Illustrative model-based analysis of vaccination and release strategies (Scotland)

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Policy relevance

- Model outputs are scenarios NOT predictions.
- Under the most optimistic assumptions about vaccine efficacy and coverage, at 200K vaccinations per week it will be 5-6 months before the population immunity threshold is reached in Scotland.
- Under more pessimistic but plausible assumptions about vaccine efficacy and coverage, the population immunity threshold will never be reached.
- There are multiple options for a phased removal of restrictions as vaccination is rolled out.
- Under all scenarios modelled here, full release of the entire population immediately after vaccination of the highest priority 33% of the population (or fewer) results in a major epidemic with significant number of cases (=high attack rate) in the most vulnerable groups,
- Most cases in the vulnerable group are in individuals who have not been vaccinated or previously exposed. Incidence declines over the first vaccination round, with attack rate approximately 2.5% in baseline scenario.
- Delaying full release until 66% of more of the population has been vaccinated results in much lower attack rates in all groups.
- Releasing the vaccinated population at the 33% point results in much lower attack rates.
- Partially releasing the entire population at the 33% point can result in lower attack rates, but this may require a very limited lifting of current restrictions.
- In the short term (12 months), the main challenges to tackle in order to reach the population immunity threshold (if it is possible) are: slow vaccine roll-out; low coverage; low transmission blocking efficacy.

Methods summary

SIRV compartment model with three equal-sized population sub-groups and sub-group specific transmission rates.

Constant fraction vaccinated per day (target coverage 90%).

Four strategies for release from lockdown: A) release each subgroup once the whole group has been vaccinated; B) release the whole population once the first group has been vaccinated; C) release the whole population once the first two groups have been vaccinated; D) release the whole population once all groups have been vaccinated.

Starting conditions: 0.79% currently infected and 7.3% have natural immunity. Equal across subgroups.

Outputs are: 1) overall attack rate over one year from start of vaccination programme; 2) attack rates by subgroup; 3) attack rate among fully susceptible individuals in group i (high priority).

Compare outputs for different values of: current R value; post-release R value (partial release); restricted mixing between subgroups; decay of natural and/or vaccine-induced immunity; transmission blocking efficacy; coverage.

<u>Results Summary</u>

Baseline population immunity threshold = 65%. New variant increases this to 77% (upper limit 79%).

Baseline scenario gives one-year attack rate in all groups below 4%, except for strategy B (full release after 33% vaccination) which has an overall attack rate of 50%. See page 11.

In baseline strategies A, C and D almost all cases occur in the first 90-day vaccination round. For strategy B cases peak in the second vaccination round. See pages 7-10.

If pre-lockdown R is higher (1.4 cf. 1.0) then attack rates increase to >10% in all groups (lowest in group i) and all epidemic extend into the second vaccination round. See page 13.

For strategy B partial rather than full lifting of restrictions limits the epidemic. 50% relaxation is too much, 25% relaxation brings the attack rates in line with other strategies. See pages 15 and 17.

Reducing transmission between subgroups (by 50%) also reduces the attack rate, especially for group i. See page 19.

Waning vaccine-induced immunity (mean duration = 6 months) compromises all strategies, though with a delay. Waning natural immunity has much less impact. See page 21.

Poor transmission blocking efficacy (75% cf. 99%) increases attack rates, but especially for strategy A (overall attack rate = 40%) making this strategy untenable. See page 23.

Low vaccination coverage severely compromises all strategies as the population immunity threshold is not attained. The full consequence of this is not seen until beyond the one-year window of these simulations. See page 25.

<u>Remarks</u>

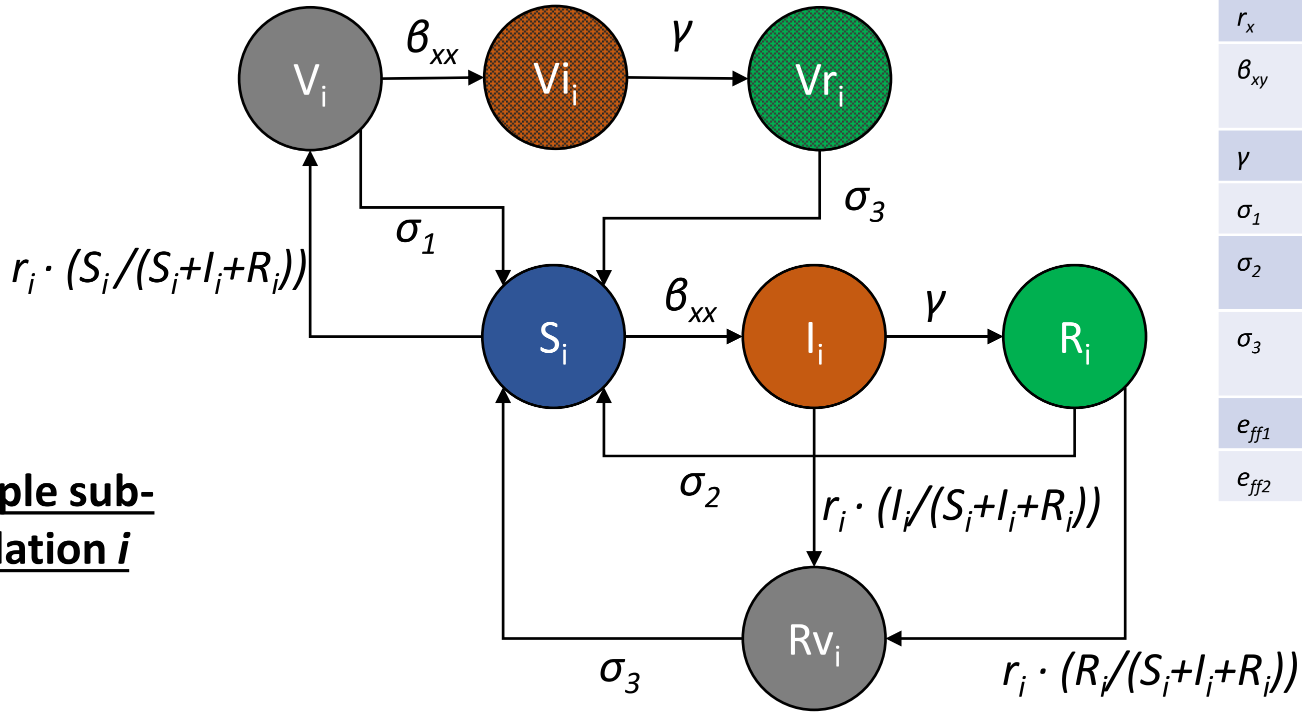
This analysis provides insights in to the complex dynamics of a combination of virus spread, the impact of NPIs and vaccine roll out. We use the model to explore different scenarios that shed light on these dynamics over a one-year period. They are <u>not</u> predictions.

We do not model time delays to full protection nor to second dose. This will shift the curves to the right on the time axis by a minimum of two weeks.

In future work we will weight attack rates by the risk of hospitalisation and death. For immediate purposes we focus on the attack rate in group i individuals who have not been vaccinated or previously infected – this is the group that are expected to make the largest contribution to hospitalisations and deaths.

We have calculated one-year attack rate as a useful metric, not least because annual vaccination may be possible/necessary. We note that different strategies result in different distributions of cases over this period.

Vaccinated susceptibles are able to get infected



Example sub-population *i*

Example Transmission Route – Infection from subpop j to i

To/From	Susceptible (S_i)	Vaccinated (V_i)
Infected (I_j)	$S_i \xrightarrow{\beta_{ij} I_j S_i} I_i$	$V_i \xrightarrow{(1-e_{ff1})\beta_{ij} I_j V_i} Vi_i$
Vaccinated but Infected (Vi_j)	$S_i \xrightarrow{(1-e_{ff2})\beta_{ij} Vi_j S_i} I_i$	$V_i \xrightarrow{(1-e_{ff1})(1-e_{ff2})\beta_{ij} Vi_j V_i} Vi_i$

Parameter	Description
r_x	Rate of Vaccination in subpopulation x
β_{xy}	Per capita rate of transmission from infectious subpopulation y to susceptible subpopulation x
γ	Per capita rate of recovery
σ_1	Per capita rate of immunity loss (vaccinated individuals)
σ_2	Per capita rate of immunity loss (from natural infection)
σ_3	Per capita rate of immunity loss (for those who have been infected/recovered and vaccinated)
e_{ff1}	Vaccine Efficacy (preventing infection)
e_{ff2}	Vaccine Efficacy (preventing onwards infectiousness)

Compartment	Description (Proportion of population in…)
S_x	Susceptibles in subpopulation x
I_x	Infectious individuals in subpopulation x
R_x	Recovered individuals in subpopulation x
Rv_x	Recovered or Infectious and subsequently vaccinated in subpopulation x
V_x	Vaccinated individuals in subpopulation x
Vi_x	Vaccinated and infectious individuals in subpopulation x
Vr_x	Vaccinated and recovered individuals in subpopulation x

Vaccination Rate (r_i)

We model the vaccination rate as a function of the:
Total fraction of individuals in S, I and R compartments (available to vaccinated) at the start of the vaccination period multiplied by the proportion divided by the duration of the vaccination period for the specific subgroup.

We assume that the rate of vaccination is constant (r_i*1), therefore the rate of vaccination in S, I and R compartments must be normalised to the total proportion of individuals in these three compartments.

Example equations sub-population i

$$\frac{dS_i}{dt} = \sigma_1 V_i + \sigma_2 R_i + \sigma_3 (Rv_i + Vr_i) - \beta_{ii} S_i I_i - \beta_{ij} S_i I_j - \beta_{ik} S_i I_k - (1 - e_{ff2}) \beta_{ii} S_i Vi_i - (1 - e_{ff2}) \beta_{ij} S_i Vi_j - (1 - e_{ff2}) \beta_{ik} S_i Vi_k - r_i \frac{S_i}{S_i + I_i + R_i}$$

$$\frac{dI_i}{dt} = \beta_{ii} S_i I_i + \beta_{ij} S_i I_j + \beta_{ik} S_i I_k + (1 - e_{ff2}) \beta_{ii} S_i Vi_i + (1 - e_{ff2}) \beta_{ij} S_i Vi_j + (1 - e_{ff2}) \beta_{ik} S_i Vi_k - \gamma I_i - r_i \frac{I_i}{S_i + I_i + R_i}$$

$$\frac{dR_i}{dt} = \gamma I_i - r_i \frac{R_i}{S_i + I_i + R_i} - \sigma_2 R_i$$

$$\frac{dRv_i}{dt} = r_i \frac{I_i + R_i}{S_i + I_i + R_i} - \sigma_3 Rv_i$$

$$\frac{dV_i}{dt} = r_i \frac{S_i}{S_i + I_i + R_i} - (1 - e_{ff1}) \beta_{ii} V_i I_i - (1 - e_{ff1}) \beta_{ij} V_i I_j - (1 - e_{ff1}) \beta_{ik} V_i I_k - (1 - e_{ff1})(1 - e_{ff2}) \beta_{ii} V_i Vi_i - (1 - e_{ff1})(1 - e_{ff2}) \beta_{ij} V_i Vi_j - (1 - e_{ff1})(1 - e_{ff2}) \beta_{ik} V_i Vi_k - \sigma_1 V_i$$

$$\frac{dVi_i}{dt} = (1 - e_{ff1}) \beta_{ii} V_i I_i + (1 - e_{ff1}) \beta_{ij} V_i I_j + (1 - e_{ff1}) \beta_{ik} V_i I_k + (1 - e_{ff1})(1 - e_{ff2}) \beta_{ii} V_i Vi_i + (1 - e_{ff1})(1 - e_{ff2}) \beta_{ij} V_i Vi_j + (1 - e_{ff1})(1 - e_{ff2}) \beta_{ik} V_i Vi_k - \gamma Vi_i$$

$$\frac{dVr_i}{dt} = \gamma Vi_i - \sigma_3 Vr_i$$

Parameter	Description
r_x	Rate of Vaccination in subpopulation x
β_{xy}	Per capita rate of transmission from infectious subpopulation y to susceptible subpopulation x
γ	Per capita rate of recovery
σ_1	Per capita rate of immunity loss (vaccinated individuals)
σ_2	Per capita rate of immunity loss (from natural infection)
σ_3	Per capita rate of immunity loss (for those who have been infected/recovered and vaccinated)
e_{ff1}	Vaccine Efficacy (preventing infection)
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Compartment	Description (Proportion of population in…)
S_x	Susceptibles in subpopulation x
I_x	Infectious individuals in subpopulation x
R_x	Recovered individuals in subpopulation x
Rv_x	Recovered or Infectious and subsequently vaccinated in subpopulation x
V_x	Vaccinated individuals in subpopulation x
Vi_x	Vaccinated and infectious individuals in subpopulation x
Vr_x	Vaccinated and recovered individuals in subpopulation x

BASELINE PARAMETERS

Model Details

We assume that 0.79% of the Scottish population is currently infected and 7.3% have already been infected and are now "Recovered". Each subpopulation is proportionately the same size.

Vaccine efficacy is modelled at 90% (both e_{ff1} and e_{ff2}) and coverage (P_i, P_j and P_k) aims for 90% of the entire subpopulation.

We currently assume a indefinite period of immunity (rate of immunity loss σ_1, σ_2 and $\sigma_3 = 0$).

Initial Conditions

$S_i = 0.3064$
$S_j = 0.3064$
$S_k = 0.3064$
$I_i = 0.0071/3$
$I_j = 0.0071/3$
$I_k = 0.0071/3$
$V_i = 0$
$V_j = 0$
$V_k = 0$
$R_i = 0.073/3$
$R_j = 0.073/3$
$R_k = 0.073/3$

Subpopulation i

Target Coverage = 90%
Duration = 90 days
Trigger Date = day 0

Subpopulation j

Target Coverage = 90%
Duration = 90 days
Trigger Date = day 90

Subpopulation k

Target Coverage = 90%
Duration = 90 days
Trigger Date = day 180

We explore 4 different scenarios:

Baseline

We model sequential vaccination of 3 sub-populations. Each vaccination schedule lasts 90 days and aims for 90% coverage of the available susceptibles, infecteds and recovereds in the vaccinated subpopulation at the beginning of the simulation.

After vaccination of each subpopulation, the sub-population is released from NPIs, with the R increasing from 1 to 4.2.

Full Release

We explore 3 different release scenarios:

1. **First Group**
We model a full release of the entire population (i, j and k) after the vaccination of the first sub-population (i) (after 90 days). This increases the R of the entire population from 1 to 4.2.

2. **Middle Group**
We model a full release of the entire population (i, j and k) after the vaccination of the second sub-population (j) (after 180 days). This increases the R of the entire population from 1 to 4.2.

3. **Last Group**
We model a full release of the entire population (i, j and k) after the vaccination of the final sub-population (k) (after 270 days). This increases the R of the entire population from 1 to 4.2.

Sequential Vaccination

We model sequential vaccination of 3 sub-populations. Each vaccination schedule lasts 90 days and aims for 90% coverage of the available susceptibles, infecteds and recovereds at the beginning of the simulation. After vaccination of each subpopulation, the sub-population is released from NPIs, with the R increasing from 1 to 4.2.

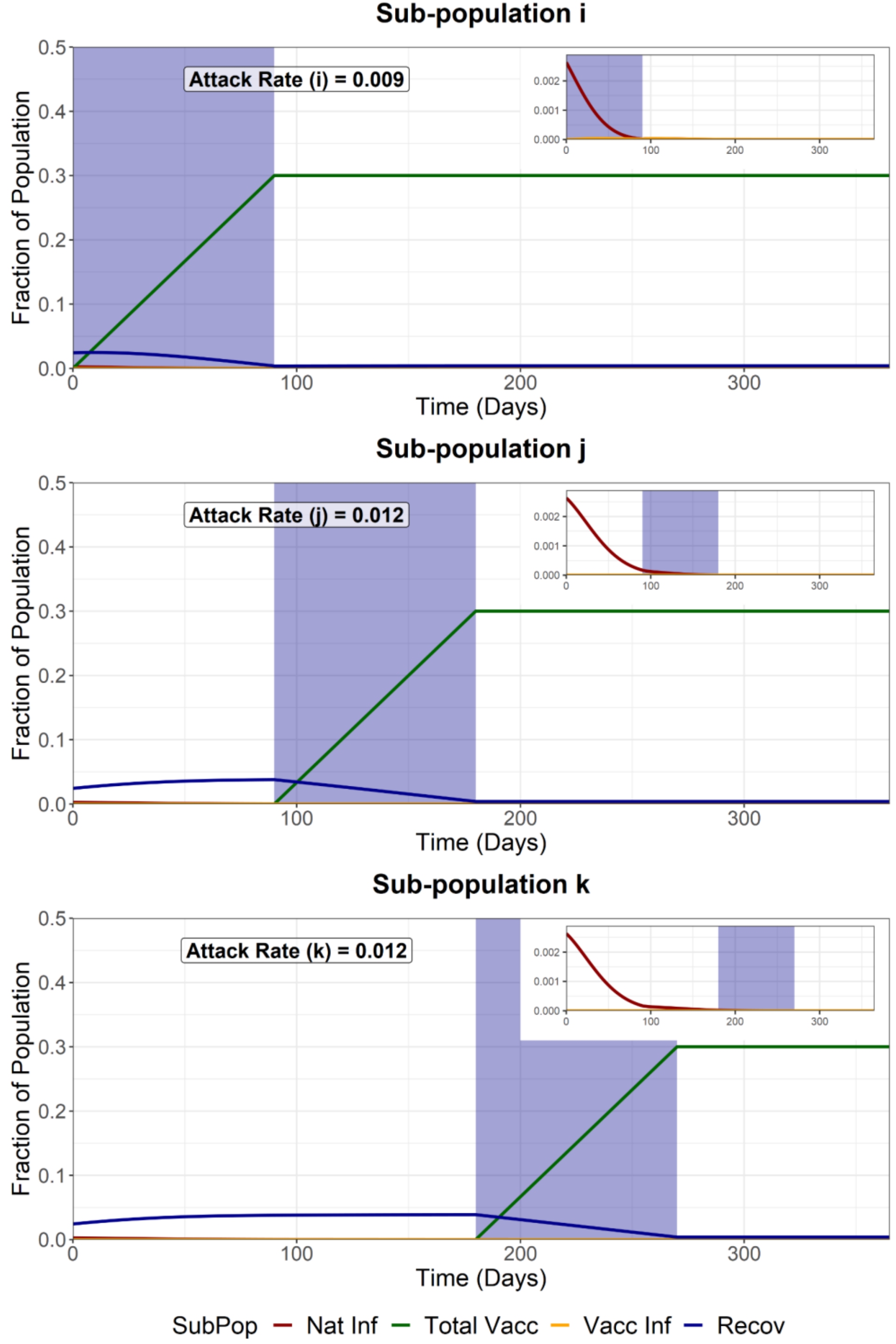
Attack Rate for fully susceptible individuals infected in sub-group i (excluding infections amongst those vaccinated) = **0.0084**

WAIFW Matrix (R) = $\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$ During the pop i vaccination (t = 0-90)

WAIFW Matrix (R) = $\begin{pmatrix} 4.2 & 4.2 & 4.2 \\ 4.2 & 1 & 1 \\ 4.2 & 1 & 1 \end{pmatrix}$ During the pop j vaccination (t = 90-180)

WAIFW Matrix (R) = $\begin{pmatrix} 4.2 & 4.2 & 4.2 \\ 4.2 & 4.2 & 4.2 \\ 4.2 & 4.2 & 1 \end{pmatrix}$ During the pop k vaccination (t = 180-270)

WAIFW Matrix (R) = $\begin{pmatrix} 4.2 & 4.2 & 4.2 \\ 4.2 & 4.2 & 4.2 \\ 4.2 & 4.2 & 4.2 \end{pmatrix}$ After final vaccination schedule (t = 270)



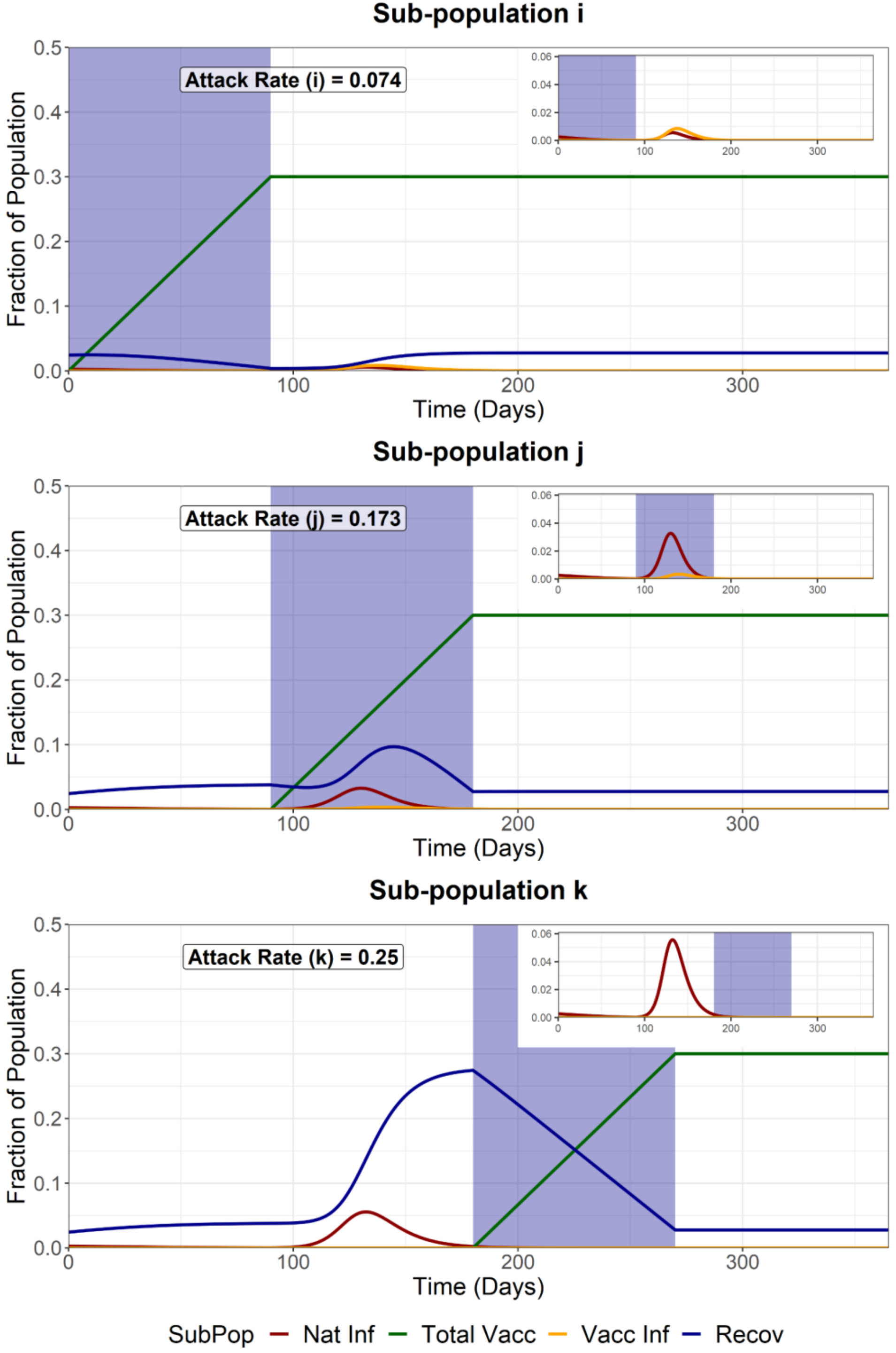
Full Release - First Group (i)

We model a full release of the entire population (i, j and k) after the vaccination of the **first** sub-population (i). This increases the R of the entire population from 1 to 4.2.

Attack Rate for fully susceptible individuals infected in sub-group i (excluding infections amongst those vaccinated) = **0.032**

WAIFW Matrix (R) = $\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$ Before first vaccination schedule (t < 90)

WAIFW Matrix (R) = $\begin{pmatrix} 4.2 & 4.2 & 4.2 \\ 4.2 & 4.2 & 4.2 \\ 4.2 & 4.2 & 4.2 \end{pmatrix}$ After first vaccination schedule (t > 90)



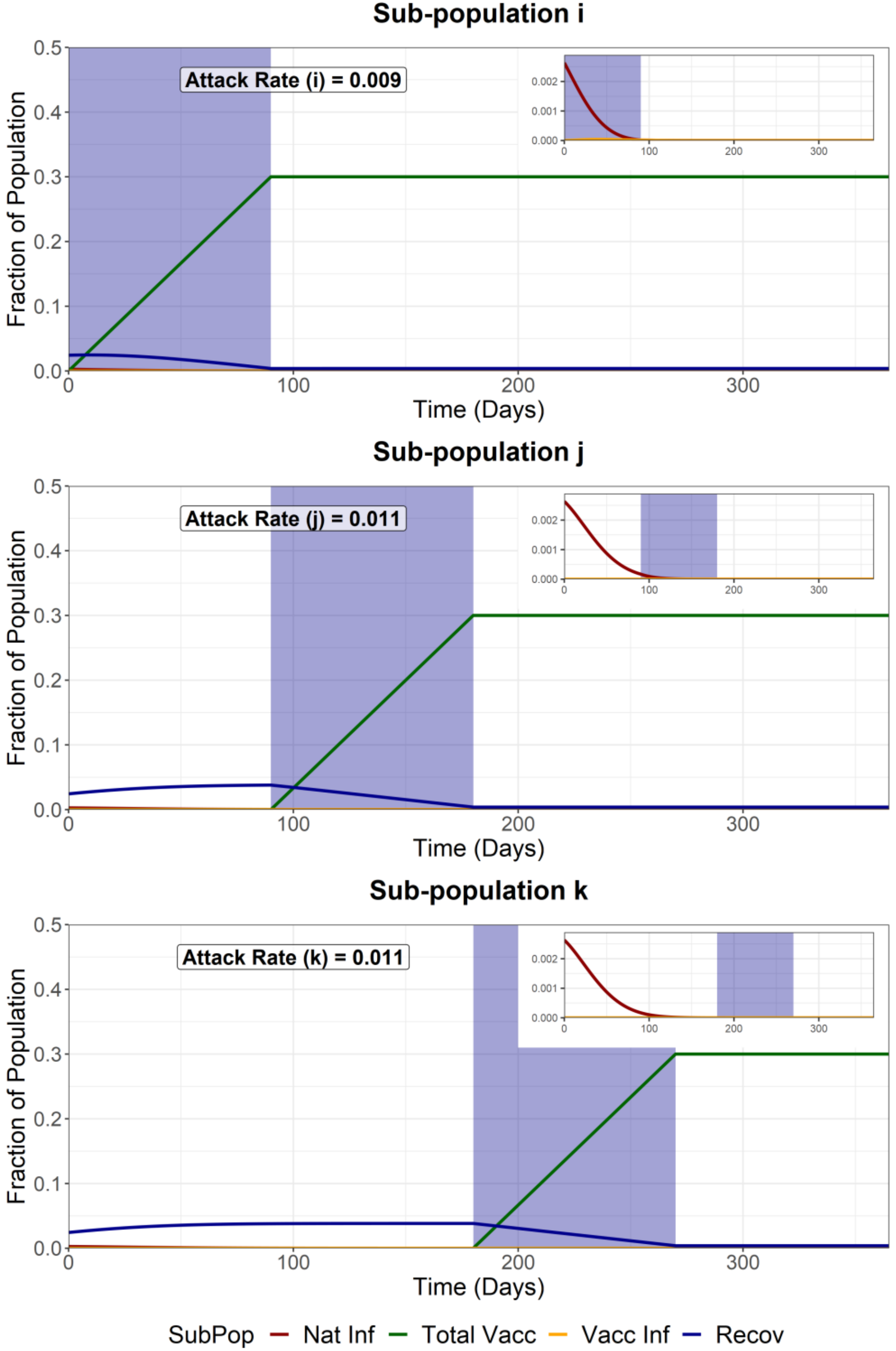
Full Release - Second Group (j)

We model a full release of the entire population (i, j and k) after the vaccination of the **second** sub-population (j). This increases the R of the entire population from 1 to 4.2.

Attack Rate for fully susceptible individuals infected in sub-group i (excluding infections amongst those vaccinated) = **0.0081**

WAIFW Matrix (R) = $\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$ Before second vaccination schedule (t < 180)

WAIFW Matrix (R) = $\begin{pmatrix} 4.2 & 4.2 & 4.2 \\ 4.2 & 4.2 & 4.2 \\ 4.2 & 4.2 & 4.2 \end{pmatrix}$ After second vaccination schedule (t > 180)



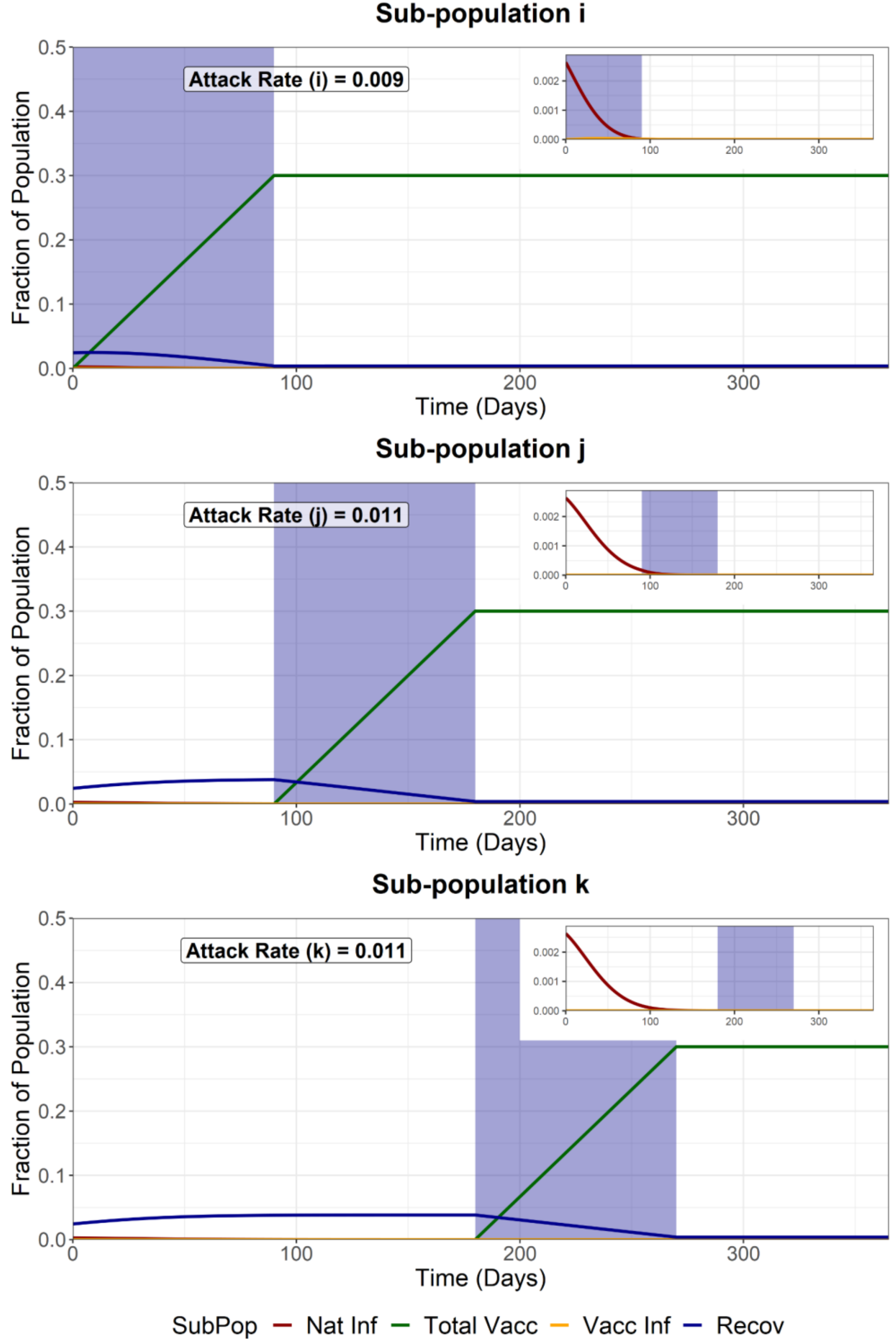
Full Release - Third Group (k)

We model a full release of the entire population (i, j and k) after the vaccination of the **last** sub-population (k). This increases the R of the entire population from 1 to 4.2.

Attack Rate for fully susceptible individuals infected in sub-group i (excluding infections amongst those vaccinated) = **0.0081**

WAIFW Matrix (R) = $\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$ Before final vaccination schedule (t < 270)

WAIFW Matrix (R) = $\begin{pmatrix} 4.2 & 4.2 & 4.2 \\ 4.2 & 4.2 & 4.2 \\ 4.2 & 4.2 & 4.2 \end{pmatrix}$ After final vaccination schedule (t > 270)



Scenario Analysis (Total Infected)

We now compare the total epidemic curve (the sum of the infectious compartment in each subpopulation) for 4 different scenarios:

1. With vaccination and sequential intervention release
2. Full release after vaccination of the first subpopulation (i)
3. Full release after vaccination of the second subpopulation (j)
4. Full release after vaccination of the last subpopulation (k)

The three shaded areas are the vaccination periods for subpopulation i, j and k respectively.

Sequential Vaccination

Attack Rate (i) – 0.009
Attack Rate (j) – 0.012
Attack Rate (k) – 0.012
Attack Rate for fully susceptible individuals infected in sub-group i = **0.0084**

Full Release after vaccination of i

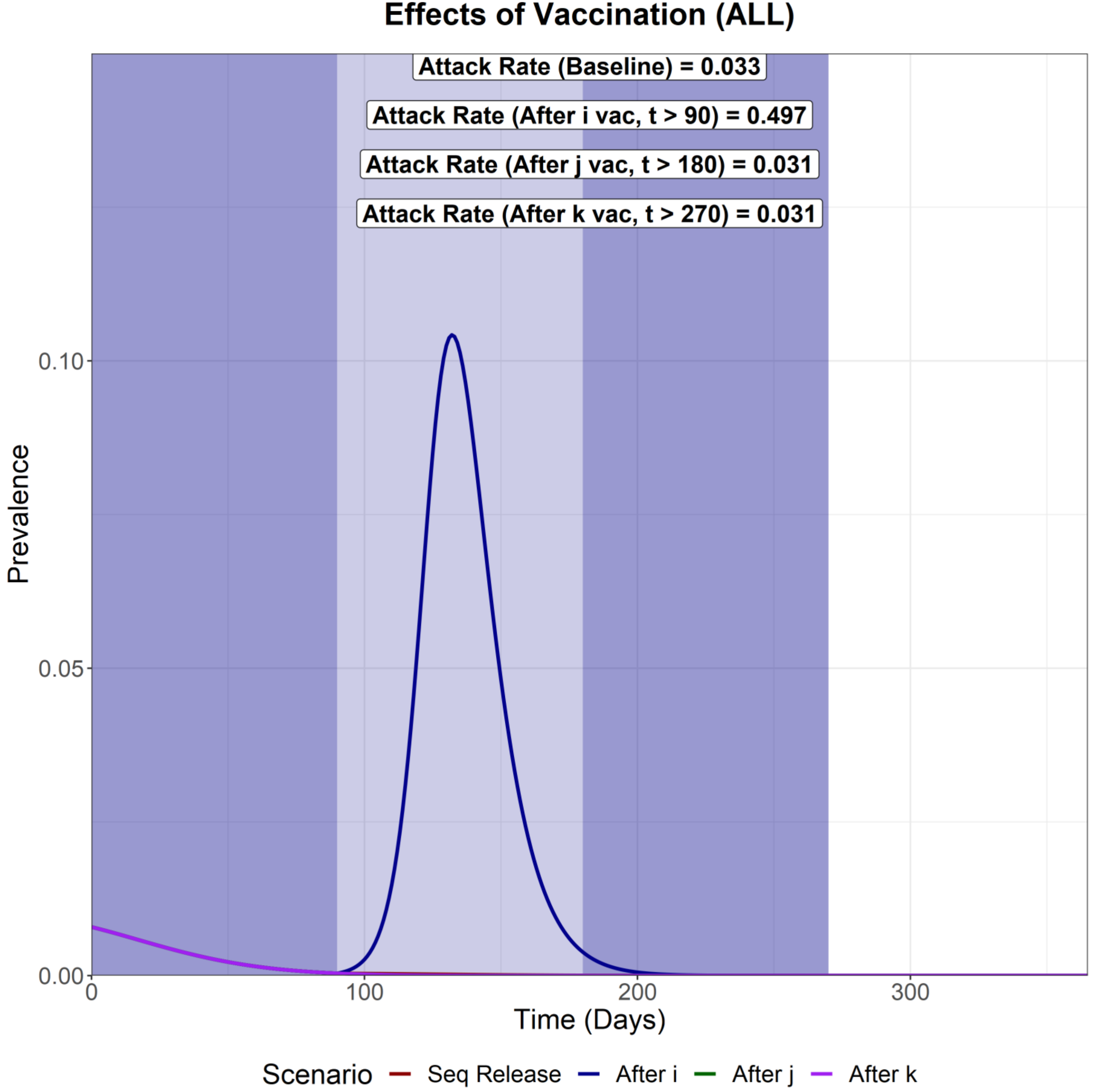
Attack Rate (i) – 0.074
Attack Rate (j) – 0.173
Attack Rate (k) – 0.25
Attack Rate for fully susceptible individuals infected in sub-group i = **0.032**

Full Release after vaccination of j

Attack Rate (i) – 0.009
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptible individuals infected in sub-group i = **0.0081**

Full Release after vaccination of k

Attack Rate (i) – 0.009
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptible individuals infected in sub-group i = **0.0081**



HIGHER PRE-RELEASE R

Pre-release R is higher (R = 1.4) compared to baseline (R = 1.0)

Scenario Analysis (Total Infected)

We now compare the total epidemic curve (the sum of the infectious compartment in each subpopulation) for 4 different scenarios:

1. With vaccination and sequential intervention release
2. Full release after vaccination of the first subpopulation (i)
3. Full release after vaccination of the second subpopulation (j)
4. Full release after vaccination of the last subpopulation (k)

The three shaded areas are the vaccination periods for subpopulation i, j and k respectively.

Sequential Vaccination

Attack Rate (i) – 0.039
Attack Rate (j) – 0.062
Attack Rate (k) - 0.065
Attack Rate for fully susceptible individuals infected in sub-group i = **0.0340**

Full Release after vaccination of i

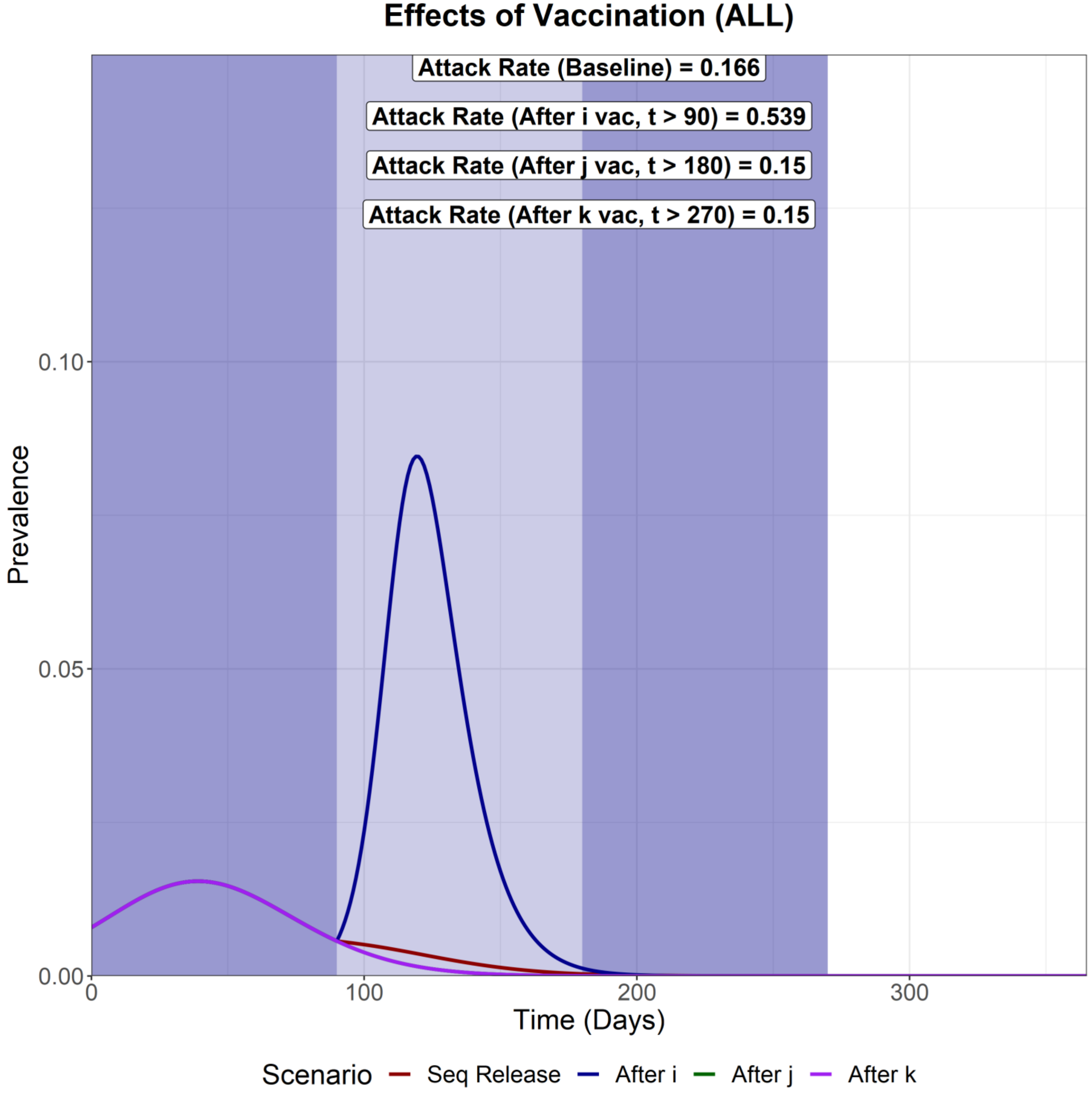
Attack Rate (i) – 0.087
Attack Rate (j) – 0.204
Attack Rate (k) – 0.248
Attack Rate for fully susceptible individuals infected in sub-group i = **0.051**

Full Release after vaccination of j

Attack Rate (i) – 0.035
Attack Rate (j) – 0.057
Attack Rate (k) – 0.058
Attack Rate for fully susceptible individuals infected in sub-group i = **0.0317**

Full Release after vaccination of k

Attack Rate (i) – 0.035
Attack Rate (j) – 0.057
Attack Rate (k) – 0.058
Attack Rate for fully susceptible individuals infected in sub-group i = **0.0317**



PARTIAL RELAXATION

R is only released from 1 to 1.8 (25% to the baseline R release of 4.2)

Scenario Analysis (Total Infected)

We now compare the total epidemic curve (the sum of the infectious compartment in each subpopulation) for 4 different scenarios:

1. With vaccination and sequential intervention release
2. Full release after vaccination of the first subpopulation (i)
3. Full release after vaccination of the second subpopulation (j)
4. Full release after vaccination of the last subpopulation (k)

The three shaded areas are the vaccination periods for subpopulation i, j and k respectively.

Sequential Vaccination

Attack Rate (i) – 0.009
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptible individuals infected in sub-group i = **0.0082**

Full Release after vaccination of i

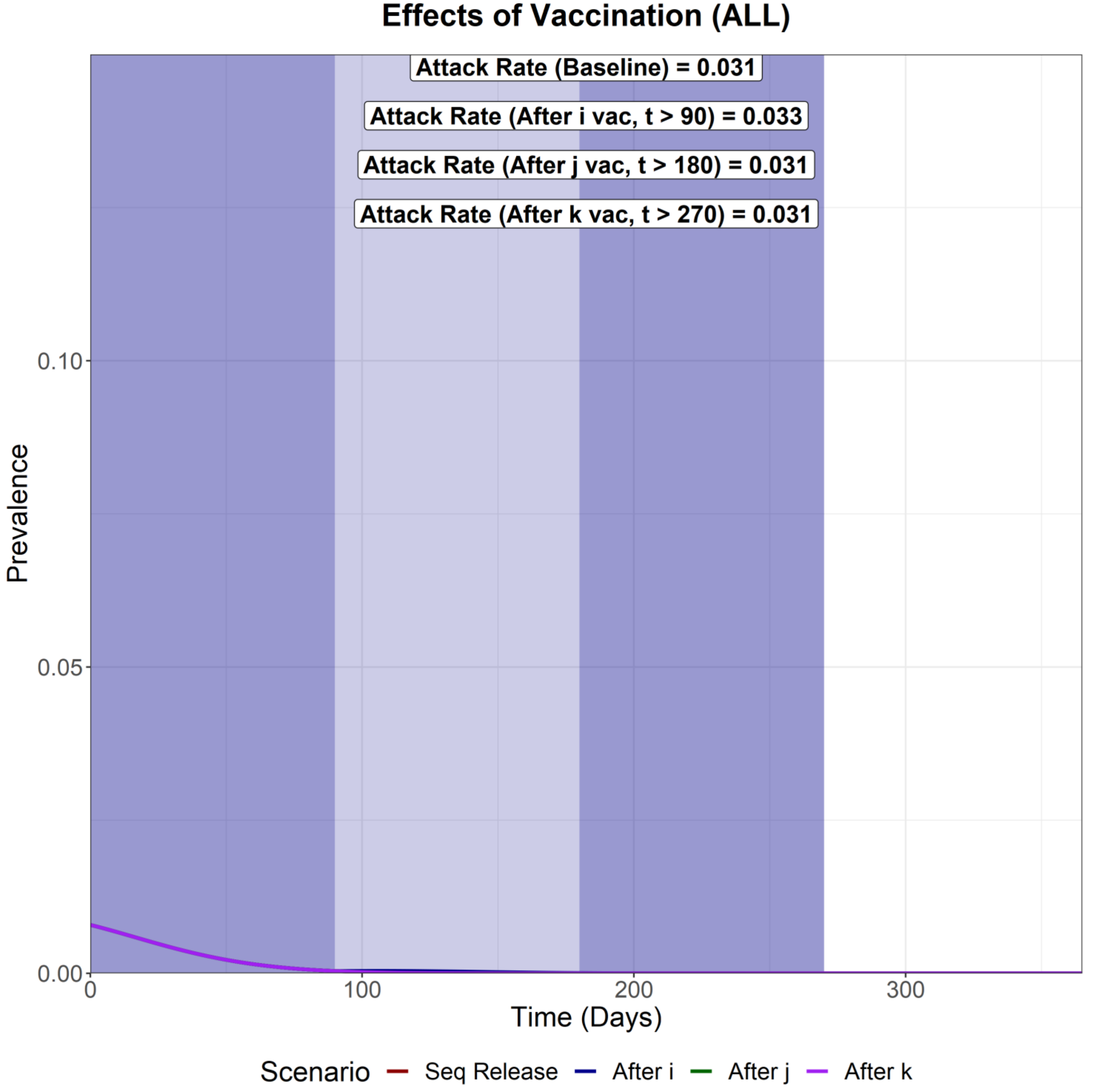
Attack Rate (i) – 0.009
Attack Rate (j) – 0.012
Attack Rate (k) – 0.013
Attack Rate for fully susceptible individuals infected in sub-group i = **0.0083**

Full Release after vaccination of j

Attack Rate (i) – 0.009
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptible individuals infected in sub-group i = **0.008**

Full Release after vaccination of k

Attack Rate (i) – 0.009
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptible individuals infected in sub-group i = **0.008**



PARTIAL RELAXATION

R is only released from 1 to 2.6 (halfway to the baseline R release of 4.2)

Scenario Analysis (Total Infected)

We now compare the total epidemic curve (the sum of the infectious compartment in each subpopulation) for 4 different scenarios:

1. With vaccination and sequential intervention release
2. Full release after vaccination of the first subpopulation (i)
3. Full release after vaccination of the second subpopulation (j)
4. Full release after vaccination of the last subpopulation (k)

The three shaded areas are the vaccination periods for subpopulation i, j and k respectively.

Sequential Vaccination

Attack Rate (i) – 0.009
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptible individuals infected in sub-group i = **0.0082**

Full Release after vaccination of i

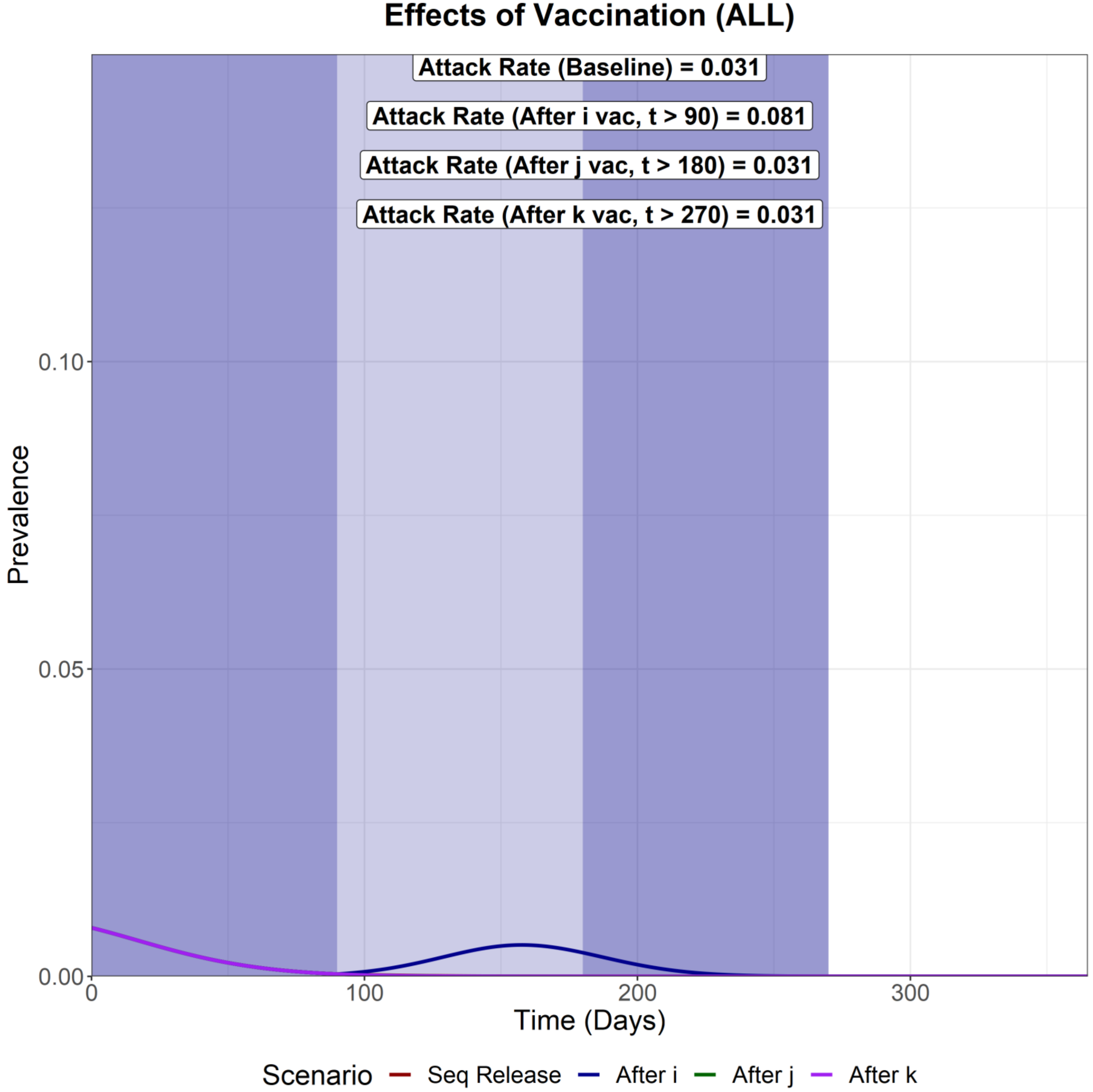
Attack Rate (i) – 0.015
Attack Rate (j) – 0.025
Attack Rate (k) – 0.042
Attack Rate for fully susceptible individuals infected in sub-group i = **0.0113**

Full Release after vaccination of j

Attack Rate (i) – 0.009
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptible individuals infected in sub-group i = **0.0082**

Full Release after vaccination of k

Attack Rate (i) – 0.009
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptible individuals infected in sub-group i = **0.0082**



DECREASED INTER-GROUP MIXING

R on the non-diagonal elements of the WAIFW matrix is half relative to a baseline NPI release.

Scenario Analysis (Total Infected)

We now compare the total epidemic curve (the sum of the infectious compartment in each subpopulation) for 4 different scenarios:

1. With vaccination and sequential intervention release
2. Full release after vaccination of the first subpopulation (i)
3. Full release after vaccination of the second subpopulation (j)
4. Full release after vaccination of the last subpopulation (k)

The three shaded areas are the vaccination periods for subpopulation i, j and k respectively.

Sequential Vaccination

Attack Rate (i) – 0.009
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptible individuals infected in sub-group i = **0.0082**

Full Release after vaccination of i

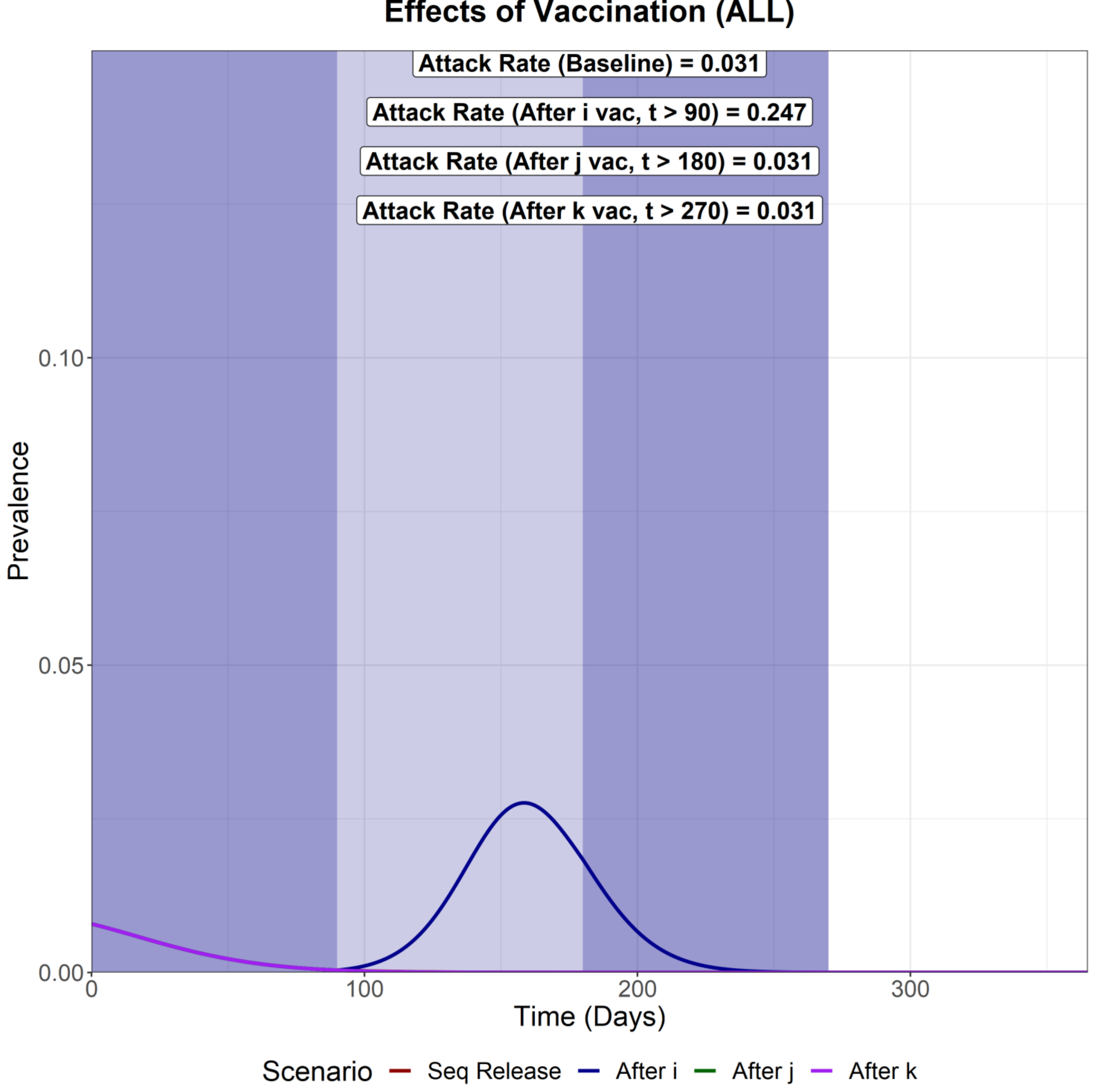
Attack Rate (i) – 0.03
Attack Rate (j) – 0.061
Attack Rate (k) – 0.157
Attack Rate for fully susceptible individuals infected in sub-group i = **0.0183**

Full Release after vaccination of j

Attack Rate (i) – 0.009
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptible individuals infected in sub-group i = **0.0082**

Full Release after vaccination of k

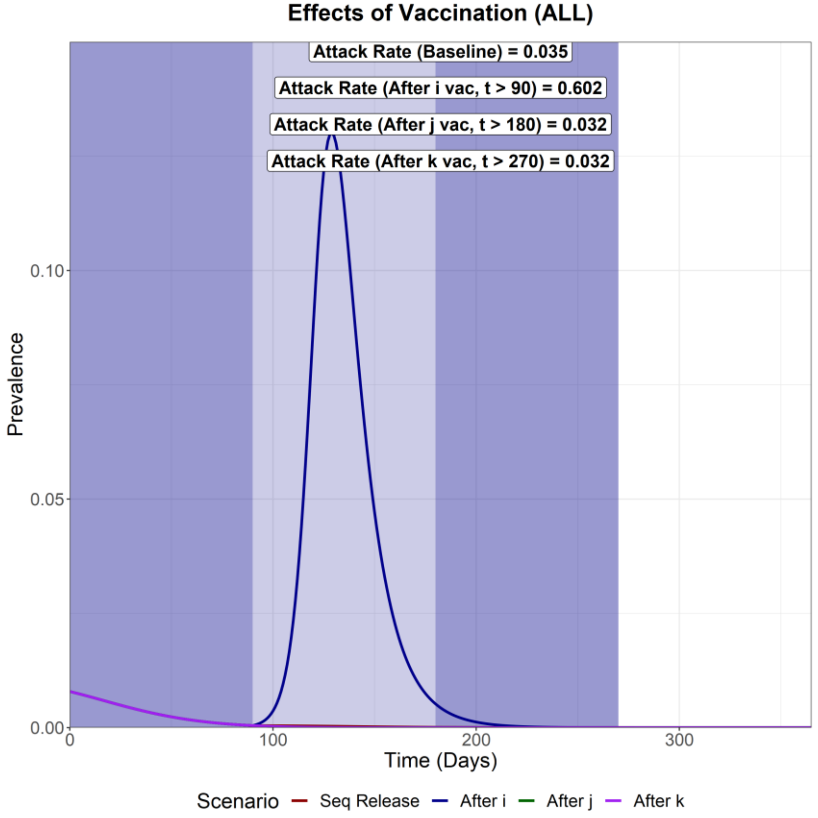
Attack Rate (i) – 0.009
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptible individuals infected in sub-group i = **0.0082**



LOSS OF NATURAL IMMUNITY, VACCINE IMMUNITY AND BOTH

Waning immunity is modelled in those who are natural infected (σ_2 = 1/6 months^{-1}), vaccinated (σ_1 = 1/6 months^{-1}) and then both are modelled in tandem (both σ_1 = 1/6 months^{-1} and σ_2 = 1/6 months^{-1})

Waning Natural Immunity
(σ_2 = 1/6 months^{-1})



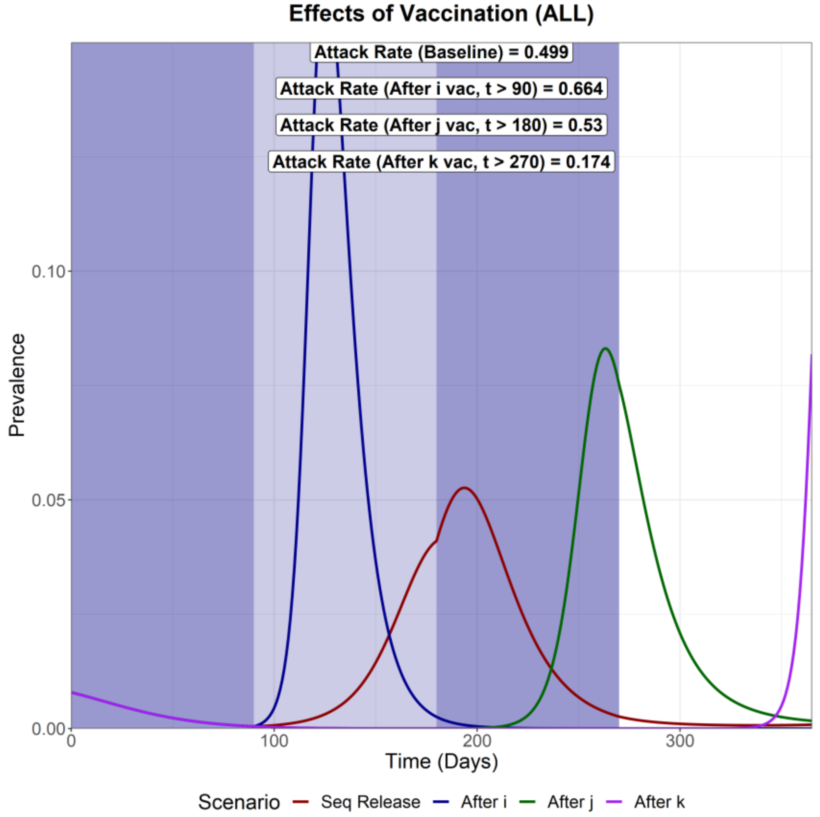
Sequential Vaccination
Attack Rate (i) – 0.009
Attack Rate (j) – 0.012
Attack Rate (k) - 0.013
Attack Rate for fully susceptibles in i - **0.0088**

Full Release after i vacc
Attack Rate (i) – 0.088
Attack Rate (j) – 0.212
Attack Rate (k) – 0.302
Attack Rate for fully susceptibles in i - **0.0374**

Full Release after j vacc
Attack Rate (i) – 0.009
Attack Rate (j) – 0.012
Attack Rate (k) – 0.012
Attack Rate for fully susceptibles in i - **0.0084**

Full Release after k vacc
Attack Rate (i) – 0.009
Attack Rate (j) – 0.012
Attack Rate (k) – 0.012
Attack Rate for fully susceptibles in i - **0.0084**

Waning Vaccine Immunity
(σ_1 = 1/6 months^{-1})



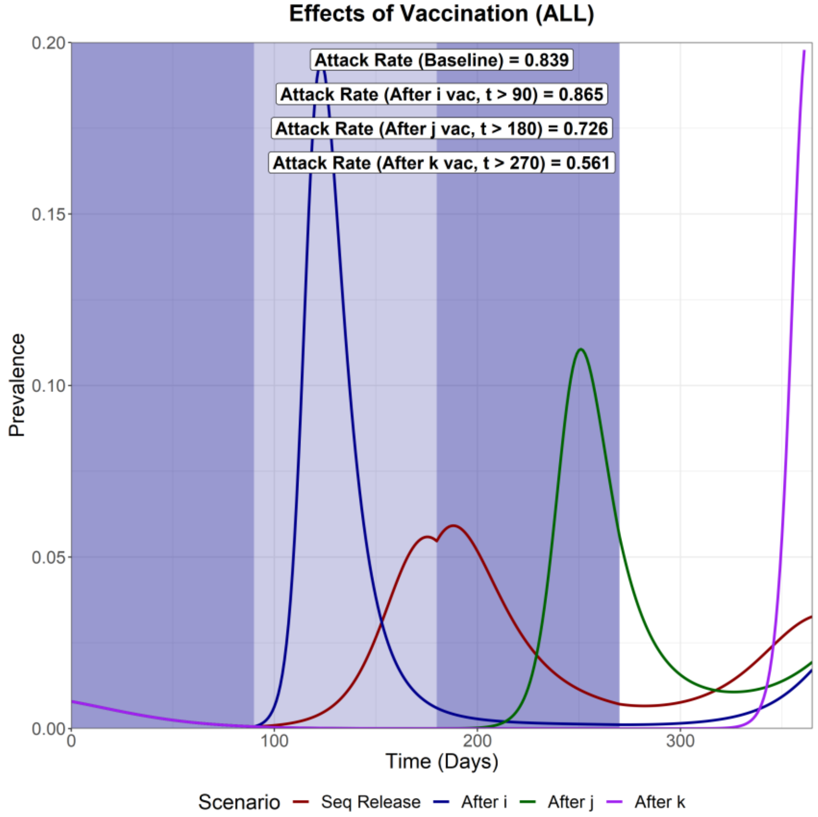
Sequential Vaccination
Attack Rate (i) – 0.179
Attack Rate (j) – 0.133
Attack Rate (k) – 0.187
Attack Rate for fully susceptibles in i - **0.159**

Full Release after i vacc
Attack Rate (i) – 0.164
Attack Rate (j) – 0.221
Attack Rate (k) – 0.279
Attack Rate for fully susceptibles in i - **0.1277**

Full Release after j vacc
Attack Rate (i) – 0.208
Attack Rate (j) – 0.177
Attack Rate (k) – 0.146
Attack Rate for fully susceptibles in i - **0.194**

Full Release after k vacc
Attack Rate (i) – 0.064
Attack Rate (j) – 0.06
Attack Rate (k) – 0.05
Attack Rate for fully susceptibles in i - **0.0621**

Waning Natural and Vaccine Immunity
(both σ_1 = 1/6 months^{-1} and σ_2 = 1/6 months^{-1})



Sequential Vaccination
Attack Rate (i) – 0.307
Attack Rate (j) – 0.244
Attack Rate (k) – 0.287
Attack Rate for fully susceptibles in i - **0.2779**

Full Release after i vacc
Attack Rate (i) – 0.233
Attack Rate (j) – 0.282
Attack Rate (k) – 0.35
Attack Rate for fully susceptibles in i - **0.1886**

Full Release after j vacc
Attack Rate (i) – 0.273
Attack Rate (j) – 0.239
Attack Rate (k) – 0.214
Attack Rate for fully susceptibles in i - **0.255**

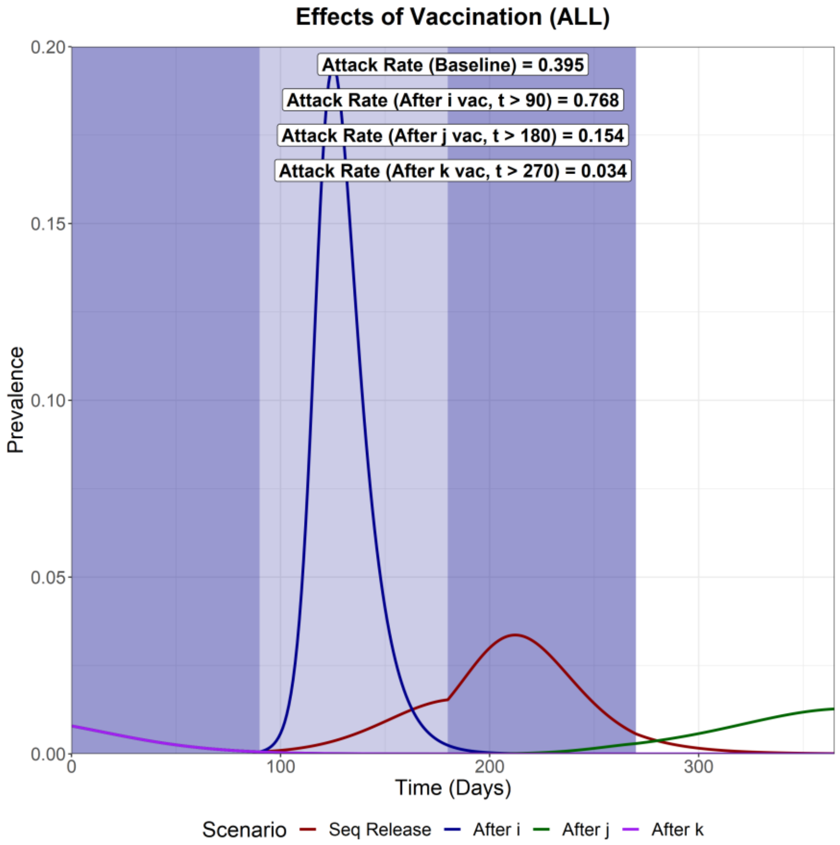
Full Release after k vacc
Attack Rate (i) – 0.205
Attack Rate (j) – 0.193
Attack Rate (k) – 0.163
Attack Rate for fully susceptibles in i - **0.19897**

VACCINE INDUCED BLOCKING OF COVID-19 TRANSMISSION

We model varying levels of vaccine induced transmission blocking. We model variations in reductions to vaccinated individuals becoming infected (e_{ff1}) and transmission from vaccinated individuals (e_{ff2}).

We model 3 levels of transmission blocking: 50%, 75% and 90% (baseline).

Transmission Blocking: **50%**
(e_{ff1} and e_{ff2} = 0.5)



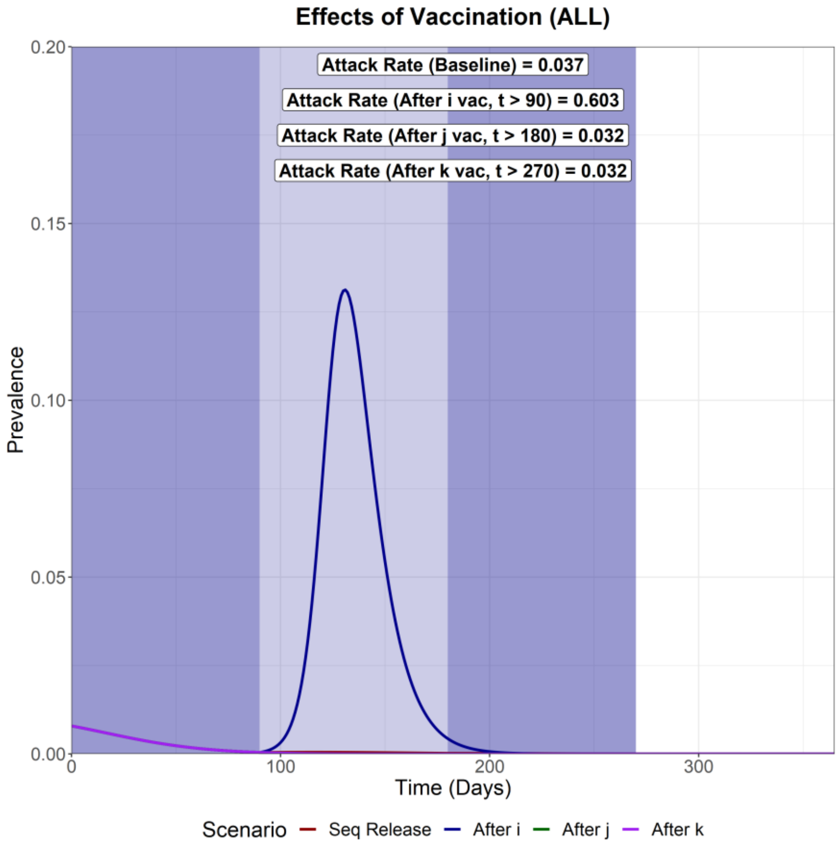
<u>Sequential Vaccination</u>
Attack Rate (i) – 0.136
Attack Rate (j) – 0.125
Attack Rate (k) – 0.135
Attack Rate for fully susceptibles in i - **0.027**

<u>Full Release after i vacc</u>
Attack Rate (i) – 0.226
Attack Rate (j) – 0.26
Attack Rate (k) – 0.281
Attack Rate for fully susceptibles in i - **0.035**

<u>Full Release after j vacc</u>
Attack Rate (i) – 0.05
Attack Rate (j) – 0.052
Attack Rate (k) – 0.052
Attack Rate for fully susceptibles in i - **0.0152**

<u>Full Release after k vacc</u>
Attack Rate (i) – 0.01
Attack Rate (j) – 0.012
Attack Rate (k) – 0.012
Attack Rate for fully susceptibles in i - **0.0085**

Transmission Blocking: **75%**
(e_{ff1} and e_{ff2} = 0.75)



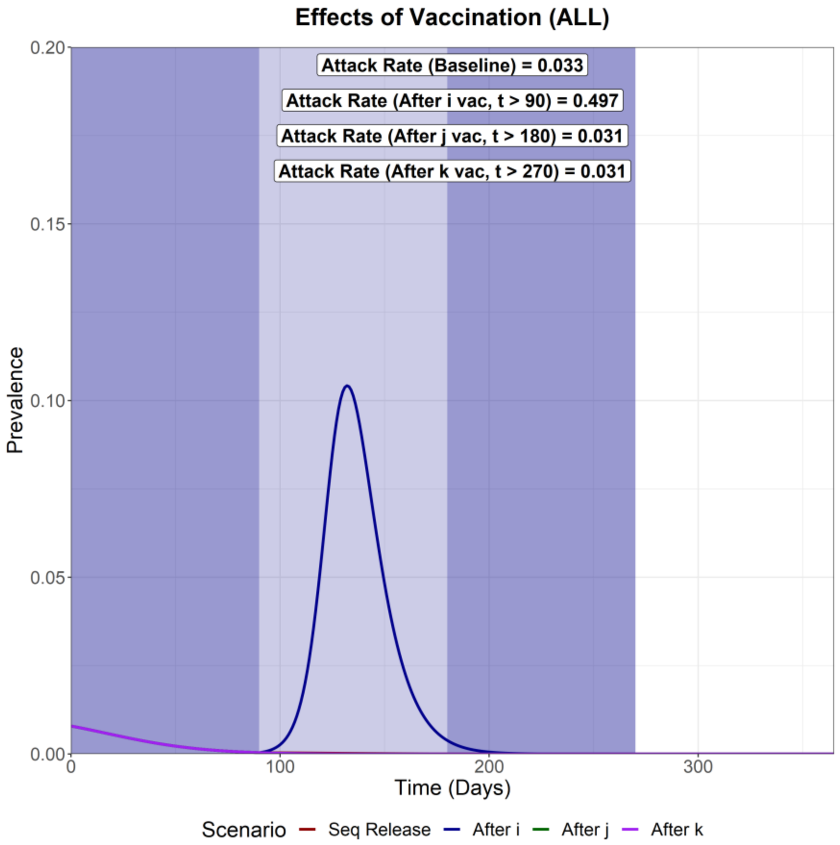
<u>Sequential Vaccination</u>
Attack Rate (i) – 0.011
Attack Rate (j) – 0.013
Attack Rate (k) – 0.013
Attack Rate for fully susceptibles in i - **0.0087**

<u>Full Release after i vacc</u>
Attack Rate (i) – 0.134
Attack Rate (j) – 0.207
Attack Rate (k) – 0.261
Attack Rate for fully susceptibles in i - **0.0332**

<u>Full Release after j vacc</u>
Attack Rate (i) – 0.009
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptibles in i - **0.0083**

<u>Full Release after k vacc</u>
Attack Rate (i) – 0.009
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptibles in i - **0.0082**

Transmission Blocking: **90%**
(e_{ff1} and e_{ff2} = 0.9)



<u>Sequential Vaccination</u>
Attack Rate (i) – 0.009
Attack Rate (j) – 0.012
Attack Rate (k) – 0.012
Attack Rate for fully susceptibles in i - **0.0084**

<u>Full Release after i vacc</u>
Attack Rate (i) – 0.074
Attack Rate (j) – 0.173
Attack Rate (k) – 0.25
Attack Rate for fully susceptibles in i - **0.032**

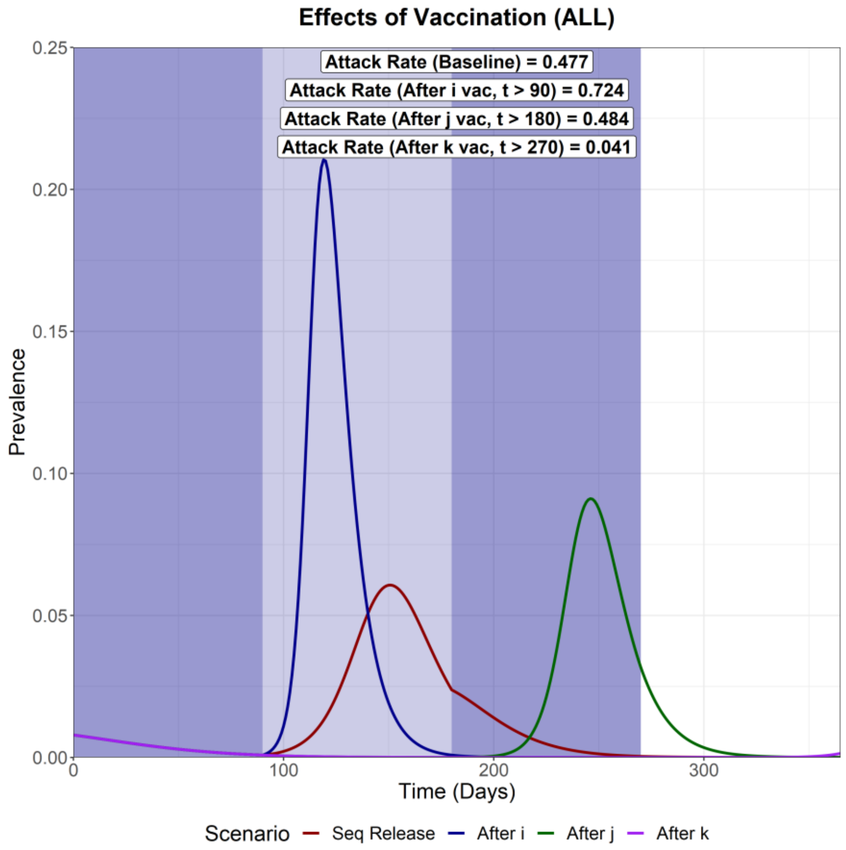
<u>Full Release after j vacc</u>
Attack Rate (i) – 0.009
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptibles in i - **0.0082**

<u>Full Release after k vacc</u>
Attack Rate (i) – 0.009
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptibles in i - **0.0082**

SENSITIVITY TO VACCINE COVERAGE

We model varying levels of vaccine coverage. Coverage is varied from 90% (baseline), 70% to 50%.

Vaccine Coverage = 50%



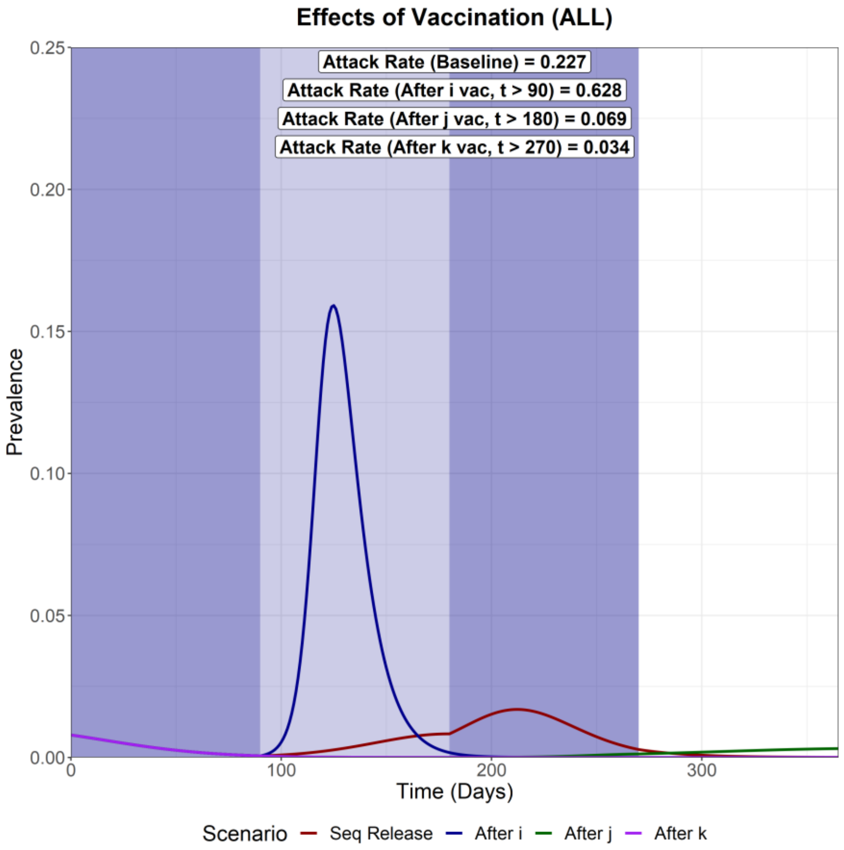
Sequential Vaccination
Attack Rate (i) – 0.154
Attack Rate (j) – 0.142
Attack Rate (k) – 0.182
Attack Rate for fully susceptibles in i - **0.131**

Full Release after i vacc
Attack Rate (i) – 0.182
Attack Rate (j) – 0.256
Attack Rate (k) – 0.286
Attack Rate for fully susceptibles in i - **0.147**

Full Release after j vacc
Attack Rate (i) – 0.151
Attack Rate (j) – 0.153
Attack Rate (k) – 0.181
Attack Rate for fully susceptibles in i - **0.128**

Full Release after k vacc
Attack Rate (i) – 0.012
Attack Rate (j) – 0.014
Attack Rate (k) – 0.015
Attack Rate for fully susceptibles in i - **0.0120**

Vaccine Coverage = 70%



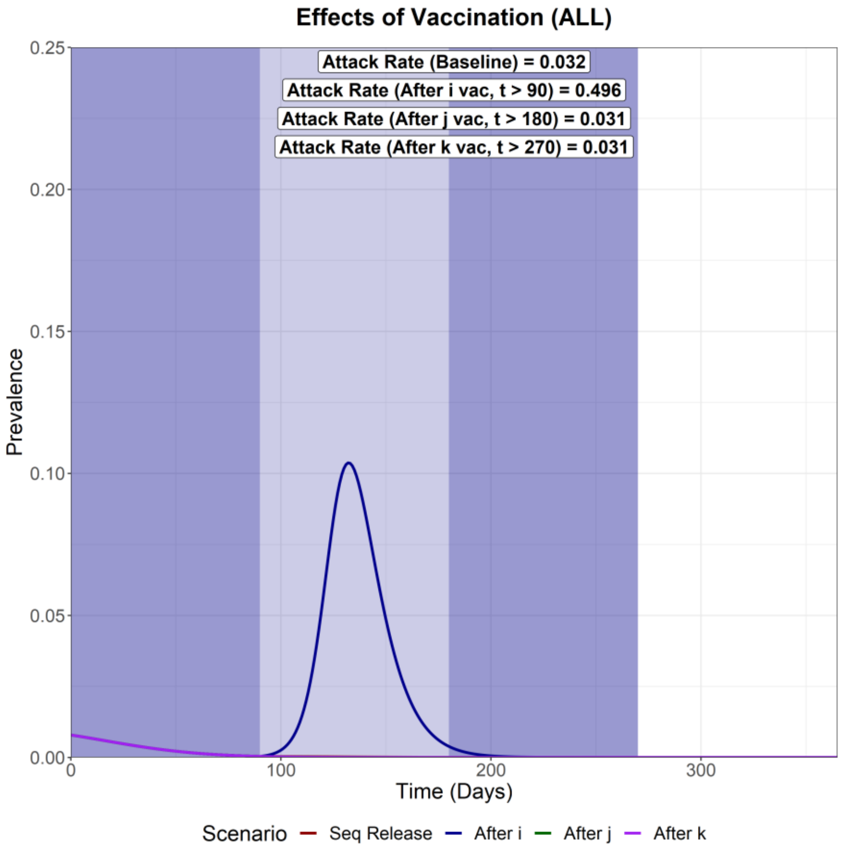
Sequential Vaccination
Attack Rate (i) – 0.067
Attack Rate (j) – 0.067
Attack Rate (k) – 0.092
Attack Rate for fully susceptibles in i - **0.053**

Full Release after i vacc
Attack Rate (i) – 0.13
Attack Rate (j) – 0.223
Attack Rate (k) – 0.274
Attack Rate for fully susceptibles in i - **0.088**

Full Release after j vacc
Attack Rate (i) – 0.021
Attack Rate (j) – 0.024
Attack Rate (k) – 0.024
Attack Rate for fully susceptibles in i - **0.0186**

Full Release after k vacc
Attack Rate (i) – 0.01
Attack Rate (j) – 0.012
Attack Rate (k) – 0.012
Attack Rate for fully susceptibles in i - **0.0094**

Vaccine Coverage = 90%



Sequential Vaccination
Attack Rate (i) – 0.009
Attack Rate (j) – 0.012
Attack Rate (k) – 0.012
Attack Rate for fully susceptibles in i - **0.0084**

Full Release after i vacc
Attack Rate (i) – 0.073
Attack Rate (j) – 0.173
Attack Rate (k) – 0.25
Attack Rate for fully susceptibles in i - **0.032**

Full Release after j vacc
Attack Rate (i) – 0.008
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptibles in i - **0.008**

Full Release after k vacc
Attack Rate (i) – 0.009
Attack Rate (j) – 0.011
Attack Rate (k) – 0.011
Attack Rate for fully susceptibles in i - **0.008**