Supplementary material S1: Submodels describing seasonal dynamics of seed degeneration in vegetatively-propagated crops

The number of healthy plants in the field at the end of a season is determined by the initial planting population in the field (*K*), the proportion of healthy seed used for planting (pHS_{s-1}) and the rate of host infection (Equation A1). The proportion of healthy seed includes the proportion of healthy seed produced in the previous season and any external input of certified seed. The rate of host infection is determined by the maximum seasonal disease transmission rate (β) between diseased ($K * pDS_{s-1}$) and healthy ($K * pHS_{s-1}$) plants and is modified by environmental conduciveness (*W*), host genetics (*H*), vector management (*M*) and external inoculum (*E*). External inoculum acts similarly to the presence of infected plants within the field, in determining the rate of infection within the field. *E* might be conceptualized as representing how many "diseased focal field equivalents" are present to supply inoculum, where greater distance from the focal field reduces availability of inoculum. The number of diseased plants in the field is also modified by the roguing rate (*A*) of removal of diseased plants from the population (Equations A2 and A3). Roguing does not affect the transmission rate during the season. The number of plants at the end of the season (continuous variable) was set to 0 if it was negative, and set to *K* if it was >*K*. Parameter details are in Table 2.

Equation A1:

$$HP_s = K * pHS_{s-1} - \beta WHM * [(K * pDS_{s-1}) * (K * pHS_{s-1}) + E * (K * pHS_{s-1})]$$

Equation A2:

$$DP'_s = K * pDS_{s-1} + \beta WHM * [(K * pDS_{s-1}) * (K * pHS_{s-1}) + E * (K * pHS_{s-1})]$$

Equation A3:

$$DP_s = A * DP'_s$$

The number of healthy seed produced at the end of the season is determined by the rate of seed production (*G*) in the healthy plants and includes the diseased plants that underwent reversion at rate *R* (Equation B1). The number of diseased seed produced depends on the number of diseased plants that remain after reversion (*1-R*), any difference in seed production due to disease (*C*), and seed selection that ultimately reduces the proportion of diseased plants used for seed (*Z*) (Equation B2). Thus in the absence of seed selection and differential seed production in diseased plants, the same number of seeds would be obtained from healthy and diseased plants.

Equation B1:

$$HS_s = G * (HP_s + R * DP_s)$$

Equation B2:

$$DS_s = Z * C * G * (1 - R) * DP_s$$

Yield loss calculations:

At the end of each season, yield (Y_s) is calculated according to equation C1, and percent yield loss (*YLs*) according to equation C2. Equation C1 was modified from Madden et al. (2007) to include a yield penality due to roguing and account for non-zero yields often observed in diseased plants in the field. Thus, *maxY* is the yield in the absence of disease (maximum attainable yield), the minimum attainable yield (*minY*) is the 'useable' yield obtained despite complete disease (where $0 \leq min\text{Y} \leq max\text{Y}$), and θ is the rate of decline of Y_s with increasing disease incidence. As the proportion of diseased plants increases in the field, the yield loss increases, with the potential for complete yield loss. In all analyses described here, yield is generally interpreted as units of food produced, but can also represent seed production if the focus is on seed producers.

Equation C1:

$$Y_s = \frac{DP_s + HP_s}{DP'_s + HP_s} * \left(minY + (maxY - minY) * \left(\frac{1 - \left(\frac{DP_s}{DP_s + HP_s}\right)}{\left((1-\theta) + \theta\left(1 - \left(\frac{DP_s}{DP_s + HP_s}\right)\right)\right)^2} \right) \right)$$

Equation C2:

$$YL_s = \frac{(maxY - Y_s)}{maxY} * 100$$

In the next season, certified seed is used at a rate ϕ with the remainder (*1*-ϕ) coming from seed produced in the field. The total proportion of healthy and diseased seed used in each season is given by Equations D1 and D2. If sufficient on-farm seed is not produced for the next season (when seed production in the diseased plant is low and disease incidence is high), we assume that seed obtained from neighbors or other uncertified sources will have the same rate of seed infection as the on-farm seed.

Equation D1:

$$pHS_s = \phi + (1 - \phi) * \left(\frac{HS_s}{HS_s + DS_s}\right)$$

Equation D2:

$$pDS_s = 1 - pHS_s$$

In a subset of analyses, we disaggregated the seasonal time step, to evaluate the effect of the time of infection and time of application of management components (e.g., roguing). Equations A1 and A2 were modified to include early season dynamics (Equations E1 and E3) and end-of-season dynamics (Equations E2 and E4). Disease incidence early in the season (Equation F1) and total disease incidence end-of-season (Equation F2) were weighted by γ to determine their relative contribution to end-of-season yield (Equation G). All other equations (B1, B2, C2, D1, and D2) were as described above.

Equation E1:

$$HP_{es} = K * pHS_{s-1} - \beta WHM * [(K * pDS_{s-1}) * (K * pHS_{s-1}) + E * (K * pHS_{s-1})]$$

Equation E2:

$$HP_s = HP_{es} - \beta WHM * [(DP_{es}) * (HP_{es}) + E * (HP_{es})]$$

Equation E3a:

$$DP'_{es} = K * pDS_{s-1} + \beta WHM * [(K * pDS_{s-1}) * (K * pHS_{s-1}) + E * (K * pHS_{s-1})]$$

Equation E3b:

$$DP_{es} = A * DP'_{es}$$

Equation E4a:

$$DP'_{s} = DP_{es} + \beta WHM * [(DP_{es}) * (HP_{es}) + E * (HP_{es})]$$

Equation E4b:

$$DP_{s} = A * DP'_{s}$$

Equation F1:

$$DI_{es} = \frac{DP_{es}}{DP_{es} + HP_{es}}$$

Equation F2:

$$DI_{s} = \frac{DP_{s}}{DP_{s} + HP_{s}}$$

Equation G:

$$Y_s = \frac{DP_s + HP_s}{DP'_s + HP_s}\left(minY + (maxY - minY) * \left(\frac{1 - \left(\left(\frac{1}{\gamma+1}\right) DI_{es} + \left(\frac{\gamma}{\gamma+1}\right) DI_s \right)}{\left((1-\theta) + \theta \left(1 - \left(\left(\frac{1}{\gamma+1}\right) DI_{es} + \left(\frac{\gamma}{\gamma+1}\right) DI_s \right) \right) \right)^2} \right) \right)$$

Reference

Madden, L. V., Hughes, G., and Van Den Bosch, F. 2007. The study of plant disease epidemics. American Phytopathological Society, St. Paul, MN.