	1	75	136	196
Illinois	50	140	137	197
Indiana	335	141	140	201
Iowa	58	141	137	197
Kansas	12	135	136	196
Kentucky	72	125	135	194
Maine	5	75	136	196
Maryland	12	135	136	196
Michigan	98	132	135	195

Minnesota	28	126	136	196
Mississippi	1	75	136	196
Missouri	91	117	133	192
Montana	5	135	136	196
Nebraska	4	75	136	196
New York	109	135	136	196
North Carolina	1	75	136	196
Ohio	474	135	135	194
Oklahoma	7	135	136	196
Ontario	38	135	136	196
Pennsylvania	431	148	148	213
South Dakota	1	75	136	196
Tennessee	17	125	136	196
Texas	1	75	136	196
Virginia	6	75	136	196
West Virginia	3	75	136	196
Wisconsin	127	128	134	193
Wyoming	1	75	136	196

Table A2 Overview of activities

Pre-scheduled activities				
Activity name	***Description/location/remarks***	***Gender restrictions?***	***Max. number of contacts***	***Contact type***
Sunday-afternoon activity	On Sunday afternoons, special activities occur for different groups of people. Children play together and adolescents go out together with a probability (p) of 50%. Adult and senior women quilt (p=50%), and adult and senior men meet to hunt/fish (p=30%). Otherwise, people spend the Sunday afternoon with family. On Sunday, some 'work' hours occur, but independent of occupation individuals only perform chores around the house.	(see activities in the second part of this table)	(see activities in the second part of this table)	(see activities in the second part of this table)
Church	Each church Sunday, the model randomly selects a household as the church location. Each person in church districts attends church. In no-church districts, 50% of complete households visit church in another district within 15 km and with a similar mindset. People in the other 50% of households replace church time by family time, possibly a family visit.	Same gender	5	Community
Do household (work)	People perform household chores somewhere within the household area. This may occasionally alternate with a short outgoing or incoming visit, which results in new contacts.	Same gender	5	Community
Family time	During family time, we assume people in the same household to sit together in one room. People may replace a block of family time by leaving for an outgoing visit or hosting an incoming visit.	None	No limit	Close
Eat	This is similar to family time, but no possibility of replacement by visits and with fewer contacts involved.	None	No limit	Close
Farm	Farmers work ground around the household area and may contact farmers from a neighboring household, even if from a different district.	Same gender	3 (within a range of 500 meter)	Community
Go out	Adolescents may sometimes go someplace in the district together.	None	8	Community
Infant time	Infants generally stay with their mothers, who carry them around. Infants contact other people in the household closely. During infant time, the set of contacts may change every half hour (this differs from other activities).	None	3	Close

Children's play	In their free time, children go someplace in their district to play with children of the same gender.	Same gender	5	Community
School	Every district includes one school, located somewhere near the center. All children in the district attend the school. During the summer, work time replaces school time (mixed schools with segregated play time).	Same gender	8	Community
Serving customers	Shop owners spend their work time serving customers.	None	5	Community
Rest	No contact occurs while resting, except between the husband and wife in each household.	None	1 (husband or wife)	Close
Travel	We assume some contact occurs between travelers. Travel time relates to distance: distances within the district never take longer than 30 minutes (by foot or carriage). For distances of 0-50 km, we assume an average speed of 15 km/h (by carriage). For distances of 50-250 km, we assume a speed of 40 km/h (regular public transport modes) and for distances of 250-800 km, we assume a speed of 100 km/h (including air traffic). If this puts the departure time before 5 AM, agents depart a day ahead, at 10 PM minus the required travel time (i.e., travelers sleep at an unspecified accommodation near their destination). Travel times divide in whole or half hours (minimum is 30 minutes).	None	3	Community
Work outside district (work)	Some men (25%) work somewhere outside the district (e.g., a factory). They do not contact other people in the district or with each other (assuming different workplaces) during work.	-	0	-

Stochastically occurring activities

(can only occur if no other stochastically occurring activity is already planned at the same time slot)

Activity name	Replaced activity	Probability of occurrence	Description/location/remarks	Gender restrictions?	Maximum number of contacts	Intensity of contact
Bishops meeting	All activities between 9 AM and 9 PM (excl. travel time)	0.000034 per district per day	A bishop generally attends two bishop meetings per year, together with 10-250 other bishops from districts within 250 km from the host that have a similar mindset.	Same gender	6	Community

Barn raising	All activities between 6 AM and 10 PM (excl. travel time)	0.0014 per district per day	During a barn raising, 50% of all people 14 years and older in the district construct a building with 25% of people of that age from 0-4 neighboring (<15 km) districts. Tasks of men and women differ, children can only participate during the summer, otherwise they will follow the basic schedule and attend school	Same gender	20	Community
Distant trip	All activities between 10 AM and 8 PM (excl. travel time)	0.004 per household per day (3 per year on average)	A family (i.e. all people in a household) sometimes sets for a distant trip (max distance 250 km) to a special location (e.g. a landmark or museum)	None	No limit	Close
Distant visit	All activities between 10 AM and 8 PM (excl. travel time)	0.004 per household per day (0.75 per year on average)	A family (i.e. all people in a household) sometimes sets for a visit to distant (max distance 250 km) relatives (75% same mindset, 25% different mindset)	None	No limit	Close
Funeral	All activities between 9 AM and noon	Triggered by an actual death	A funeral is like a regular church service (9:00 – 12:00), but not necessarily on Sunday and usually with more people: all people from the home district of the deceased, as well as 10-30 households from districts within 15km and 5-10 households from districts within 50 km.	Same gender	5	Community
Hunt/fish	Sunday-afternoon activity	0.3 per Sunday afternoon	On Sunday afternoon, adult and senior men may go hunting or fishing together.	Same gender	4	Community

Household auction	All activities between 10 AM and 3 PM (excl. travel time)	0.0055 per district per day (2 per year)	Every district hosts 2 household auctions per year, on average. 20% of adults and seniors from that district and from 4-9 other districts within 15 km attend the event.	None	8	Community
Livestock auction	All activities between 10 AM and 3 PM (excl. travel time)	0.011 per district per day (4 per year)	Every district hosts 4 livestock auctions per year, on average. 25% of male adolescents, adults and senior with the 'farmer' job from the district and from 4-9 other districts within 15 km attend the event.	Same gender	6	Community
Ministers meeting	All activities between 9 AM and 9 PM (excl. travel time)	0.00004 per district per day	The two ministers of a district generally attend two minister meetings per year, together with 10-250 other bishops from districts within 250 km from the host that have a similar mindset.	Same gender	6	Community
Random family event	All activities between 9 AM and 11 PM (excl. travel time)	0.00027 per household per day (one per 10 years on average)	A household hosts a family event other than marriage or funeral approximately once in 10 years. One complete household from each of 4-24 districts within 50 km attends the event. This means that a given household attends such events approximately once per year.	None	5	Community
Quilt	Sunday-afternoon activity	0.5 per Sunday afternoon	On Sunday afternoon, adult and senior women may sit together to quilt, at the same location as where service took place.	Same gender	3	Community
Reunion	All activities between 9 AM and 9 PM (excl. travel time)	0.000032 per district per day	At a reunion, 20% of all shop-owners from 50-250 districts within 800 km of the host gather to discuss the latest developments in their field of trade.	Same gender	6	Community

Shop visit	30 minutes of household activity	0.1 per 30-minute block of household work	Shop visits may replace 30-minutes blocks of household chores. 50% of these visits are to an Amish shop (located at the households of the shop-owners in the model), the other 50% to a non-Amish shop (in which case no contact occurs within the model boundaries)	None	5 (none when shopping outside district)	Community
Travel to/from event	Any other scheduled activity. Travel time relates to distance	Before and after each event	For the relation between travel time and distance we refer to the previous table	None	No limit	Close
Visit neighbor	Household activity	0.15 per 30-minutes of household work	Instead of spending all time working around the house, women and seniors may replace such time by a short individual visit to a person located two or fewer patches away.	None	No limit	Community
Visit within district	a) Evenings (7 PM) b) Off-church Sunday morning (8 AM – 1 PM) c) Sunday afternoon	a) 0.15 b) 2x 0.15 c) 0.15	Follows the household procedure. One of the people in the household initiates the visit. 40%: entire household joins on the visit. 60%: a uniformly distributed number of the people present will join. In case of visit outside district: max. 15 km away (90% same mindset, 10% different mindset). Only people that are at home can be candidates to function as host. Duration: a) 2-4 hours. b) 5 hours. c) 4.5 hours (only the afternoon, 50% probability) or 8.5 hours (afternoon and evening, also 50%)	None	No limit	Close
Visit outside district		a) 0.1 b) 2x 0.1 c) 0.1				

Wedding	All activities between 2 PM and 9 PM (excl. travel time)	Triggered by actual marriage in the model and then scheduled according to the probabilities shown in Table A3 (only on Tuesdays and Thursdays)	The whole home district of the broom attends (that’s where it takes place). Also, 50% of the district of the bride (if not the same). Furthermore, 10-30 households from districts within a radius of 50 km (same mindset)	None	5	Community

Table A3. Estimated fraction of weddings by month

Month	Fraction of weddings	Survey data[32]	Distribution of remaining 60%
January	1%	1/3 of 3%	
February	1%	1/3 of 3%	
March	3%		less than 1/7 of 60% because still mostly winter
April	7%		less than 1/7 of 60% because still mostly winter (although less so than March)
May	19%	1/2 of 37%	
June	19%	1/2 of 37%	
July	7%		less than 1/7 of 60% because harvest season
August	7%		less than 1/7 of 60% because harvest season
September	9%		approx 1/7 of 60%
October	15%		more than 1/7 of 60% because traditional wedding season[30]
November	12%		more than 1/7 of 60% because traditional wedding season but less than October because already getting closer to winter
December	1%	1/3 of 3%	

Table A4. Default activity schedules

Age group and day	Young child, weekday	Young child, Sunday	Child, weekday	Child, Sunday	Adolescent, weekday	Adolescent, Sunday	Adult, weekday	Adult, Sunday	Senior, weekday	Senior, Sunday
Time										
0-0:30 AM	R	R	R	R	R	R	R	R	R	R
0:30-1 AM	R	R	R	R	R	R	R	R	R	R
1-1:30 AM	R	R	R	R	R	R	R	R	R	R
1:30-2 AM	R	R	R	R	R	R	R	R	R	R
2-2:30 AM	R	R	R	R	R	R	R	R	R	R
2:30-3 AM	R	R	R	R	R	R	R	R	R	R
3-3:30 AM	R	R	R	R	R	R	R	R	R	R
3:30-4 AM	R	R	R	R	R	R	R	R	R	R
4-4:30 AM	R	R	R	R	R	R	R	R	R	R
4:30-5 AM	R	R	R	R	R	R	R	R	R	R
5-5:30 AM	R	R	R	R	R	R	R	R	R	R
5:30-6 AM	R	R	R	R	W	W	W	W	R	R
6-6:30 AM	R	R	W	R	W	W	W	W	R	R
6:30-7 AM	R	R	W	R	W	W	W	W	R	R
7-7:30 AM	E	E	E	E	E	E	E	E	E	E
7:30-8 AM	I	I	T	T	W	T	W	T	W	T
8-8:30 AM	I	I	S	C	W	C	W	C	W	C
8:30-9 AM	I	I	S	C	W	C	W	C	W	C
9-9:30 AM	I	I	S	C	W	C	W	C	W	C
9:30-10 AM	I	I	S	C	W	C	W	C	R	C
10-10:30 AM	I	I	S	C	W	C	W	C	R	C
10:30-11 AM	I	I	S	C	W	C	W	C	W	C
11-11:30 AM	I	I	S	C	W	C	W	C	W	C
11:30-12 noon	I	I	S	C	W	C	W	C	W	C
12-12:30 PM	E	I	S	C	E	C	E	C	E	C
12:30-1 PM	I	I	S	C	W	C	W	C	W	C
1:30-2 PM	I	I	S	T	W	T	W	T	W	T
2-2:30 PM	I	I	S	A	W	A	W	A	W	A
2:30-3 PM	I	I	S	A	W	A	W	A	R	A
3-3:30 PM	I	I	S	A	W	A	W	A	R	A
3:30-4 PM	I	I	T	A	W	A	W	A	R	A
4-4:30 PM	I	I	P	A	W	A	W	A	R	A
4:30-5 PM	I	I	P	A	W	A	W	A	W	A
5-5:30 PM	I	I	P	A	W	A	W	A	W	A
5:30-6 PM	I	I	W	A	W	A	W	A	W	A
6-6:30 PM	I	I	W	A	W	A	W	A	W	A
6:30-7 PM	E	E	E	E	E	E	E	E	E	E
7-7:30 PM	E	E	E	E	E	E	E	E	E	E
7:30-8 PM	I	I	F	F	F	T	F	F	F	F
8-8:30 PM	I	I	F	F	F	G	F	F	F	F
8:30-9 PM	I	I	F	F	F	G	F	F	F	F
9-9:30 PM	R	R	F	F	F	G	F	F	F	F
9:30-10 PM	R	R	F	F	F	G	F	F	F	F
10-10:30 PM	R	R	R	R	F	G	F	F	F	F
10:30-11 PM	R	R	R	R	R	G	R	R	R	R
11-11:30 PM	R	R	R	R	R	T	R	R	R	R
11:30-12 midnight	R	R	R	R	R	R	R	R	R	R

A = Sunday Afternoon activity, C = Church, E = Eat, F = Family time, G = Go out, I = Infant time, P = Play time, R = Rest, S = School, T = Travel, W = Work.

Table A5 Compatibility of activities

Legend:
- U — *Contact without restrictions on gender*
- S — *Contact restricted to people with the same gender*
- C — *Contact between couples of husband and wife only*
- (empty) — *No contact*

from \ to	*Barn raising*	*Bishops meeting*	*Church*	*Distant trip*	*Do household*	*Eat*	*Family time*	*Family event*	*Farm*	*Go out*	*Household auction*	*Hunt*	*Infant time*	*Livestock auction*	*Ministers meeting*	*Work outside district*	*Children's Play*	*Quilt*	*Rest*	*Reunion*	*School*	*Serve customers*	*Shop visit*	*Travel*	*Travel from event*	*Travel to event*	*Visit neighbor*	*Visit within district*	*Visit outside district*
Barn raising	S																												
Bishops meeting		S																											
Church			S																										
Distant trip				U	U	U	U						U														U	U	U
Do household				U	U								U														U	U	U
Eat				U		U																						U	U
Family time				U			U						U														U	U	U
Family event								U																					
Farm									S																				
Go out										U																			
Household auction											U																		
Hunt												S																	
Infant time				U	U		U						U					U									U	U	U
Livestock auction														S															
Ministers meeting															S														
Work outside district																													
Children's Play																	S												
Quilt													U					S											
Rest																			C										
Reunion																				S									
School																					S								
Serve customers																						U	U						
Shop visit																						U	U						
Travel																								U					
Travel from event																									U	U			
Travel to event																									U	U			
Visit neighbor				U	U		U						U														U	U	U
Visit within district				U	U	U	U						U														U	U	U
Visit outside district				U	U	U	U						U														U	U	U

Table A6. Summary of NetLogo turtle attributes and values

District attributes	
Attribute	**Possible values**
Location (xcor, ycor)	Location on grid
County/Town/State	Pre-specified (no impact on model)
Mindset	1,2,3 (relates to degree of conservatism)
Church day	1,2 (first or second of each two Sundays, randomly generated with equal probabilities)
Church location	One of the households (church location rotates within district)
Person attributes	
Attribute	**Possible values**
Activity start/end time	1 – 48, measured in half hours from the beginning of a day
District id	Any natural positive number
Household id	Any natural positive number
Household location	Coordinates
Birthday	1-365
Gender	1 (male) or 2 (female)

Age	1-120
Age group	1 (infant) to 5 (senior)
Spouse	Another person in the household (if married)
Mother	Another person in the household (if age group = 1)
Number of children	0-16 (only positive if female and married)
Target number of children	0-16 (only positive if female and married)
Job	Farmer, shop-owner, outside-district-worker, or house-work
Minister?	True or false
Bishop?	True or false
Health state	Susceptible or infectious
Immunity type	Fully susceptible; 1 recent live poliovirus (LPV) infection; 1 historic LPV infection state; 2 or more recent LPV infections; 2 or more historic LPV infections; recent IPV vaccination; historic IPV vaccination[11]
Day of last exposure	Any natural positive number
Case?	True or false
Location	Coordinates
Current activity	Sleeping, eating, attending school, performing work, family time, etc.
Scheduled events	Barn raising, family event, auction

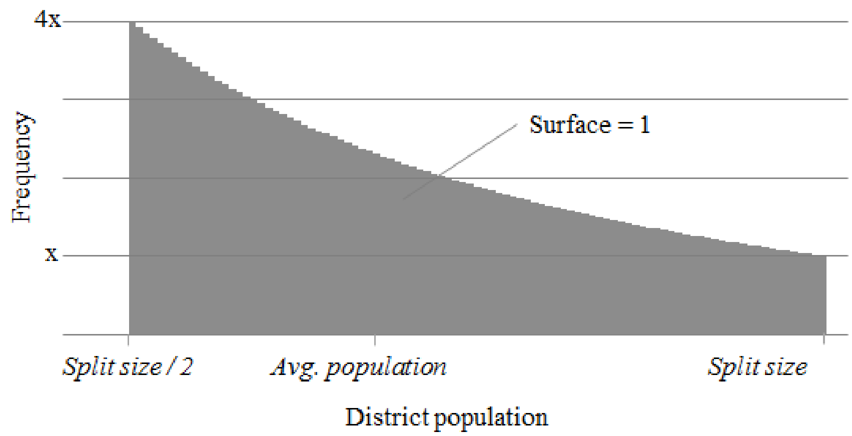

Figure A1. Distribution of district population size, given a certain average district population, which differs by state (ranging from 75 to 150), with the split size equal to 1.44 times the average population size. Smaller district sizes occur more frequently in the long term due to a slower absolute growth rate and the fact that a large district always splits into two small districts half that size upon reaching the split size.

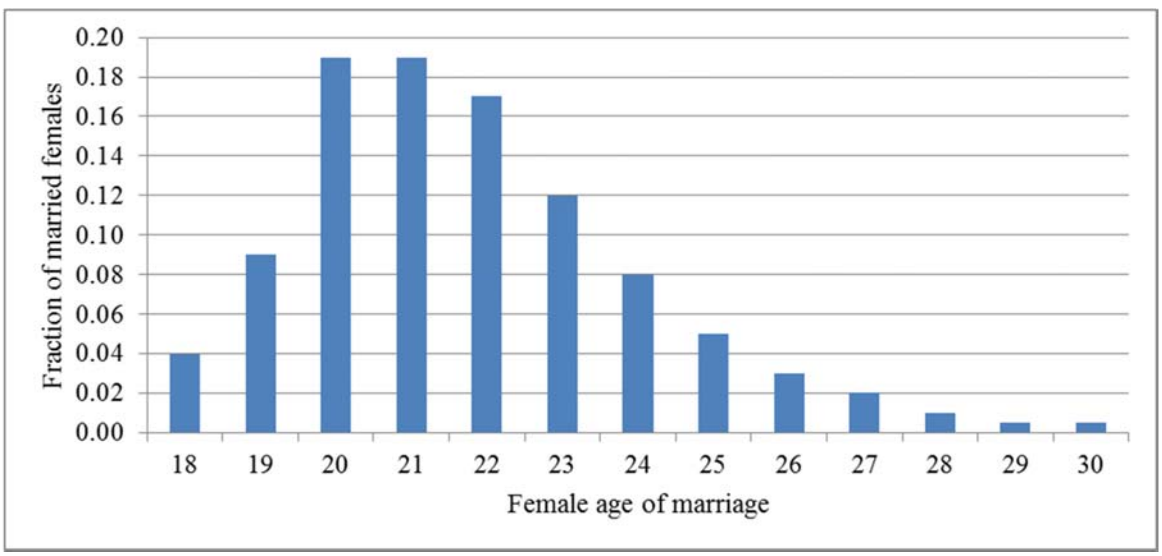

Figure A2. Assumed distribution for the age of marriage for Amish women (constructed based on Greksa LP (2002)[41] and Kraybill DB (2013)[32])

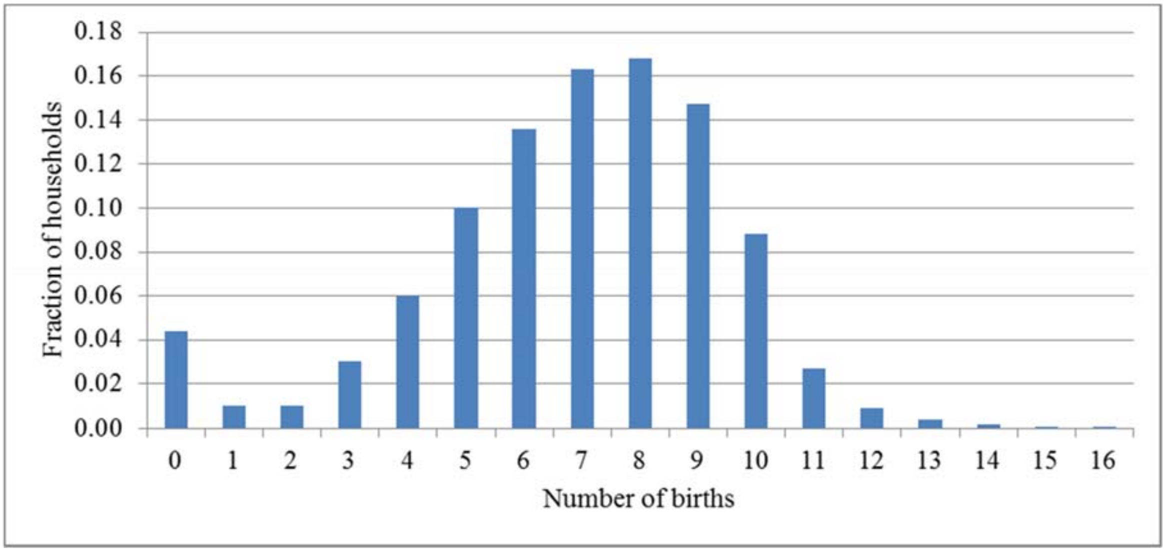

Figure A3. Distribution of the number of births per household (constructed based on Hostetler JA (1993)[31])

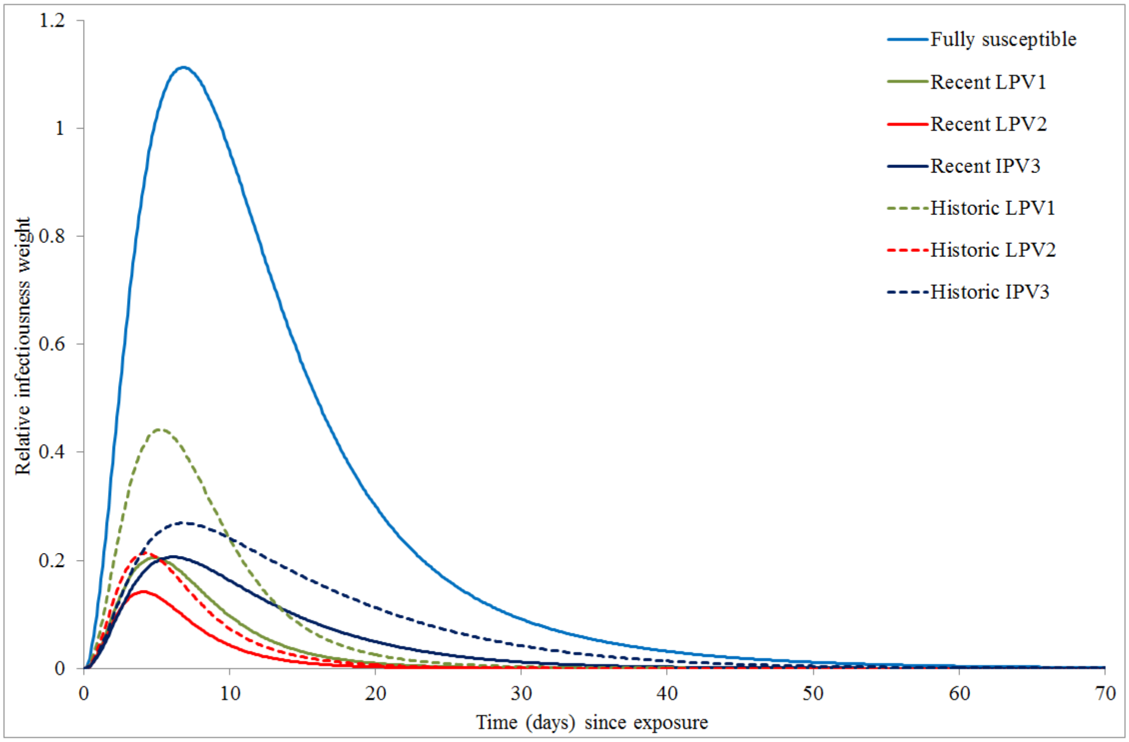

Figure A4. Assumed relative infectiousness over time since exposure for seven immunity states[11]

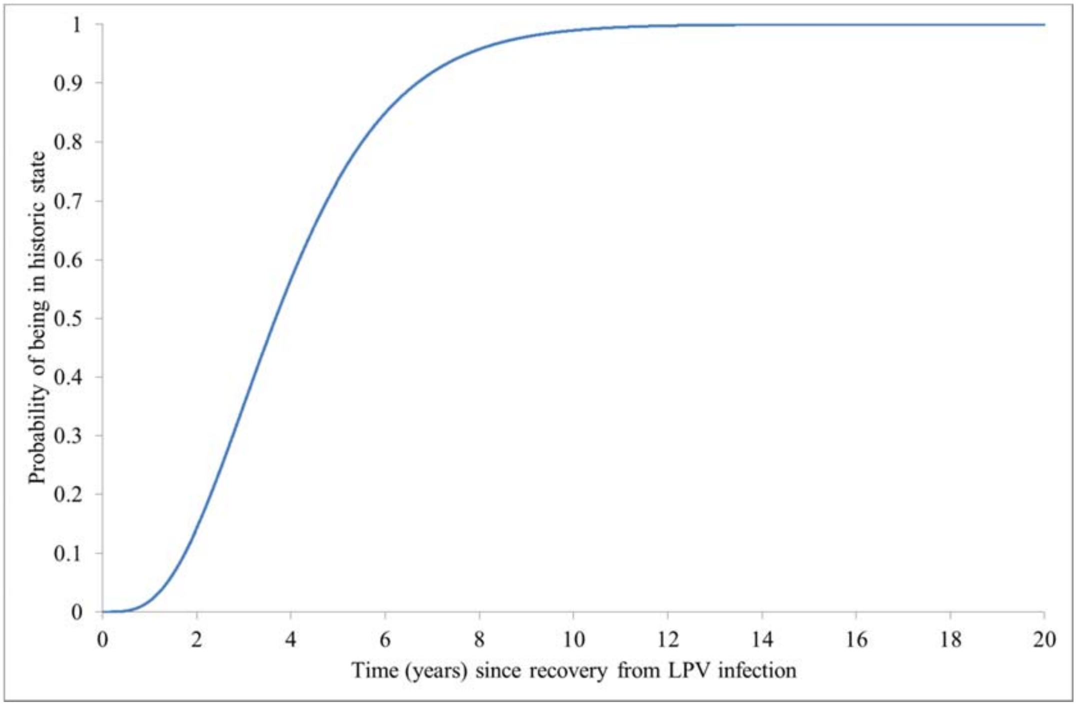

Figure A5. Assumed cumulative probability distribution for the waning duration

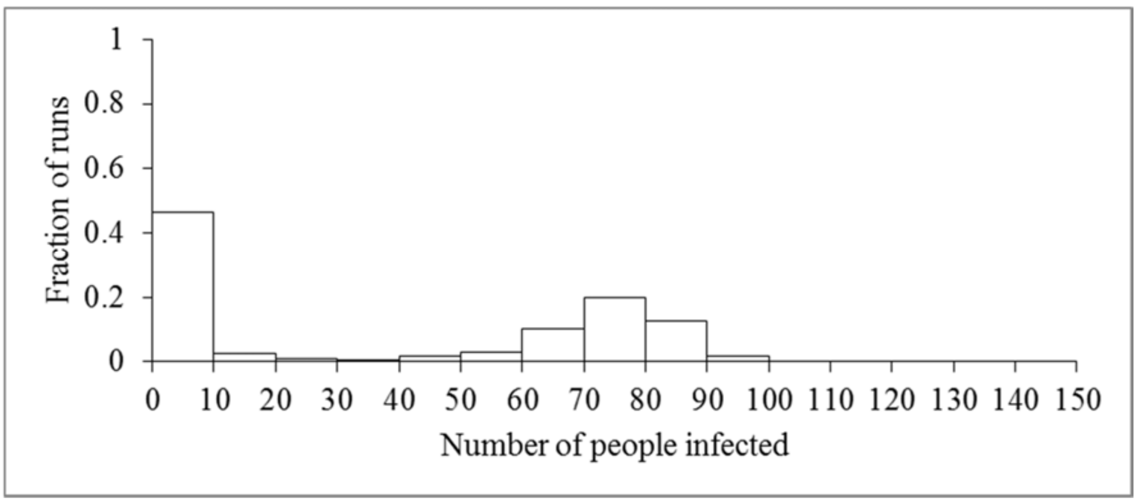

Figure A6: Distribution of results from 1,000 runs for the number of people infected following an introduction into a remote community in Montana

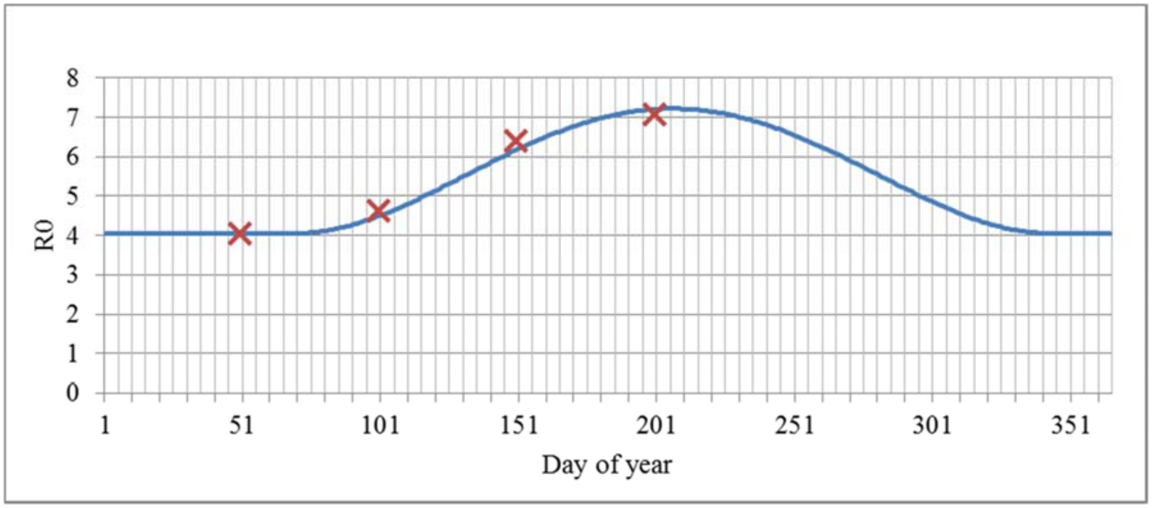

Figure A7: Seasonal R0 curve in the model and marked points representing simulated average R0 over 200 runs starting at the given day of year

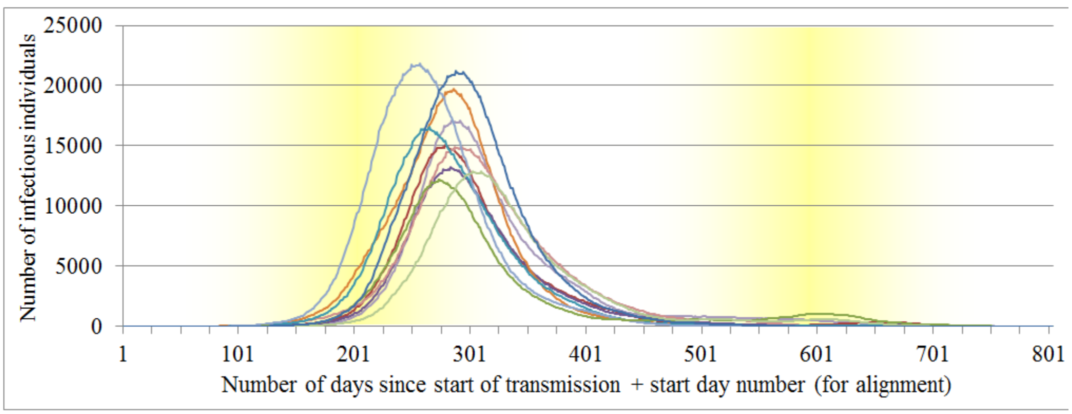

Figure A8: Number of infectious people over time for 10 randomly selected runs at the lowest immunity settings with more than 100 total cases (representing 2% of all runs since most runs result in less transmission). The yellow highlighting indicated the summer months.