Model Description
North American Animal Disease Spread Model
Version 1.0.3

NAADSM Development Team
Neil Harvey, Francisco J. Zagmutt-Vergara, Aaron Reeves,
and Mark Schoenbaum

Document history

- Version 1.0 (19 May 2004) – Initial specification.
- Version 1.0.1 (15 September 2004) – RFC20040915NHa accepted and incorporated.
- Version 1.0.2 (19 February 2005) – Resolves differences between "*SpreadModel*" and "*SHARCSpread*" implementations, as discussed in Guelph, Ontario, Canada, Feb. 14 – 15, 2005.
- Version 1.0.2a (11 June 2005) – Identical content, slight rearrangement of text to make parameters easier to identify.
- Version 1.0.3 (02 November 2005) – Incorporates changes described in the following RFCs:
    - RFC20050922ARa: *Clarification of language regarding trace-back destruction*
    - RFC20050922ARb: *Change in destruction and vaccination priority*
    - RFC20050922ARc: *Initiation of a vaccination program*
    - RFC20050927ARa: *Clarification of infection timing*
    - RFC20050927ARb: *Clarification of detection timing*
    - RFC20050928AR: *Vaccination parameters for individual production types*

Contents

1. Introduction

This document is intended to be a plain-language description of the simulation model implemented in the North American Animal Disease Spread Simulator v3.0. Its purpose is to facilitate agreement among current team members on details of the model, to provide a basis for functional testing, and to provide the validation committee and future team members with a complete but accessible description of the model.

The description is based on the paper *Modeling alternative mitigation strategies for a hypothetical outbreak of foot-and-mouth disease in the United States* by Mark A. Schoenbaum and W. Terry Disney, the document *SpreadModel Version 3.0 Diagrams and pseudocoding* by Mark A. Schoenbaum and Francisco Zagmutt-Vergara, observations of *SpreadModel* v2.14 and beta versions of 3.0, and discussions with the project team.

Keywords

herd-level stochastic spatial state-transition simulation

2. Basics

A collection of animals, called a "unit," is the basis of the simulation. A unit has a production type, size, location, and disease state. The production type may be a single kind of livestock (e.g., "dairy cattle") or a mixed type (e.g., "sheep and poultry"). Figure 1 shows the states a unit may be in and possible transitions among them.

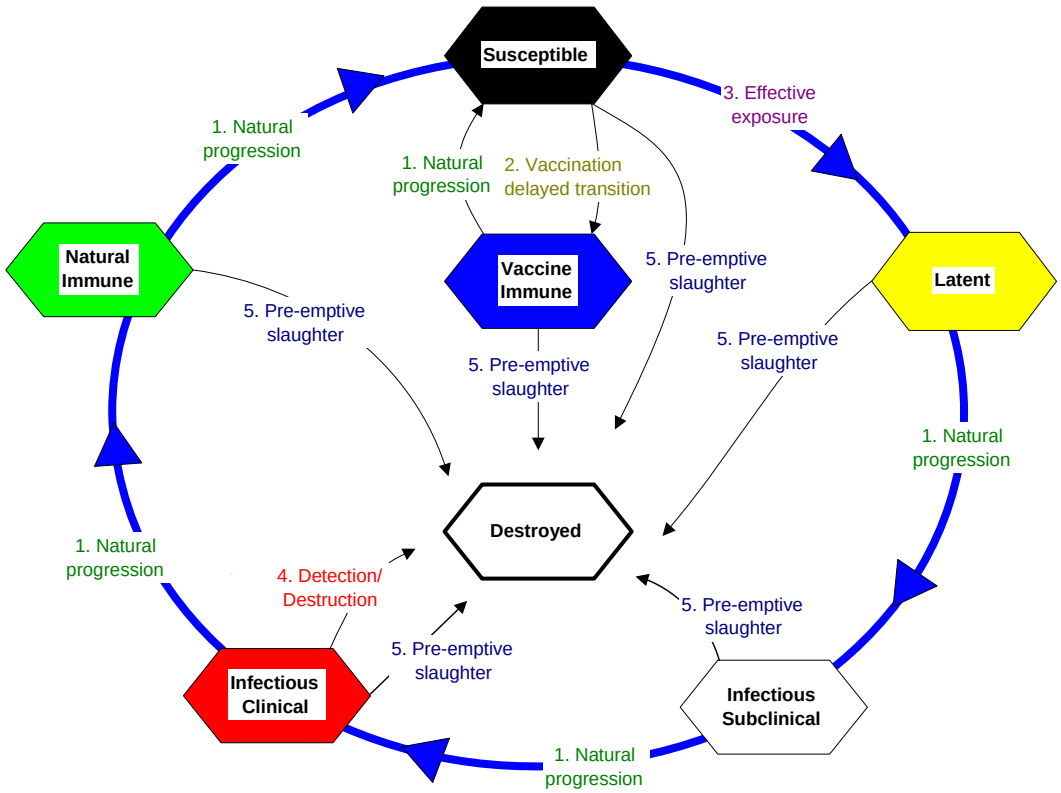


Figure 1. States and transitions

The simulation proceeds in time steps of one day. Each day units may be affected by biological processes happening in the animals (*e.g.* the natural progress of the disease), processes happening in the environment (*e.g.* airborne spread), and/or human actions (*e.g.* detection, vaccination, and destruction). The "model" is the sum of these processes and actions.

3. Disease

When a Susceptible unit is infected, it becomes Latent. The infection progresses in the unit from Latent to Infectious Subclinical (shedding agent without visible signs of disease), to Infectious Clinical (shedding agent with visible signs of disease), to Natural Immune, and back to the Susceptible state. Probability functions characterize the length of the periods and this length is determined stochastically for each new infection. The disease is never fatal: that is, all infected units will eventually return to Susceptible unless destroyed. If time-frames for simulations are long, a particular unit may progress through the infected states more than once.

A unit can spend zero time in a state. For example, the parameter for time spent as Infectious Subclinical can be zero. In that case, units will change directly from Latent to Infectious Clinical. A unit undergoes its first transition state change on the day immediately following its infection.

Attempting to infect a unit that is not Susceptible has no effect.

If two units are at the same location, infecting one does not automatically infect the other.

Disease parameters

Parameters specified for each production type:

- latent period (days)  [1]
- infectious subclinical period (days) 
- infectious clinical period (days) 
- natural immune period (days) 

The parameters are given separately for each production type. That is, the duration of the disease stages can be different for cattle, pigs, *etc*.

4. Spread

4.1. Direct contact spread

The simulation of direct contact – movement of animals among units – works as follows:

On each day,

1. Look up a multiplier to adjust the rate of movement of animals based on the number of days since the first detection of the disease. Use this multiplier to scale the movement rate. This approximates applying movement-controls over the course of an infection spreading through the population of units.
2. For each unit *A*,
    (a) Check whether *A* can be the source of an infection. That is, is it Latent, Infectious Subclinical, or Infectious Clinical, and not quarantined?[2] (Infectious Clinical is always a source. Latent and Infectious Subclinical are optionally a source.)
    (b) If *A* cannot be a source, go on to the next unit.
    (c) Sample a number *N* from a Poisson distribution whose mean is the movement rate (adjusted by 1 above).
    (d) Create *N* shipments from *A*.
3. For each shipment,
    (a) Sample a number, *distance*, from the movement distance distribution.
    (b) From all units that can be the target of disease exposure (that is, those that are not Destroyed or are the source), choose the unit *B* whose distance from the source is closest to *distance*. If several possible targets are the same

[1]  indicates a parameter that is given as a probability density function.
[2] see section 6. Control measures) for a description of quarantine.

distance from the source, choose one randomly, giving preference to larger units (a unit with twice as many animals is twice as likely to be chosen).

(c) If *B* is not Susceptible, the shipment has no effect on the disease state but is recorded as an exposure; go on to the next shipment.

(d) Generate a random number *r* in [0,1), that is, from 0 up to but not including 1.

(e) If $r < P$, the probability of infection given exposure, turn *B* Latent after a shipping delay.

The progress of the disease in the receiving unit starts at Latent, with the duration of each stage of the disease chosen stochastically, regardless of whether the shipping unit was Latent, Infectious Subclinical, or Infectious Clinical. A unit that receives Infectious Clinical animals could technically be regarded as immediately Infectious Clinical (able to infect other units by airborne spread and indirect contact, and detectable by a farmer or attending veterinarian) but starting the receiving herd at Latent reflects the fact that *most* of the animals in the receiving unit have to progress through the earlier disease-stages. The disease-state is an attribute of the unit as a whole rather than a direct reflection of the state of a particular animal in the unit.

Direct contacts (even ones that do not result in a new infection) are recorded and can be discovered later during trace-investigations.

The size of a shipment is not considered, and the number of animals in each unit does not change during the simulation.

The distance between lat_1, lon_1 and lat_2, lon_2 is approximated as:

$$y = lat_2 - lat_1$$

$$x = (lon_2 - lon_1) \cdot \cos(lat_1)$$

$$d = \frac{c}{360} \cdot \sqrt{x^2 + y^2}$$

where c = the circumference of the earth.

Parameters for direct contact spread

Parameters for each pair of production types:

- Mean rate of movement (recipient-units for shipments per source-unit per day)
- movement distance (km) 
- shipping delay (days) 
- probability of infection given exposure
- movement rate multiplier vs. days since the first detection  [1]

When more than one production-type is considered, the above parameters are specified for each pairing of one production-type with another. Consider the production-types "Beef" and "Dairy", referring to herds of beef cattle and dairy cattle. You specify the

[1]  indicates a parameter that is given as a relational chart.

most important pairings of these production-types with regard to direct-contact parameters. For example: “Beef” to “Beef”, “Beef” to “Dairy”, “Dairy” to “Beef”, and “Dairy” to “Dairy” are the possible pairings of these production-types. Separate parameters are specified for each of these pairs since the direct-contact among different production-type may vary.

Note that parameters are separate for movement in each direction between each pair of production-types. That is, the parameters for movement from “Beef” to “Dairy” can be different from the parameters for movement from “Dairy” to “Beef”, and the parameters for movement from “Beef” to say “Pigs” can be different again.

If parameters are given for movements from “Beef” to “Beef” and from “Beef” to “Dairy”, the number of shipments a “Beef” cattle herd *A* sends to “Beef” cattle herds on a particular day and the number of shipments *A* sends to “Dairy” cattle herds on the same day are independent.

Shipping animals from a Latent, Infectious Subclinical, or Infectious Clinical unit to a Natural Immune or Vaccine Immune unit has no effect on the disease-stage of the recipient unit. Shipping animals from a unit in a more advanced disease stage to a unit in a less advanced disease stage (e.g., from an Infectious Clinical unit to a Latent unit) also has no effect.

4.2. Indirect contact spread

Indirect contact – movement of people, materials, vehicles, equipment, animal products, etc among units – is simulated in the same manner as direct contact, except that only Infectious Subclinical and Infectious Clinical units, not Latent units, can be the source of infection. The parameters for indirect contact are similar to but independent of those for direct contact.

Indirect contacts can be discovered later during trace-investigations.

Parameters for indirect contact spread

Parameters for each pair of production types:

- Mean rate of movement (recipient-units for shipments per source-unit per day)
- movement distance (km) 
- shipping delay (days) 
- probability of infection given exposure
- movement rate multiplier vs. days since the first detection 

4.3. Airborne spread

The simulation of airborne spread works as follows:

On each day,

1. For each unit *A*,
    (a) Check whether *A* can be the source of an infection. That is, is it Infectious Subclinical or Infectious Clinical?
    (b) If *A* cannot be a source, go on to the next unit.
    (c) For each other unit *B*,
        i. Check whether *B* can be the target of an infection. That is, is it Suspectible, is the distance from *A* to *B* < the maximum distance of spread, and is the direction from *A* to *B* inside the wind direction range?
        ii. If *B* cannot be a target, go on to the next unit.
        iii. Compute the probability of infection *P* = probability of infection at 1 km × *DistanceFactor*(*A*,*B*) × *HerdSizeFactor*(*A*) × *HerdSizeFactor*(*B*).
        iv. Generate a random number *r* in [0,1).
        v. If *r* < *P*, turn *B* Latent after a delay.

Where
DistanceFactor(*A*,*B*) = (maximum distance of spread - distance from *A* to *B*) / (maximum distance of spread - 1)
HerdSizeFactor(*A*) = (area under histogram of unit sizes from 0 to size of *A*) × 2

The distance between lat_1, lon_1 and lat_2, lon_2 is approximated as before. The direction from lat_1, lon_1 to lat_2, lon_2 is approximated with the inverse tangent using the same *x* and *y*.

Airborne spread can occur from and to quarantined units.[1]

Airborne exposure is not recorded since it would not be used directly by mitigation processes such as movement-controls, vaccination, and destruction.

Parameters for airborne spread

Parameters for each pair of production types:

- probability of infection at 1 km from source (Infectious Subclinical or Infectious Clinical unit)
- wind direction, given as a range (*start* and *end*) in degrees
- maximum distance of spread (km)
- airborne transport delay (days) 

The parameters are given separately for spread in each direction between each pair of production types. That is, the parameters for spread from pig herds to cattle herds can be different from the parameters for spread from cattle herds to pig herds, to account for

[1]See section 6. Control measures for a description of quarantine.

potential differences in amount of virus produced and/or different minimum-infective-doses for animals in different production-types.

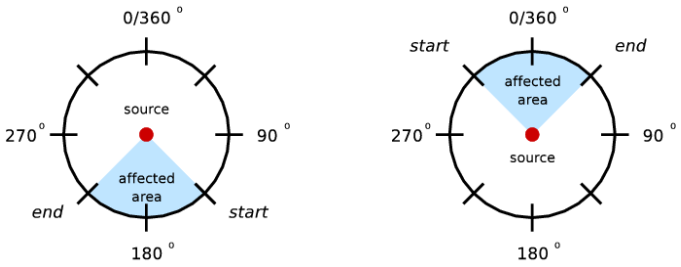


Figure 2. Example parameters for north winds (left) and south winds (right).

5. Detection

The simulation of detection works as follows:

On each day,

1. Look up the probability that a farmer or attending veterinarian, for example, will report signs of disease to authorities based on the number of days since the first detection in the population. A static probability represents the baseline before the first detection.
2. For each Infectious Clinical unit,
   (a) Look up the probability of detecting signs of disease based on the number of days the unit has been Infectious Clinical.
   (b) Compute the probability of detection and reporting (Equation 1 X 2a).
   (c) Generate a random number r in [0,1).
   (d) If $r < P$, the disease is detected and reported.

There are no false-positive detections.

A report is immediately known to the authorities.

Detection parameters

Parameters for each production type:

- probability of reporting vs. days since the first detection
- probability of detection vs. days the unit has been Infectious Clinical

The parameters are given separately for each production type, to account for the possibility that signs of disease may be more obvious in animals of certain production-types, e.g., signs may be reported more rapidly in intensive swine production systems versus cow-calf operations on pastures.

6. Control measures

6.1. Quarantine

A diseased unit is quarantined on the day immediately following its detection. Quarantined units cannot be involved in direct contact, but indirect contact and airborne spread may still occur to or from a quarantined unit.

6.2. Destruction

When the first detection happens in the study population, the authorities may initiate a destruction program. It can take several days before the authorities are ready to begin destroying.

All detected units are marked for destruction. Units that have had contact with diseased units within a given number of days prior to detection of the diseased unit (found through trace-investigations) and units within a given distance of diseased units may also be marked for destruction. The destruction of these units associated by trace or distance has been called pre-emptive or dangerous-contact slaughter.

Trace-investigations are immediate. Tracing goes one level forward, that is, it identifies units that were recipients of direct or indirect contact from infected, detected units. Tracing does not identify contacts that led to the infection of infected, detected units. (Figure 3).

Destruction parameters

Global parameters (applied to all production types):

- delay to begin a destruction program (days)
- destruction capacity vs. days since the first detection (units per day)  (see section 6.2.1)
- destruction priorities (see section 6.2.2)

Parameters specified separately for every production type:

- probability of a trace-out investigation succeeding
- period of interest for trace-out investigations
- radius of destruction ring (km)

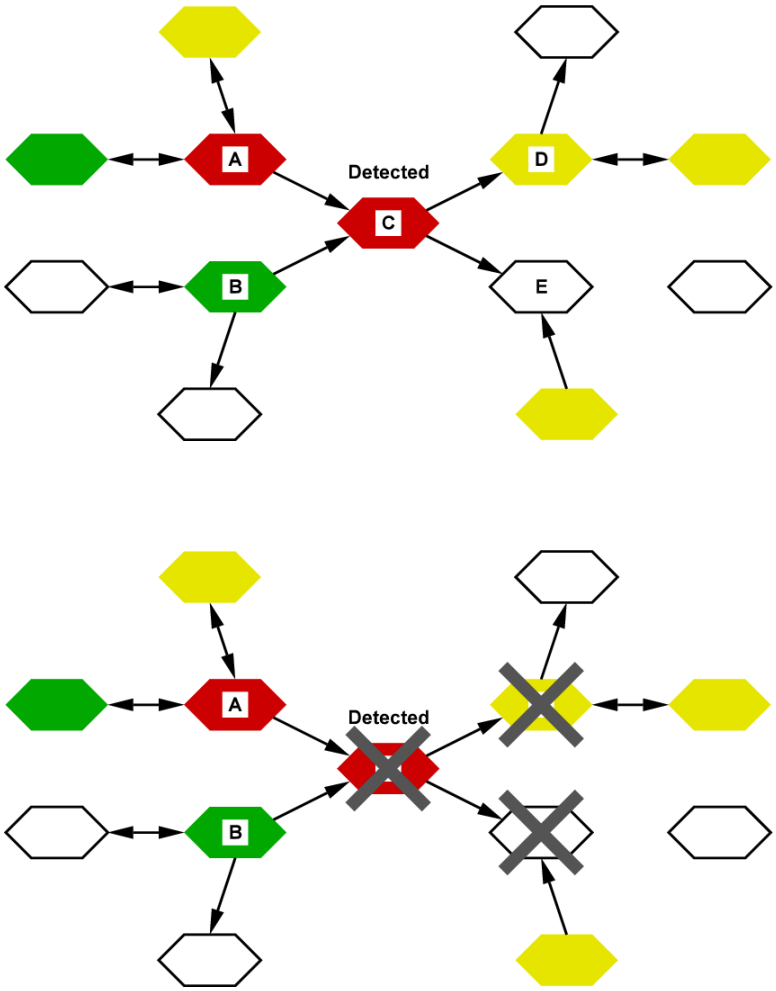


Figure 3. Trace out. When unit C is detected, units to which C has shipped animals or sent people or equipment are marked for destruction. The trace does not extend further, e.g., to units that shipped animals to C (A or B), or units that received animals from D.

6.2.1 Destruction capacity

There is a limit (called destruction capacity) on how many units can be destroyed per day. Destruction capacity does not consider unit size (*i.e.* the number of animals in each unit). Destruction capacity is specified as a relational chart of the number of units which can be destroyed per day versus the number of days since the first detection of disease. A single destruction capacity applies to units of all production types: for example, if the destruction capacity on a given day is 10 units, then 10 beef units may be destroyed on that day, or 10 swine units, or six units of one and four of the other, depending on the assigned destruction priorities (see section 6.2.2).

6.2.2 Destruction priorities

If a unit is marked for destruction but cannot be destroyed immediately, it is quarantined and goes onto a prioritized waiting list.

There are three criteria which may be used to set destruction priorities: the production type of the unit, the reason for destruction of the unit, and the number of days a unit has been waiting in the destruction queue. Within the production type criterion, the production types present in a scenario are further prioritized (*e.g*. cattle may have a higher destruction priority than swine, or *vice versa*). Similarly, within the action reason criterion, the reasons for destruction are further prioritized: these reasons are detection of disease, exposure by direct contact, exposure by indirect contact, and presence within a specified destruction ring. For example, cattle herds that are marked for destruction because they were detected as diseased may have a higher priority than cattle herds that are marked for destruction because they are near a diseased unit.

The order in which the three criteria are applied must be specified in each scenario. For example, the number of days a unit has been in the destruction queue may be the overriding priority, so that units of any production type, holding for any reason, that have been holding for the longest period of time are destroyed before any others. Criteria with the highest priority are applied first. In the event that two units are encountered that have the same priority based on the top criterion, subsequent criteria are applied (see examples below).

No two production-type/reason for destruction combinations can have the same priority. That is, cattle herds that were detected as diseased *must* have a strictly higher priority than pig herds that were detected as diseased (or *vice versa*), and cattle herds that were detected as diseased *must* have a strictly higher priority than cattle herds that were simply near to a detected unit (or *vice versa*).

No distinction in destruction priority is made based on source of exposure: cattle herds that have been exposed by a swine herd, for example, are treated no differently than cattle herds exposed to infection by other cattle herds.

On each day, the authorities destroy as many units as possible (up to the destruction capacity for that day) from the destruction queue, beginning with the highest priority.

Examples of destruction priorities

Consider the following examples, using these four units which have been designated for destruction:

Unit A. Cattle herd, detected infection, holding for 3 days
Unit B. Cattle herd, indirect contact, holding for 5 days

Unit C. Swine herd, direct contact, holding for 1 day
Unit D. Swine herd, within circle/ring, holding for 5 days

Example 1:

With the following destruction priorities:
Days holding > production type (swine > cattle) > destruction reason (detected > direct> indirect > circle/ring)

The four herds are destroyed in the following order:
D, B, A, C

Example 2:

Priorities: production type (cattle > swine) > destruction reason (detected > direct> indirect > circle/ring) > days holding:

Destruction order: A, B, C, D

Example 3:

Priorities: production type (cattle > swine) > days holding > destruction reason (detected > direct > indirect > circle/ring):

Destruction order: B, A, D, C

Example 4:

Priorities: destruction reason (detected > circle/ring > direct > indirect) > production type (cattle > swine) > days holding:

Destruction order: A, D, C, B

6.3. Vaccination

When the disease is detected, authorities may also initiate a vaccination campaign. This consists of vaccinating units within a specified distance of the detected units – in circles or rings around detected units. A production-type-specific parameter determines whether detection of an infected unit of a particular production type will trigger the formation of a vaccination ring or not: for example, detection of an infected swine unit might lead to the vaccination of surrounding units of various production types, while detection of an infected sheep unit might not trigger vaccination of surrounding units.

A production-type-specific parameter also governs whether units of a particular production type are included in a vaccination program. For example, dairy cattle units might be vaccinated in response to the detection of a diseased unit nearby, while sheep units might not be vaccinated.

The initiation of a vaccination program may be delayed until a certain trigger point is

reached in terms of numbers of detected units (see section 6.3.1)

If a unit is marked for vaccination but cannot be vaccinated immediately, it goes onto a prioritized waiting list (see sections 6.3.2 and 6.3.3).

For a unit to receive multiple vaccinations, vaccination of that individual unit must be triggered multiple times (see section 6.3.4.). It is not currently possible to schedule revaccination of units without an additional trigger.

Vaccination program parameters

Global parameters (applied to all production types):

- number of detected units before vaccination begins (see section 6.3.1)
- vaccination capacity vs. days since the first detection (units per day)  (see section 6.3.2)
- vaccination priorities (see section 6.3.3)

Parameters set individually for each production type:

- indication of whether detection of units of the production type will trigger a vaccination ring (yes/no)
- radius of vaccination ring (km) , if units of the production type will trigger a vaccination ring
- indication of whether units of the production type will be vaccinated in response to detection of nearby units (yes/no)
- minimum time between vaccinations (days) , if units of the production type will be vaccinated (see section 6.3.4)

6.3.1 Initiation of a vaccination program

A vaccination program is initiated when the user-specified number of infected units has been detected. Until or unless this number is reached, units are not marked for vaccination. Once this critical number has been reached, units within the specified vaccination ring surrounding the most recently detected unit are marked for vaccination. Vaccination rings also will be created around any unit that is detected on the same simulation day that the critical number is reached. Similarly, vaccination rings will be created around infected units detected on subsequent simulation days. Units marked for vaccination are then treated according to the steps described below.

6.3.2 Vaccination capacity

Vaccination capacity (the number of units which can be vaccinated per day) is handled in the same way as destruction capacity (see section 6.2.1), and is specified as a relational chart of the number of units which can be vaccinated per day versus the number of days

since the first detection of disease. Vaccination capacity does not consider unit size (*i.e.* the number of animals in each unit). A single vaccination capacity applies to units of all production types.

Personnel for destruction cannot be temporarily loaned to vaccination teams, or *vice versa*, during a simulation run. In other words, the daily limits for destruction and vaccination operate independently of one another.

6.3.3 Vaccination priorities

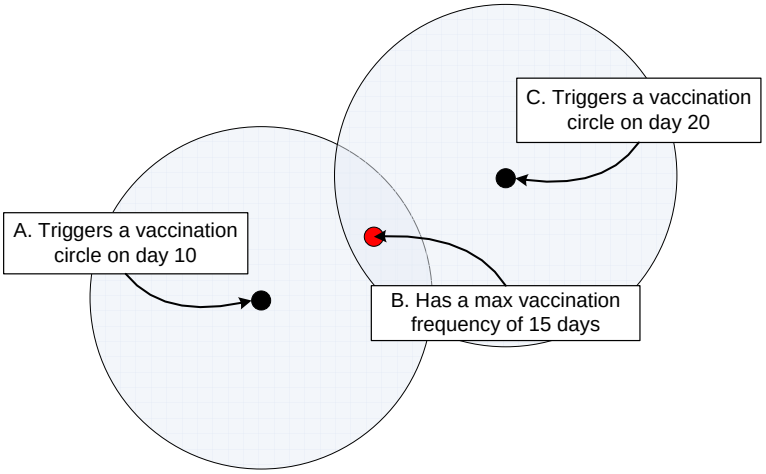
Vaccination priorities are set in fashion similar to destruction priorities (see section 6.2.2). There are two criteria which may be used to set vaccination priorities for units which fall within a vaccination circle. These criteria are production type of the unit and the number of days that a unit has been in the vaccination queue. Within the production type criterion, the production types present in a scenario are further prioritized.

The order in which these two criteria are applied must be specified in each scenario. For example, the number of days a unit has been in the vaccination queue may be the overriding priority, so that units of any production type that have been holding for the longest period of time are vaccinated before any others. The criterion with the highest priority is applied first. In the event that two units are encountered that have the same priority based on the top criterion, the next criterion is applied.

6.3.4 Minimum time between vaccinations

The minimum time between vaccinations is the number of days which must pass before a unit may be revaccinated. Once the specified number of days has passed, a unit may be revaccinated if vaccination of that unit is triggered again.

Consider the simple situation involving units *A*, *B*, and *C* as shown in the figure below. Disease is detected in unit *A* ten days before disease is detected in unit *C*. Both detections trigger vaccination circles as shown.



Unit *B* is within vaccination circles triggered by detection of units *A* and *C*, and will be added twice to the queue of units to be vaccinated. If there is no waiting period for vaccination (*i.e.* vaccination capacity is not reached), unit *B* will receive only one vaccination: its minimum time between vaccinations will not have been reached before it comes to the head of the queue the second time.

If vaccination capacity has been reached, unit *B* will receive two vaccinations only if the elapsed time between the first and second scheduled vaccinations exceeds the unit's minimum time between vaccinations. This subsequent vaccination resets the vaccine-immune period for unit *B*. If the elapsed time is less than the unit's maximum vaccination frequency, unit *B* will not be revaccinated.

7. Biological effects of vaccination

When a unit is vaccinated, it remains Susceptible for a time while immunity develops, then becomes Vaccine Immune. The length of the immune period is determined stochastically for each new vaccination. After the immune period, the unit reverts to a Susceptible state.

If a unit is infected after being vaccinated but before turning Vaccine Immune, the effects of the vaccination are cancelled.

Vaccinating a unit that is not Susceptible has no effect on its disease state.

Parameters for effects of vaccination

Parameters specified for each production type:

- delay to produce immunity (days)
- immunity period (days) 

The parameters are given separately for each production type.

8. Priorities of action

Because the events in one simulation day should be considered to happen simultaneously, and because different processes may try to make conflicting changes to a unit, there is a need to order or prioritize the processes.

The ordering is:

1. Infection, destruction, or vaccination
2. Biological processes happening within units

(Note that these correspond to the transition labels in Figure 1.)

If a unit is both infected or vaccinated, or infected and destroyed, the order in which these happen is chosen randomly. If a unit is to be vaccinated and destroyed on the same day, destruction will always have precedence. If all three are scheduled to occur on the same day, a unit may or may not be infected before it is destroyed, but it will never be vaccinated.

If two or more processes infect the same unit on the same day, one process is chosen randomly as the cause of the infection, for the purpose of reporting in simulation statistics. Similarly, if there are two or more reasons for vaccinating or destroying a unit, one reason is chosen randomly for the purpose of reporting.

Some examples illustrating the effects of this ordering:

- If unit *A* is due to change from Susceptible to Vaccine Immune on day *D*, and a shipment of infectious animals arrives on day *D*, *A* is infected. (The exposure happens "before" the natural progression to Vaccine Immune.)
- If unit *A* is due to change from Vaccine Immune to Susceptible on day *D*, and the wind carries virus from an infectious unit on day *D*, *A* is not infected. (The exposure happens "before" the natural progression to Susceptible.)
- If unit *A* is destroyed on day *D*, and the wind carries virus from an infectious unit on day *D*, *A* may be reported in simulation statistics as having been an infected unit or a healthy unit. (Whether the infection happens "before" the destruction is determined randomly.)