10 Appendix 1: Supplementary Methods

10.1 Parameterisation

The rate of horizontal transmission, β, is parameterised such that after 10 seasons, 60% of fields are infectious. This gives a value of $\beta = 0.055$ day^{-1}. To account for the reduced susceptibility of resistant plants, we set the parameter $\delta_\beta = 0.5$ as an illustrative example (so "resistant" plants still have some probability of being infected, as would be the case for quantitative disease resistance French et al. (2016)). Resistant plants are less likely to act as sources of inoculum for whitefly vectors than susceptible plants (Lapidot et al. (2002), Legarrea et al. (2015)). We set the reduced probability of infection from an infectious, resistant field (δ_σ) as 0.5 as an illustrative example of this phenomenon.

The cropping period, γ, is 120 days, in line with tomato cultivation regimes (Holt et al. (1999*a*), Rocco & Morabito (2016)).

Complete crop losses due to TYLCV have been historically reported in many regions (e.g. in the Middle East (Czosnek & Laterrot (1997)) and the United States of America (Fonsah et al. (2018))), though certain management practices can alleviate such extreme events. Use of improved cultivars when TYLC is present can increase yield by up to 40% (Vijeth et al. (2018), Riley & Srinivasan (2019)). Riley & Srinivasan (2019) evaluated tomato yield for a combination of commonly-used control methods. When grown with silver mulch and cyantraniliprole insecticide, a susceptible variety *FL47* had a yield of 47 kg per plot, which we use as a proxy for maximum yield. Without either of those treatments, the yield was 18 kg per plot. The best resistant variety (*Security*) had a yield of 50 kg and 28 kg per plot respectively. However, under our definition, *Security* is better defined as a tolerant variety rather than a resistant one, as it did not completely restrict viral replication. Using these values we can estimate the yield loss to be $\approx 60\%$ for susceptible and resistant cultivars and up to $\approx 45\%$ in tolerant cultivars. As such, $L = 0.6$ and $\delta_L L \leq 0.45$,

though both of these parameters can be scanned over to account for environmental and cultivar effects.

The latent period $\left(\frac{1}{\epsilon}\right)$, during which the host plant is infected but not infectious, can be estimated by using the number of days post infection when DNA can be detected. Significant amounts of viral DNA can be detected after 8 days (Ber et al. (1990)), which can be up to a week before symptoms appear. In Holt et al. (1999*b*), a latent period of 13 days was used. Here, we use an intermediate value of $1/\epsilon = 10$ days as the latent period of a single plant. Using the model stipulated in Holt et al. (1999*a*), though where the rate of harvesting and replanting is zero, if we then begin the season with 100% of plants in the E compartment, it takes around 41 days for 95% of these latently-infected plants to become infectious. We use this as our field-scale latent period (i.e. $\frac{1}{\epsilon} = 41$ days).

We assume that symptoms and infectivity develop over roughly the same time scale (as symptoms can develop as early as two weeks after infection (Levy & Lapidot (2008)) and we use an individual-level latent period of 10 days). Thus we assume that the $P_{SC} = P_{EC}$ and $P_{SU} = P_{EU}$.

Economic analysis of tomato production in Georgia, USA estimates that the cost of improved cultivars is approximately 25% that of the total expected profits (Fonsah et al. (2018)), though these profit forecasts included other aspects of disease control. We set the value of the cost of control, ϕ_C, as 0.1 of the total yield as an example of the extra costs control can entail, though our investigations involve a scan over possible costs.

The relative degree of tolerance and resistance will depend on both the unimproved and improved cultivars being compared. To allow for flexibility, the parameters presented in Table 2 are used to illustrate the effect of tolerance and resistance, though a range of parameters will be used in our investigations.

Similarly, the probability of symptom detection in an infectious field (ν) will depend on a variety of anthropological, environmental and biological factors. The

values presented in Table 2 are baseline parameters that can then be varied in our investigations. Importantly, when improved crop is tolerant, we assume that $\delta_\nu \nu < \nu$, whereas for resistant crop we assume $\delta_\nu \nu = \nu$.

For roguing to be worthwhile, it must reduce the potential losses to a grower. Though premature harvest of fruit can incur a yield penalty (between 16-19% for vine-ripened tomatoes, Davis & Gardner (1994)), we presume that if a grower notices a field is infectious and harvests it before the end of the growing season, it is overall more beneficial and their loss due to disease is reduced by some factor, $\phi_R < 1$. The value of ϕ_R will vary with crop cultivar and environmental conditions; the value presented in Table 2 is illustrative though can be varied.

10.2 Calculating expected profits

To calculate the expected profits required for the behavioural model, we must first know the probability of each event (horizontal transmission of TYLCV, roguing *etc.*).

The probability of horizontal transmission for a grower using unimproved crop (q_U) is given by:

$$\begin{aligned} q_U &= \begin{array}{c}\text{Instantaneous probability} \\ \text{of horizontal infection (non-control),}\end{array} \\ &= \frac{\text{Instantaneous infection rate}}{\text{Instantaneous infection rate + Harvesting rate}}, \\ &= \frac{\beta(\delta_\sigma I_C + I_U)}{\beta(\delta_\sigma I_C + I_U) + \gamma}, \end{aligned} \tag{App.1}$$

and for a grower using improved crop (q_C) is:

$$\begin{aligned} q_C &= \begin{array}{c}\text{Instantaneous probability of} \\ \text{horizontal infection (control),}\end{array} \\ &= \frac{\text{Instantaneous infection rate}}{\text{Instantaneous infection rate + Harvesting rate}}, \\ &= \frac{\delta_\beta \beta(\delta_\sigma I_C + I_U)}{\beta(\delta_\sigma I_C + I_U) + \gamma}. \end{aligned} \tag{App.2}$$

We must also consider the probability that, once infected, a grower will be latently infected (E) or infectious (I). The probabilities that a field planted with unimproved or improved crop will be latently infected at the time of harvest (q_{EU} and q_{EC}) are given by:

$$q_{EU} = q_U \left(\frac{\gamma}{\epsilon + \gamma} \right), \tag{App.3}$$

$$q_{EC} = q_C \left(\frac{\gamma}{\delta_\epsilon \epsilon + \gamma} \right), \tag{App.4}$$

whilst the probabilities the field is infectious (q_{IU} and q_{IC}) are:

$$q_{IU} = q_U \left(\frac{\epsilon}{\epsilon + \gamma} \right), \tag{App.5}$$

$$q_{IC} = q_C \left(\frac{\delta_\epsilon \epsilon}{\delta_\epsilon \epsilon + \gamma} \right). \tag{App.6}$$

Finally, we must consider the probability that a field is infectious and then rogued (q_{IUR} and q_{ICR}) before it is harvested:

$$q_{IUR} = q_{IU} \left(\frac{\mu_U}{\gamma + \mu_U} \right), \tag{App.7}$$

$$q_{ICR} = q_{IC} \left(\frac{\mu_C}{\gamma + \mu_C} \right), \tag{App.8}$$

or that it is harvested (q_{IUH} and q_{ICH}) before being rogued:

$$q_{IUH} = q_{IU}\left(\frac{\gamma}{\gamma+\mu_U}\right), \tag{App.9}$$

$$q_{ICH} = q_{IC}\left(\frac{\gamma}{\gamma+\mu_U}\right). \tag{App.10}$$

The expected profits for a non-controller, P_U is therefore given by:

$$\begin{aligned} P_U &= \text{Grower's estimate of the expected profit next season if control is not adopted,} \\ &= (1-q_U)P_{SU} + q_{EU}P_{EU} + q_{IUH}P_{IUH} + q_{IUR}P_{IUR}, \end{aligned} \tag{App.11}$$

and for a controller (P_C) it is:

$$\begin{aligned} P_C &= \text{Grower's estimate of the expected profit next season if control is adopted,} \\ &= (1-q_C)P_{SC} + q_{EC}P_{EC} + q_{ICH}P_{ICH} + q_{ICR}P_{ICR} \end{aligned} \tag{App.12}$$

Using Equations 9 - 16, Equations App.11 and App.12 be further simplified:

$$P_U = Y - q_U\frac{\epsilon}{\epsilon+\gamma}L\left(\frac{\gamma}{\gamma+\mu_U} + \frac{\mu_U}{\mu_U+\gamma}\phi_R\right), \tag{App.13}$$

$$P_C = Y - \phi_C - q_C\frac{\delta_\epsilon\epsilon}{\delta_\epsilon\epsilon+\gamma}\delta_L L\left(\frac{\gamma}{\gamma+\mu_C} + \frac{\mu_C}{\mu_C+\gamma}\phi_R\right). \tag{App.14}$$

11 Appendix 2: Ordering of switching terms

The values of the switching terms are determined by the values of the profits laid out in Equations 9-16. The ordering will depend on the relative values of three key parameters: the loss due to disease for unimproved crop (L), the loss due to disease for the improved crop ($\delta_L L$) and the cost of control (ϕ_C).

11.1 Scenario (i)

If we assume that $L > \delta_L L$ and $L > (\delta_L L + \phi_C)$ (as for the default tolerant parameterisation), the ordering of the profits is as follows:

$$P_{SU} = P_{EU} > P_{SC} = P_{EC} > P_{ICR} > P_{ICH} > P_{IUR} > P_{IUH} \tag{App.15}$$

There are five possible combinations of values for the switching terms:

$$z_{SC}, z_{EC}, z_{ICR}, z_{ICH}, z_{IUR}, z_{IUH} > 0 \tag{App.16}$$

$$z_{ICR}, z_{ICH}, z_{IUR}, z_{IUH} > 0 \tag{App.17}$$

$$z_{ICH}, z_{IUR}, z_{IUH} > 0 \tag{App.18}$$

$$z_{IUR}, z_{IUH} > 0 \tag{App.19}$$

$$z_{IUH} > 0 \tag{App.20}$$

11.2 Scenario (ii)

For higher costs of tolerant crop, it may be the case that though $L > \delta_L L$, $L < (\delta_L L + \phi_C)$. If the rogued tolerant crop is is more expensive than the rogued unimproved crop (i.e. $\phi_R \delta_L L + \phi_C > \phi_R L$), and the harvested unimproved crop is more expensive than the rogued tolerant crop ($L > \phi_R \delta_L L + \phi_C$) the payoffs and switching terms will be:

$$P_{SU} = P_{EU} > P_{SC} = P_{EC} > P_{IUR} > P_{ICR} > P_{IUH} > P_{ICH} \tag{App.21}$$

$$z_{SC}, z_{EC}, z_{IUR}, z_{ICR}, z_{IUH}, z_{ICH} > 0 \quad \text{(App.22)}$$

$$z_{IUR}, z_{ICR}, z_{IUH}, z_{ICH} > 0 \quad \text{(App.23)}$$

$$z_{ICR}, z_{IUH}, z_{ICH} > 0 \quad \text{(App.24)}$$

$$z_{IUH}, z_{ICH} > 0 \quad \text{(App.25)}$$

$$z_{ICH} > 0 \quad \text{(App.26)}$$

11.3 Scenario (iii)

Conversely, for $L > \delta_L L$, $L < (\delta_L L + \phi_C)$, if the rogued tolerant crop is more expensive than the rogued unimproved crop (i.e. $\phi_R \delta_L L + \phi_C < \phi_R L$), but the harvested unimproved crop is cheaper than the rogued tolerant crop ($L < \phi_R \delta_L L + \phi_C$), then the payoffs are:

$$P_{SU} = P_{EU} > P_{SC} = P_{EC} > P_{IUR} > P_{IUH} > P_{ICR} > P_{ICH} \quad \text{(App.27)}$$

and the switching terms are given by:

$$z_{SC}, z_{EC}, z_{IUR}, z_{IUH}, z_{ICR}, z_{ICH} > 0 \quad \text{(App.28)}$$

$$z_{IUR}, z_{IUH}, z_{ICR}, z_{ICH} > 0 \quad \text{(App.29)}$$

$$z_{IUH}, z_{ICR}, z_{ICH} > 0 \quad \text{(App.30)}$$

$$z_{ICR}, z_{ICH} > 0 \quad \text{(App.31)}$$

$$z_{ICH} > 0 \quad \text{(App.32)}$$

11.4 Scenario (iv)

For the default resistant parameterisation, $L = \delta_L L$ and $L < (\delta_L L + \phi_C)$. The profits are ordered as:

$$P_{SU} = P_{EU} > P_{SC} = P_{EC} > P_{IUR} > P_{IUH} > P_{ICR} > P_{ICH}. \quad \text{(App.33)}$$

The following combinations of switching terms are possible:

$$z_{SC}, z_{EC}, z_{IUH}, z_{ICR}, z_{ICH}, z_{IUR} > 0 \quad \text{(App.34)}$$

$$z_{IUH}, z_{ICR}, z_{ICH}, z_{IUR} > 0 \quad \text{(App.35)}$$

$$z_{ICR}, z_{ICH}, z_{IUR} > 0 \quad \text{(App.36)}$$

$$z_{ICH}, z_{IUR} > 0 \quad \text{(App.37)}$$

$$z_{ICH} > 0 \quad \text{(App.38)}$$

12 Appendix 3: Mathematical details of non-behavioural model

We use the NGM method (van den Driessche (2017)) to calculate the basic reproduction number when there are two types of crop (improved and unimproved) present at the disease-free equilibrium, but growers cannot change strategy.

We focus only on the infected compartments, which are given by:

$$\frac{dE_C}{dt} = \delta_\beta \beta S_C (I_U + \delta_\sigma I_C) - \delta_\epsilon \epsilon E_C - \gamma E_C, \quad \text{(App.1)}$$

$$\frac{dI_C}{dt} = \delta_\epsilon \epsilon E_C - \mu_C I_C - \gamma I_C, \quad \text{(App.2)}$$

$$\frac{dE_U}{dt} = \beta S_U (I_U + \delta_\sigma I_C) - \epsilon E_U - \gamma E_U, \quad \text{(App.3)}$$

$$\frac{dI_U}{dt} = \epsilon E_U - \mu_U I_U - \gamma I_U. \quad \text{(App.4)}$$

We first linearise these equations to give the Jacobian matrix and evaluate it around the disease-free equilibrium. We then decompose this Jacobian matrix into two further

matrices: F, which is the matrix of terms relating to disease transmission, and $V = -Q$, where Q is the matrix containing non-epidemiological transition terms. The NGM, K, is then given by FV^{-1} (van den Driessche (2017)).

For this system,

$$F = \begin{bmatrix} 0 & \delta_\sigma \delta_\beta \beta C & 0 & \delta_\beta \beta C \\ 0 & 0 & 0 & 0 \\ 0 & \delta_\sigma \beta U & 0 & \beta U \\ 0 & 0 & 0 & 0 \end{bmatrix}, \tag{App.5}$$

and

$$V = \begin{bmatrix} \delta_\epsilon \epsilon + \gamma & 0 & 0 & 0 \\ -\delta_\epsilon \epsilon & \mu_C + \gamma & 0 & 0 \\ 0 & 0 & \epsilon + \gamma & 0 \\ 0 & 0 & -\epsilon & \gamma + \mu_U \end{bmatrix}. \tag{App.6}$$

The inverse of V is given by:

$$V^{-1} = \begin{bmatrix} \frac{1}{(\delta_\epsilon \epsilon + \gamma)} & 0 & 0 & 0 \\ \frac{\delta_\epsilon \epsilon}{(\delta_\epsilon \epsilon + \gamma)(\mu_C + \gamma)} & \frac{1}{\gamma + \mu_C} & 0 & 0 \\ 0 & 0 & \frac{1}{\epsilon + \gamma} & 0 \\ 0 & 0 & \frac{\epsilon}{(\epsilon + \gamma)(\mu_U + \gamma)} & 1/(\mu_U + \gamma) \end{bmatrix}. \tag{App.7}$$

The NGM, $K = FV^{-1}$, is then given by:

$$K = \begin{bmatrix} \frac{\delta_\epsilon \epsilon \delta_\sigma \delta_\beta \beta C}{(\delta_\epsilon \epsilon + \gamma)(\mu_C + \gamma)} & \frac{\delta_\sigma \delta_\beta \beta C}{(\mu_C + \gamma)} & \frac{\epsilon \delta_\beta \beta C}{(\epsilon + \gamma)(\mu_U + \gamma)} & \frac{\delta_\beta \beta C}{(\mu_U + \gamma)} \\ 0 & 0 & 0 & 0 \\ \frac{\delta_\epsilon \epsilon \delta_\sigma \beta U}{(\delta_\epsilon \epsilon + \gamma)(\mu_C + \gamma)} & \frac{\delta_\sigma \beta U}{(\mu_C + \gamma)} & \frac{\epsilon \beta U}{(\epsilon + \gamma)(\mu_U + \gamma)} & \frac{\beta U}{(\mu_U + \gamma)} \\ 0 & 0 & 0 & 0 \end{bmatrix}. \tag{App.8}$$

1185 R_0 is given by the leading eigenvalue of this matrix:

$$R_0 = \frac{\epsilon\beta U}{(\gamma + \mu_U)(\gamma + \epsilon)} + \frac{\delta_\epsilon \epsilon \delta_\sigma \delta_\beta \beta C}{(\gamma + \mu_C)(\gamma + \delta_\epsilon \epsilon)} \quad \text{(App.9)}$$

1186

1187 13 Appendix 4: Supplementary results for non-
1188 behavioural model

1189 13.1 Parameters relating to tolerance and resistance

1190 A broad range of parameter values relating to tolerant and resistant traits are possible
1191 depending on the cultivar and environmental conditions. As illustrative examples of
1192 the effect of changing parameters along the tolerance/resistance continuum, we in-
1193 vestigate the effects of changing the probability of detection for improved crop ($\delta_\nu \nu$;
1194 Fig. 1) and relative susceptibility of improved crop (δ_β; Fig. 2). In each case, prof-
1195 its were highest for both controllers and non-controllers when the parameterisation
1196 approached that of the resistant crop (i.e. a high probability of detection and low
1197 relative susceptibility). However, there was little impact on the profits of controllers
1198 who grew tolerant crop (Fig. 1c and Fig. 2c), as the low loss due to disease for toler-
1199 ant crop means that the reduced probability of infection conferred by high δ_ν and low
1200 δ_β is of little benefit. We note that by lowering the relative susceptibility of tolerant
1201 crop, it contravenes the typical definition of tolerance (which does not have a reduced
1202 probability of infection). However, in terms of the relative yield loss, this crop type
1203 retains some tolerant characteristics and we therefore refer to it as "tolerant" for this
1204 result.

1205 Disease elimination was possible under many parameterisations for the resistant
1206 crop (due to the lower background infectivity of resistant crop, as well as its lower
1207 susceptibility). For the "tolerant" crop, when the relative susceptibility was very

low, only then was disease elimination possible (Fig. 2a,c). This allowed growers to earn the maximum possible profits.

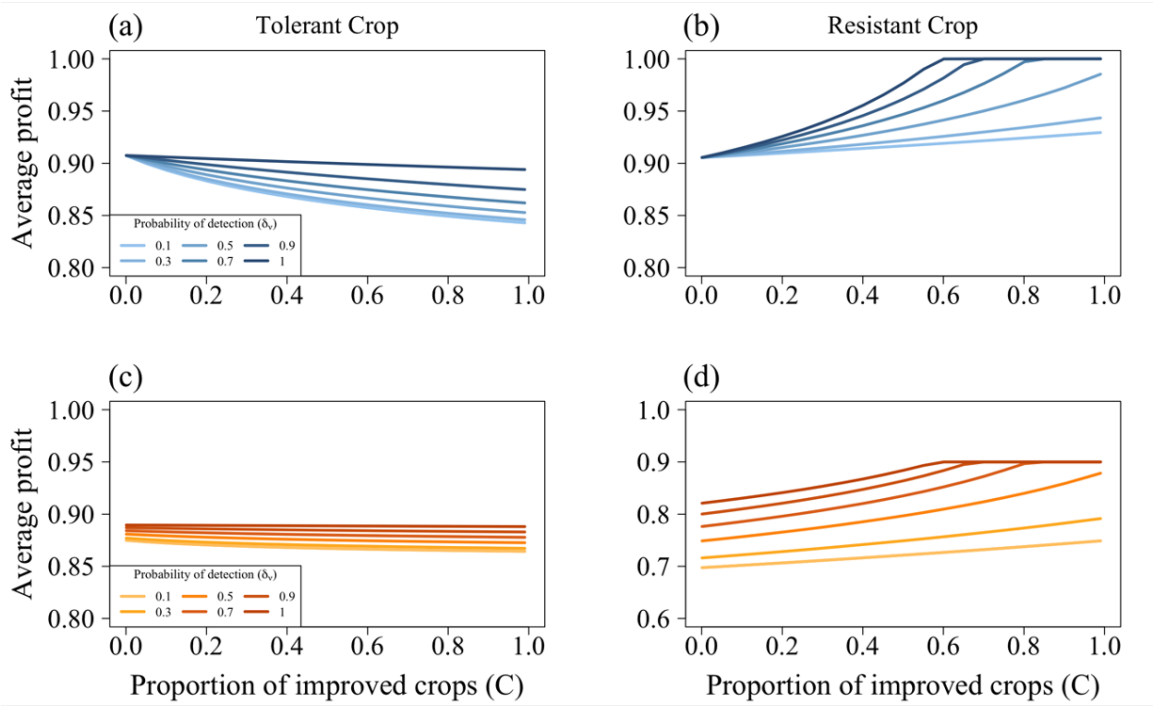

Figure 1: **Change in average profits for tolerant and resistant parameterisation when the probability of detection for improved crop ($\delta_\nu\nu$) is varied.** (a) and (c) show the average profit for unimproved and improved crop respectively for the tolerant parameterisation, whilst (b) and (d) show the same for the resistant parameterisation. In all cases, the highest profits were achieved when $\delta_\nu = 1$ (i.e. infectious crop is always detected). The probability of detection had little impact on the average profit of controllers (c). This is because the probability of detection affects the rate at which infectious plants are removed; the higher the probability of detection, the lower the disease pressure and thus the lower the probability of incurring the loss due to disease. As the loss due to disease is low for tolerant crop, there is little impact on the profits of controllers. Additionally, disease was not eliminated when the crop was tolerant. When the crop was resistant, this also allowed disease elimination to occur at lower proportions of resistant crop ($C = 0.6$ when $\delta_\nu\nu = 1$, (b) and (d)). Other than those scanned over, parameters are as in Table 2.

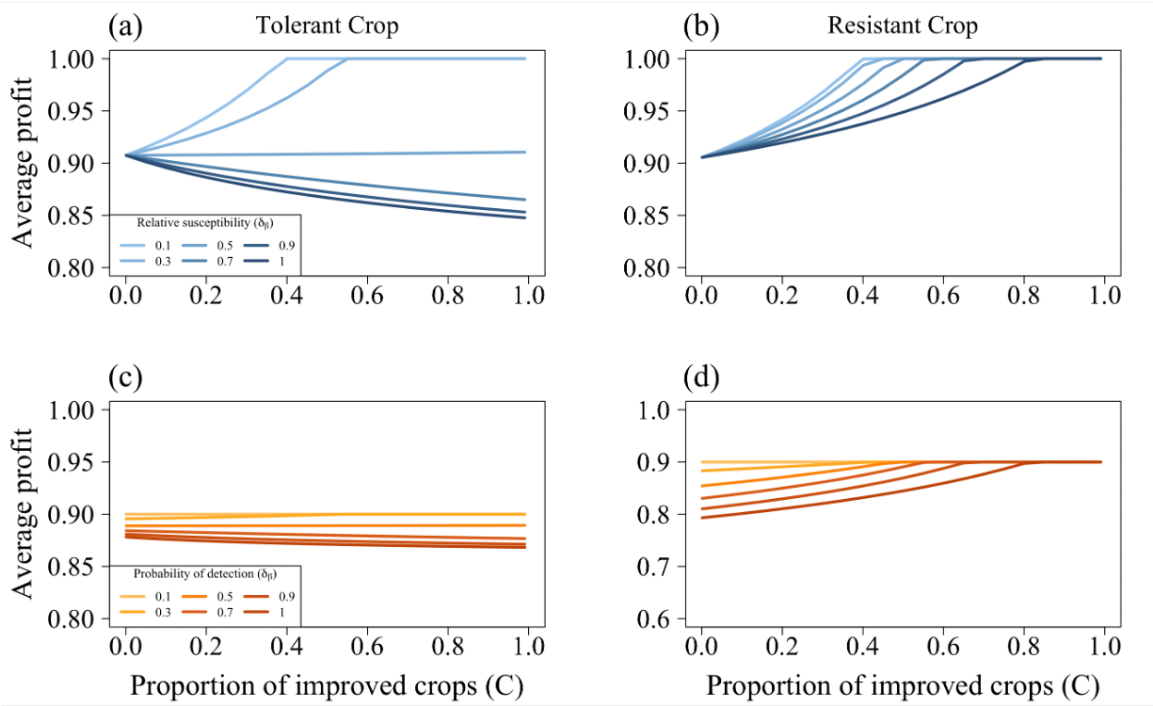

Figure 2: **Change in average profits for "tolerant" and resistant parameterisation when the relative susceptibility of improved crop (δ_β) is varied.** (a) and (c) show the average profit for unimproved and improved crop respectively for the tolerant parameterisation, whilst (b) and (d) show the same for the resistant parameterisation. We note that by altering the relative susceptibility of tolerant crop, it contravenes the typical definition of tolerance and instead is more akin to quantitative resistance. In all cases, at lower susceptibilities (which means the improved crop is less likely to become infected), profit increases. Indeed, under this parameterisation, disease can go extinct under the tolerant parameterisation (at $C = 0.4$ when $\delta_\beta = 0.1$, (a) and (c)). There is little impact on the average profit for controllers when the improved crop is tolerant (c), as the low loss due to disease in the tolerant parameterisation means that the reduced probability of infection brought about by a lower δ_β have little effect. Disease elimination can occur in under all values of δ_β when the improved crop is resistant ((b) and (d)). Even at high values of δ_β, the resistant crop still has a lower relative infectivity (δ_σ) and higher probability of detection (δ_ν) than tolerant crop. Other than those scanned over, parameters are as in Table 2.

14 Appendix 5: Mathematical details of behavioural model

14.1 Evaluating stability for behaviour model

To investigate how the initial conditions affected the equilibrium, we conducted a randomisation scan with 10,000 sets of initial conditions and used *nleqslv* (Hasselman & Hasselman (2018)) in *R* to investigate the number of equilibria attained for each parameter set. The nature of the switching terms means that the system is discontinuous, and the equations will have a different form depending on the values of the state variables. There are ten possible Jacobians, depending on the values of the switching terms (Appendix 2). For each set of equilibrium values found from our randomisation scan, we evaluated the stability of that equilibrium using the appropriate Jacobian matrix.

14.2 Basic reproductive number of behavioural model

As the form of the equations differs between the model with fixed proportions and the behavioural model, R_0 must be calculated separately for the behavioural model. For the disease-free equilibrium given by $(S_U, E_U, I_U, S_C, E_C, I_C) = (U, 0, 0, 0, 0, 0)$, all switching terms should be non-zero. As there is no disease, there is no need for control, so no growers should use the control strategy. Additionally, any growers whose fields do become infected will have a lower payoff than the expected payoff of the alternative strategy (as there is no disease), so all non-controllers with infectious

fields should switch strategy. The system of equations is therefore:

$$\frac{dS_C}{dt} = \gamma\theta_C - \delta_\beta\beta S_C(I_U + \delta_\sigma I_C) + M_C - \gamma S_C, \tag{App.1}$$
$$\frac{dE_C}{dt} = \delta_\beta\beta S_C(I_U + \delta_\sigma I_C) - \delta_\epsilon\epsilon E_C - \gamma E_C, \tag{App.2}$$
$$\frac{dI_C}{dt} = \delta_\epsilon\epsilon E_C - \mu_C I_C - \gamma I_C, \tag{App.3}$$
$$\frac{dS_U}{dt} = \gamma\theta_U - \beta S_U(I_U + \delta_\sigma I_C) + M_U - \gamma S_U, \tag{App.4}$$
$$\frac{dE_U}{dt} = \beta S_U(I_U + \delta_\sigma I_C) - \epsilon E_U - \gamma E_U, \tag{App.5}$$
$$\frac{dI_U}{dt} = \epsilon E_U - \mu_U I_U - \gamma I_U. \tag{App.6}$$

where:

$$\theta_C = (1 - z_{SC})S_C + (1 - z_{EC})E_C + (1 - z_{ICH})I_C + z_{IUH}I_U, \tag{App.7}$$
$$\theta_U = S_U + E_U + (1 - z_{IUH})I_U + z_{SC}S_C + z_{EC}E_C + z_{ICH}I_C, \tag{App.8}$$
$$M_C = (1 - z_{ICR})\mu_C I_C + z_{IUR}\mu_U I_U, \tag{App.9}$$
$$M_U = z_{ICR}\mu_C I_C + (1 - z_{IUR})\mu_U I_U, \tag{App.10}$$
$$N = S_C + E_C + I_C + S_U + E_U + I_U. \tag{App.11}$$

Using Equations App.1 - App.6, and the method outlined in van den Driessche (2017) and the main text, we find:

$$F = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & \beta\delta_\sigma N + 0 & 0 & \beta N \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{App.12}$$

$$V = \begin{bmatrix} \gamma + \delta_\epsilon \epsilon & 0 & 0 & 0 \\ -\delta_\epsilon \epsilon & \gamma + \mu_C & 0 & 0 \\ 0 & 0 & \gamma + \epsilon & 0 \\ 0 & 0 & -\epsilon & \gamma + \mu \end{bmatrix} \tag{App.13}$$

$$V^{-1} = \begin{bmatrix} \frac{1}{\gamma+\delta_\epsilon \epsilon} & 0 & 0 & 0 \\ \frac{\delta_\epsilon \epsilon}{(\delta_\epsilon \epsilon+\gamma)(\gamma+\mu_C)} & \frac{1}{\gamma+\mu_C} & 0 & 0 \\ 0 & 0 & \frac{1}{\gamma+\epsilon} & 0 \\ 0 & 0 & \frac{\epsilon}{(\epsilon+\gamma)*(\gamma+\mu)} & \frac{1}{\gamma+\mu} \end{bmatrix} \tag{App.14}$$

The NGM, FV^{-1}, can then be simplified to:

$$K = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ R_{0C} & \frac{\beta \delta_\sigma N}{\gamma+\mu_C} & R_0 & \frac{\beta N}{\gamma+\mu} \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{App.15}$$

where $R_0 = \frac{\beta \epsilon N}{(\mu_U+\gamma)(\epsilon+\gamma)}$ (Equation 46) and $R_{0C} = \frac{\delta_\beta \beta \delta_\epsilon \epsilon \delta_\sigma N}{(\mu_C+\gamma)(\delta_\epsilon \epsilon+\gamma)}$ (Equation 47). The eigenvalue of K is given by R_0, so the basic reproduction number is the same regardless of the whether behaviour is included in the model, depending only on whether $N = U$ or $N = C$.

15 Appendix 6: Supplementary results for behavioural model

15.1 Underlying behaviour of switching terms for resistant parameterisation with variable cost of control

The kinks in Fig. 6b in the main text are caused by changes in the values of the switching terms. As the epidemic progresses, the expected profits for each strategy change. If they fall below the profit for a particular outcome (for example, the profit for a controller with an infected field, P_{IUH}), growers who have earned that outcome switch from having a non-zero probability of switching strategy to never switching. For different values of ϕ_C, this occurs at different values of β (Fig. 1).

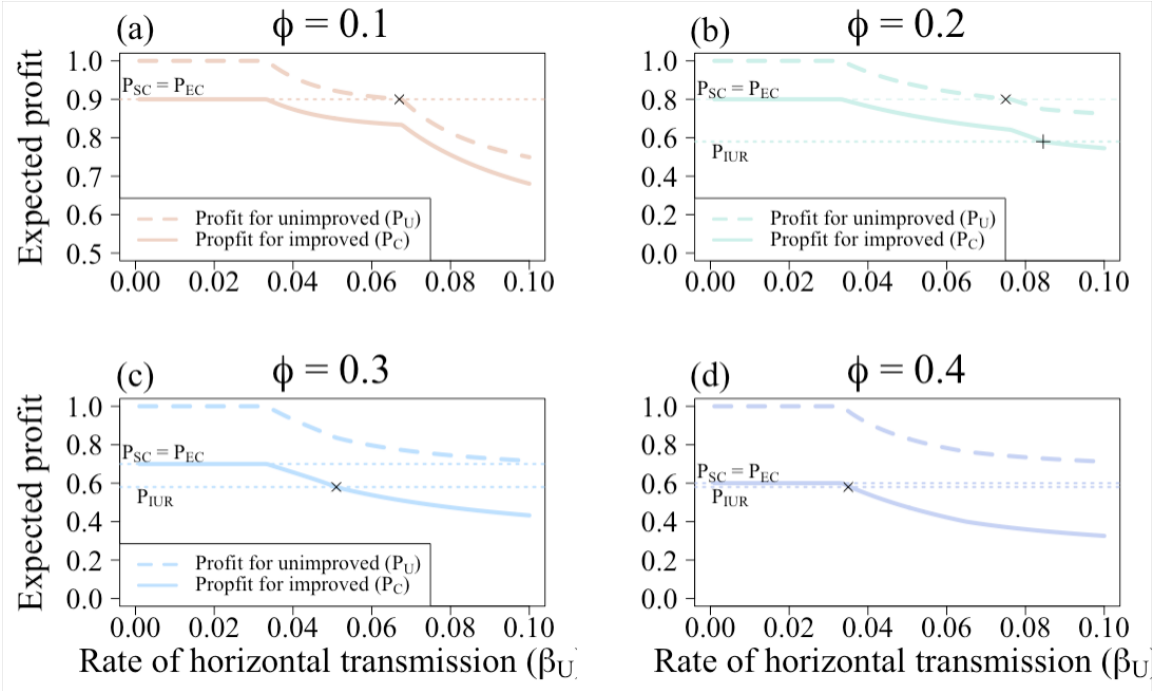

Figure 1: **Change in expected profits with different values of the cost of control (ϕ_C) for resistant parameterisation.** (a) When $\phi_C = 0.1$, the expected profits for non-controllers falls below the expected profits for controllers with susceptible or latently-infected (S_C or E_C) crop at $\beta = 0.068$ day^{-1} ("x"). At this point, those with S_C or E_C fields stop switching strategy. (b) When $\phi_C = 0.2$, S_C and E_C growers stop switching strategy at $\beta = 0.075$ day^{-1} ("x"). At $\beta = 0.0845$ day^{-1} ("+"), non-controllers with infectious fields that have been rogued also stop switching strategy (as $P_C < P_{IUR}$). (c) When $\phi_C = 0.3$, non-controllers with I_{UR} fields stop switching strategy at $\beta = 0.051$ day^{-1} ("x"), and controllers with S_C or E_C fields stop when $\beta = 0.1$ day^{-1}. (d) When $\phi_C = 0.4$, growers with P_{IUR} fields stop switching strategy at $\beta = 0.035$ day^{-1} ("x"). Controllers always have a non-zero probability of switching strategy for this parameter set. Other than those scanned over, parameters are as in Table 2.

15.2 Expected profits for unimproved, tolerant and resistant crop

The pattern outline below is the same as that for Fig. 5 in the main text, though for a two-way scan of the rate of horizontal transmission (β) and the cost of control (ϕ_C).

Irrespective of whether the improved crop was tolerant or resistant, as β increased there was a corresponding increase in the proportion of infectious fields ($I_U + I_C$; Fig. 2a,b). This increase occurred more quickly when the improved crop was tolerant, as tolerant crop has the same susceptibility and infectivity as unimproved crop, but is less likely to be detected and removed once infected.

Resistance is incomplete (Table 1 in the main text), so fields planted with resistant crop may still be infected. However, the reduced probability of infection means that there are overall lower proportions of infected fields. Participation in control is relatively high for low values of β and ϕ_C, though this decreases as β gets larger (approaches 0.067 day^{-1} in Fig. 5 in the main text; where it occurs in Fig. 2a,c depends on the value of ϕ_C). For these parameter values, P_U approaches $P_{SC,EC}$ (Fig. 5a in the main text), so fewer controllers with susceptible or latently-infected fields should switch strategy. There is still a high infectious pressure, though, so more of these controlled fields will become infected. They will therefore incur the loss due to disease (L_C), resulting in the lowest possible payoff. Expected profits for controllers (and consequently proportion of growers using control) briefly increase when $P_C < P_{IUR}$ (which occurs at at $\beta = 0.067$ day^{-1} in Fig. 5a in the main text). The non-controllers who rogued their fields (achieving P_{IUR}), should no longer switch strategy, and they replant S_U fields. There is still a high probability of infection, however, and many of these non-controlled fields will be infected by the time they are harvested. Some will be rogued before harvesting, preventing some loss of yield. Those that have not rogued achieve a low payoff and switch into the control strategy.

After this point, however, the proportion of controllers falls. The increased infec-

tion pressure means that the expected profit of non-controllers is lower than the profit of controllers with susceptible or latently-infected fields ($P_U < P_{SC,EC}$). Controllers that harvest susceptible or latently-infected fields should therefore never consider switching strategy. The high infection pressure, however, means that many of these resistant fields will be infected before they are harvested. As $P_{ICH,ICR} < P_U$ for these values of β, controllers with infectious fields should always switch strategy. As fewer growers control and plant resistant crop, the disease pressure increases and there are more infectious fields.

When the improved crop was tolerant, we chose initial conditions such that there would always be a disease-endemic equilibrium in the bistable region ($I_{U0} + I_{C0} = 0.15, S_{C0} + E_{C0} + I_{C0} = 0.2$, Fig. 4 in the main text). A high proportion of infectious fields was seen for most parameter combinations, in part due to the lower probability of infectious tolerant fields being removed by roguing. This accompanied a high degree of participation in control, as the low default value of L_C ($= 0.06$) and lower probability of paying the roguing cost. Additionally, once $R_0 > 1$ and the costs of control < 0.2, an "all-control" equilibrium persists, where $S_C + E_C + I_C = N$.

This "all-control" equilibrium was not seen in the parameterisation where the improved crop was resistant. This is both due to the positive externalities generated by the crop reducing the probability of infection for non-controllers and the structure of the model, which means growers with infectious resistant crop should always have a non-zero probability of switching strategy (as P_{ICR} is the lowest payoff).

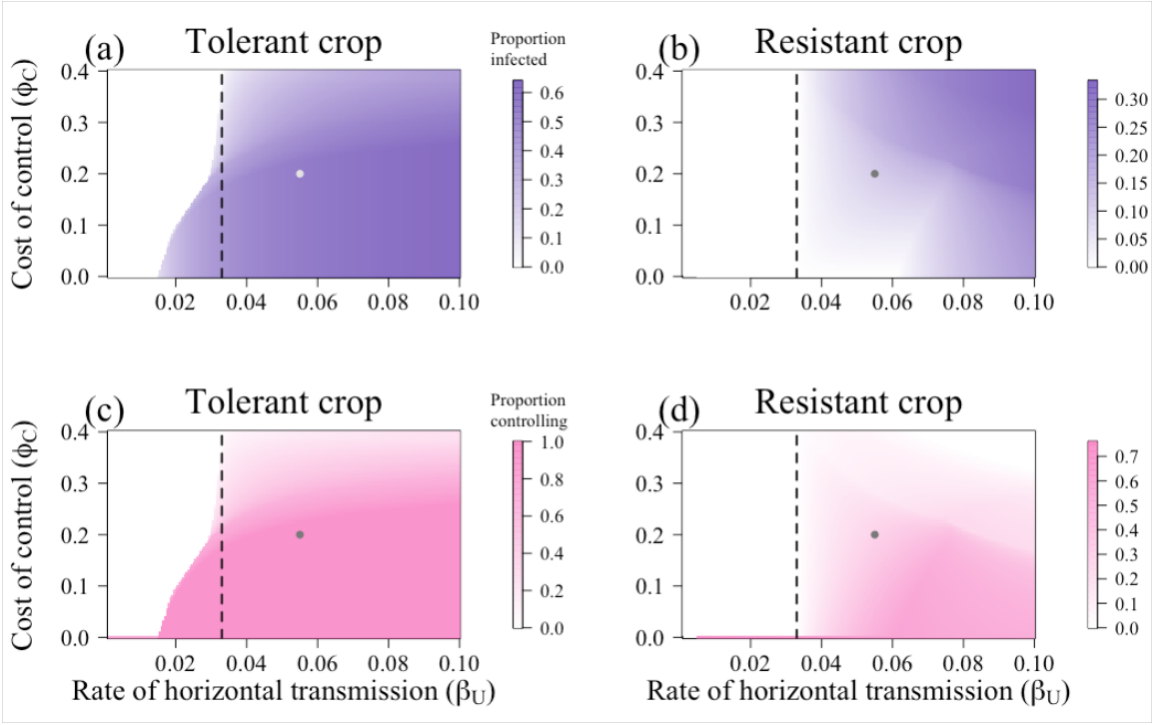

Figure 2: **Response of the number of infectious fields and participation in control to the rate of horizontal transmission in non-improved crops (β) and the cost of control (ϕ_C).** (a) The change in proportion infectious fields ($I_U + I_C$) and (b) change in participation in control when the improved crop has tolerant characteristics. Equivalent plots for resistant improved crop are shown in (c) and (d). In all graphs, the vertical dashed line at $\beta = 0.0333$ day $^{-1}$ is where $R_0 = 1$. When the crop used by controllers tolerant to infection, there are high levels of infection and participation in control. Additionally, at low values of ϕ_C, disease can invade when $R_0 < 1$ (a). For resistant crop, there is a much lower proportion of infectious fields and controllers for most values of β. Other than those being varied, parameters and initial conditions are as in Tables 2 and 3 respectively.

The expected profits of both controllers and non-controllers follow a similar pattern to that of the proportion of infectious fields and controllers (Fig. 5 in the main text). In both cases, when $R_0 < 1$ the profit of non-controllers (P_U) is equal to

that of susceptible/latently-infected non-controllers (except where bistability exists in the tolerant parameterisation). Once disease invades, profits of both controllers and non-controllers fall. However, for the majority of values of β and ϕ_C, P_U is higher when there is resistant crop than when there is tolerant crop, indicating that non-controllers benefit more from the presence of resistant crop. However, the profits of growers using tolerant crops were generally higher than those using resistant crops, as the benefits generated by tolerant crops were experienced privately by the growers using them.

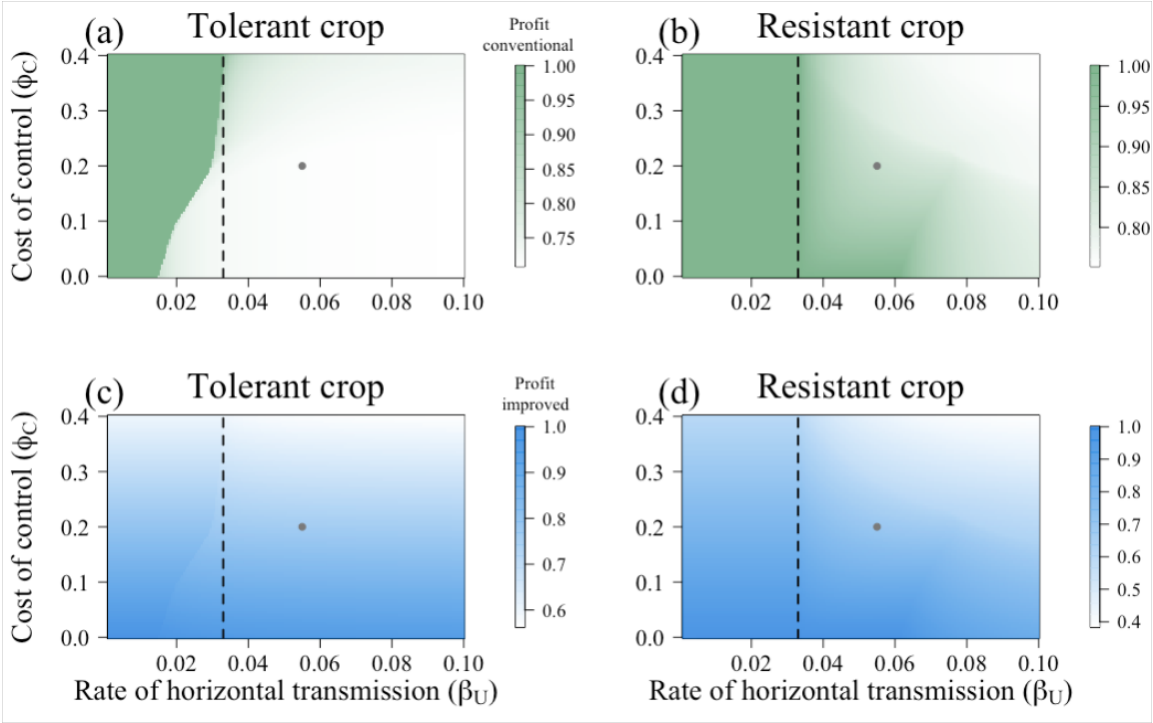

Figure 3: **Response of the expected profits to the rate of horizontal transmission in non-improved crops (β) and the cost of control (ϕ_C).** (a) and (c) are the expected profits for non-controllers (P_U) and controllers (P_C) respectively when the improved crop is tolerant; (b) and (d) show the same for resistant crop. The highest profits for non-controllers are seen when $R_0 < 1$, though P_U is generally higher for those in the resistant-crop scenario than the tolerant crop. Conversely, controllers that used tolerant crop generally had higher profits than those using resistant crop. The grey dots indicate the default parameterisation. Other than those being varied, parameters and initial conditions are as in Tables 2 and 3 respectively.