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Modelling the effectiveness of collaborative schemes for disease and pest outbreak prevention

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Abstract

Preventing disease outbreaks has widespread benefits that are dependent on the actions of many agents but can be undermined by the inaction of others. This paper explores whether a voluntary biosecurity-related assurance scheme can be an effective mechanism for curbing the risks of animal and plant pests and diseases. The decision to engage in such schemes is modelled using a coalition game where agents consider both direct costs of infection and regional outbreak costs like trade bans and movement restrictions. We find that government needs to support the scheme through incentives that reduce members' outbreak costs like pre-agreed outbreak compensation or preferential regulatory treatment. Assurance schemes could provide significant improvements in biosecurity if membership is high; but without government incentives, stable coalitions are either small or ineffective at improving biosecurity. Government support can lead to large coalitions and robust improvement in overall biosecurity, with the optimal level of support being the smallest incentive that leads to a stable grand coalition. Policies that focus on either monetary or non-monetary incentives can lead to more robust improvements in biosecurity. In particular, targeting regional outbreak costs to members like movement restrictions leads to improved biosecurity for all levels of support.

Keywords: Animal health, Biosecurity, Coalition game, Disease control, Disease prevention, Plant health

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1. Introduction

The presence of a pest or pathogen can lead to substantial private costs like reduced yield or quality of produce. However, such outbreaks can have impacts that go ‘beyond the farm fence’ onto others like culling, movement restrictions, trade bans and shifts in demand and market access (Knight-Jones and Rushton, 2013), and to the wider environment, potentially leading to losses in biodiversity and ecosystem services (Boyd et al., 2013). These impacts can be considerably larger than the costs for infected farms. For example, the 2001 Foot and Mouth Disease outbreak in the UK cost an estimated US\$9 billion, the vast majority of which was due to culling, control measure costs, movement restrictions and other ‘indirect’ costs aimed at restoring disease-free status to lift the resulting trade bans (FAO, 2002; Knight-Jones and Rushton, 2013); whereas the current outbreak in the UK of Ash dieback has an estimated cost of £15 billion, the majority of which is due to the loss of ecosystem services (Hill et al., 2019).

With the potentially massive costs associated with pest or disease outbreaks to industry, environment and society, compulsory regulations are often put in place to try to improve biosecurity. However, regulations do not necessarily mean compliance, and can lead to behavioural changes and potentially create illegal markets (Epanchin-Niell, 2017). Regulations often put additional costs on farmers (Bennett, 2012) and are often reactionary (Hulme et al., 2018), inflexible (Barnes et al., 2015) and discourage exceeding regulatory minimum standards (Lansink, 2011). An alternative approach to compulsory regulations are voluntary agreements like biosecurity-related assurance schemes, certification schemes and codes of conduct, whereby firms join to meet an agreed set of standards. In the related area of food safety and quality, assurance schemes like British Lion Eggs and Red Tractor have improved food safety in the UK, with raw and lightly cooked Lion-marked eggs are now deemed safe for vulnerable groups like pregnant women, the young and the elderly, having previously been deemed unsafe due to *Salmonella* risks (FSA, 2017; BEIC, 2015; Gray, 2018). Such assurance schemes have also been applied to endemic diseases like Johne’s disease in cattle in several countries (Kennedy and Allworth, 2000; Hop et al., 2011; Geraghty et al., 2014, the latter reviews Johne’s disease schemes in six countries). However, many assurance schemes suffer from limited uptake and consequently little overall impact (Wolf, 2005).

32 For example, schemes to reduce Johne’s Disease in cattle herds failed to have
33 widespread membership in Australia, USA and UK (and concerns of declining
34 membership in Netherlands) (Geraghty et al., 2014).

35 The issue of a lack of membership is a particular problem for biosecurity-related
36 assurance schemes as outbreak prevention is a weaker-link public good (Arce and
37 Sandler, 2001; Perrings et al., 2002). This means cooperation would lead to benefits for
38 everyone, but benefits are hard to obtain as there are strong incentives to freeride on
39 the biosecurity measures of others. Moreover, the weaker-link nature of biosecurity
40 means that it only requires a few freeriders to potentially undermine these benefits for
41 everyone by introducing an invasive species, pests or pathogens, which can cause a wide
42 range of costs and affect both those who cooperate and those who freeride.

43 In this paper, we consider whether the support of a government, public agency or
44 other external body is needed for an assurance scheme to have a large membership that
45 leads to significant improvements in biosecurity. This support is through policies that
46 could incentivise membership by lowering costs for members such as post-outbreak
47 compensation or giving members preferential regulatory treatment such as relaxing
48 movement restrictions.

49 To find the uptake and impact of an assurance scheme and whether government
50 support is necessary, we need to model the decision-making process for each farmer as a
51 potential member of the assurance scheme. This situation is analogous to the process of
52 forming international agreements by ways of coalitions. Coalition theory has been
53 applied to such agreements on issues like climate change and pollution (e.g. Carraro and
54 Siniscalco, 1993, 1998; Barrett, 2003, 2005; Finus, 2008; Finus et al., 2009; Nordhaus,
55 2015; Barrett, 2016; Ansink et al., 2018) and fishing (e.g. Pintassilgo, 2003; Kronbak
56 and Lindroos, 2007; Bailey et al., 2010). The realm of international agreements is seen
57 as most appropriate for such coalition games since Westphalian sovereignty means that
58 actions must be voluntary at a country to country level (Nordhaus, 2015). However,
59 voluntary actions also apply to individual farms and coalition theory has been applied to
60 local issues like resource conservation (Ansink and Bouma, 2013) and agri-environmental
61 agreements (Zavalloni et al., 2019). The key difference between international issues to
62 more national and local public goods (at which scale biosecurity is normally framed) is
63 that governments have the power to incentivise farmers into joining the coalition.

64 The horticultural industry in the UK is developing a biosecurity-related assurance
65 scheme to encourage voluntary investment in preventing disease outbreaks; in particular,
66 they seek to prevent the plant pathogen *Xylella fastidiosa* from spreading to the UK
67 (HTA, 2017; DEFRA, 2018). *X. fastidiosa* is a bacterial pathogen with a large number
68 (300+) of plant hosts including olive, stone fruits, citrus, grapevine, oak, oleander, coffee
69 and lavender (EFSA Panel on Plant Health, 2015; Sicard et al., 2018). It has spread
70 across parts of Italy (where it is killing olive trees by olive quick decline syndrome),
71 France and Spain (Sicard et al., 2018; Saponari et al., 2019; Brunetti et al., 2020). The
72 trade in live plants is the major pathway for introducing many new plant pests and
73 pathogens around the world (Brasier, 2008; Dehnen-Schmutz et al., 2010), including for
74 *X. fastidiosa* in the UK (DEFRA, 2018). An outbreak of *X. fastidiosa* in the UK could
75 have massive impact to ecosystem services and the environment, especially if the
76 outbreak is of a strain that causes major damage to oak trees (DEFRA, 2018). For the
77 UK horticultural industry, an outbreak of *X. fastidiosa* has more certain impacts, the
78 costly ‘draconian outbreak measures’ (HTA, 2017). These measures are set by European
79 Union regulations (European Commission, 2015, 2017) that include destroying all hosts
80 immediately around an outbreak and enforcing a buffer zone¹ around an outbreak
81 where no host can be moved for 5 years. This amounts to an effective cull (at personal
82 expense) of all potential hosts within the buffer zone for those in the horticultural trade
83 since 5 years is considerably longer than the lifespan of any plant in a plant nursery or
84 garden centre. This means there can be large costs from regulatory compliance to those
85 in horticultural trade from biosecurity failures that occur either on-site or off-site but
86 within the buffer zone. However, there are real concerns around whether such
87 biosecurity-related assurance schemes can get enough members to significantly reduce
88 the likelihood of an outbreak of *X. fastidiosa* without governmental support to
89 encourage membership (HTA, 2017). In other words, are additional incentives like
90 compensation for culling, preferential regulatory treatment (e.g. allow scheme members
91 to move less risky hosts within the buffer zone that would otherwise be prohibited) or
92 other ways to reduce the cost for members from an outbreak needed for an assurance

¹The buffer zone is currently either 1km or 5km for most outbreaks (European Commission, 2017). It is the original 10km buffer zone (European Commission, 2015) that was called ‘draconian’ by HTA (2017).

93 scheme to have enough members for there to be a substantial improvement in biosecurity.
94 Even though this example is in horticulture, the same issues also apply to animal and
95 plant health in general (Waage and Mumford, 2008; Bennett, 2012; FAO, 2016).

96 In this paper, we explore the effectiveness of an industry-led biosecurity-related
97 assurance scheme by analysing whether farmers (which we consider a general term that
98 encompasses agricultural, horticultural and aquacultural growers and traders) would
99 voluntarily join such schemes (like the one proposed for *X. fastidiosa* in the UK) and
100 under what conditions such schemes actually achieve improved overall biosecurity. We
101 use a coalition game approach based on Carraro and Siniscalco (1993, 1998), where
102 farmers' act based on the costs from an outbreak on the farm, the costs from being
103 within the buffer zone of an outbreak and costs of implementing biosecurity. We explore
104 whether the assurance scheme can have a large number of members and substantial
105 improvement in biosecurity. We investigate the effect government support (by way of a
106 members-only reduction in outbreak costs) has as an incentive for membership to see if
107 these incentives can lead to a more effective scheme that has a larger membership and
108 substantial improvements in biosecurity. Lastly, we consider how varying the size of the
109 monetary and non-monetary incentive influences the level of biosecurity, to find out
110 which incentives lead to improvements in biosecurity; in particular, which incentives
111 lead to the best level of biosecurity and how robust are these improvements.

112 **2. Methods**

113 *2.1. General assumptions*

114 The model describes a set of N farms who decide on their preventative biosecurity,
115 given that a disease/pest outbreak results in costs for that farm. Additionally, an
116 outbreak on a farm will impose costs on n other neighbouring farms that are not
117 infected. The number of neighbours (n) depends on the type of neighbourhood cost; for
118 example, $n = N - 1$ would represent neighbourhood costs where one infected farm
119 affects everyone, which is appropriate for trade bans and industry wide movement
120 restrictions (like Foot and Mouth Disease), whereas smaller n represent neighbourhood
121 costs that are more 'local' (like the movement restrictions and buffer zone regulations
122 for *X. fastidiosa*). We assume that each farm will experience one of three mutually

123 exclusive scenarios: (i) the farm experiences ‘direct costs’ if the farm is infected, which
124 includes all private costs that are a consequence of infection, from the costs from the
125 reduction in quantity and quality of yield to the costs of controls, movement restrictions,
126 trade bans, post-outbreak compensation and regulatory compliance²; (ii) the farm
127 experiences ‘neighbourhood costs’ if the farm is not infected but at least one ‘nearby’
128 farm is infected, which are associated with the consequences of a ‘nearby’ outbreak like
129 trade bans, movement restrictions, controls and regulatory compliance; (iii) the farm
130 experiences no outbreak costs if the farm is not infected and there are no ‘nearby’
131 infected farms. All farms experience some cost for their (preventative) biosecurity.

132 Each farm is assumed to be the same except for its membership status, which is
133 either a member or a freerider. The decision-making process is different for members
134 and freeriders as to how they consider the impact of their actions on others arising from
135 disease outbreaks. Farmers choose their level of biosecurity, which we will take as the
136 probability of avoiding infection. We consider only one time step and ignore the
137 prospect of an epidemic spreading. Given this, we will use a the standard two-stage
138 coalition game based on Carraro and Siniscalco (1993, 1998):

139 Stage 1: Farms decide whether to join the scheme based on what gives them the best
140 payoff, given the actions of others. Scheme members will act as a coalition (i.e.
141 members assume that other members in the coalition will reciprocate their action, and
142 thus will consider the impact their actions have on other members), whereas freeriders
143 act as singletons (i.e. freeriders assume that the actions of others are fixed and
144 independent of their choice). The stability of the coalition will be assessed, where we
145 look for coalitions where no freerider has the incentive to join, and no scheme member
146 has the incentive to leave.

147 Stage 2: Farms decide on their probability of infection. Freeriders will set biosecurity
148 by optimising their own private payoff, whereas coalition members optimise their
149 probability of infection for the coalition, i.e. taking into account the benefits their
150 contributions to biosecurity has on other members.

151 The method to solve this is by back calculation; we will work out what the optimal
152 probability of infection and the resulting the payoffs are for any given size of the

²This definition is broadly consistent with FAO (2002).

153 coalition, then determine which coalition(s) are stable. This process will give us the
 154 stable coalition size and the resulting probability of infection and levels of biosecurity
 155 for freeriders, members and overall. The stable coalition size and overall biosecurity are
 156 the two key measures of success for a biosecurity-related assurance scheme that we will
 157 analyse.

158 2.2. Payoffs

159 The payoff of every farm consists of three terms: expected direct costs from an
 160 outbreak on the farm, expected neighbourhood costs for being an uninfected farm but
 161 with one or more infected neighbour, and the costs of biosecurity. The probability of
 162 infection is P_k and the direct cost of infection is D_{Dk} , where $k \in \{J, F\}$ (J is for
 163 members or ‘joiners’ and F is for freeriders); thus the expected direct costs are $D_{DF}P_F$
 164 for freeriders and $D_{DJ}P_J$ for members.

165 The expected neighbourhood costs for farm i are determined by two factors; the
 166 probability that farm i avoided infection (as farm i would otherwise already have
 167 experienced direct costs), and the probability that at least one neighbour of farm i is
 168 infected. We assume that if at least one neighbour gets infected, the corresponding
 169 neighbourhood costs for farm i are D_{Nk} (where $k \in \{J, F\}$). To calculate the expected
 170 neighbourhood costs, we need to calculate the probability one or more neighbouring
 171 farms are infected; to do so, we first calculate the probability an individual neighbour
 172 avoids infection. We assume that the probability of an individual neighbour avoiding
 173 infection is the geometric mean of $(1 - P_j)$'s (i.e. $\prod_{j \neq i} (1 - P_j)^{\frac{1}{N-1}}$). If there are n
 174 neighbours, the probability of all n of the neighbours avoiding infection is
 175 $\left(\prod_{j \neq i} (1 - P_j)^{\frac{1}{N-1}}\right)^n$ (i.e. treating each neighbour as an independent Bernoulli trial).
 176 The use of a geometric mean keeps the property that if everyone is in the neighbourhood
 177 of farm i ($n = N - 1$), then the probability that every neighbouring farm avoids
 178 infection is the product of the probability of each farm avoids infection, $\prod_{j \neq i} (1 - P_j)$.
 179 Additionally, a geometric mean is consistent with biosecurity being a weaker-link public
 180 good (Cornes, 1993). From this we can establish the probability of neighbourhood costs,
 181 where one or more neighbours are infected, is $\left(1 - \left(\prod_{j \neq i} (1 - P_j)^{\frac{1}{N-1}}\right)^n\right)$.

182 The final term of the payoff is the biosecurity costs, which we assume is a function of
 183 the probability of infection. We set the cost of biosecurity as $c(P_i) = \frac{\ln(b-a) - \ln(P_i - a)}{d}$,

206 the entire ‘at least 1 neighbour infected’ term in (2)) are considered fixed constants. To
 207 illustrate this, we place ‘*’ on the relevant parts of (1) and (2) to emphasise that the
 208 focal farm considers these fixed constants that they have no control over.

209 To find the optimal probability of infection, we need to calculate first-order
 210 conditions of their respective payoffs. Therefore, the optimal level of P_F is given by:

$$\frac{\partial Q_F}{\partial P_F} = -D_{DF} + D_{NF} \left(1 - (1 - P_J^*)^{\frac{nM}{N-1}} (1 - P_F^*)^{\frac{n(N-M-1)}{N-1}} \right) - \frac{dc(P_F)}{dP_F} = 0. \quad (3)$$

Noting that $P_F \in (0, b]$, we either have an internal solution for (3) or $\frac{\partial Q_F}{\partial P_F} < 0$ for all $P_F \in (0, b]$ and thus $P_F = b$ maximises (2). The latter follows from $\frac{\partial Q_F}{\partial P_F}$ being continuous in $(0, b]$ together with $\frac{dc(P_F)}{dP_F} \rightarrow \infty$ as $P_F \rightarrow 0$. For members, the first order condition determines the optimal level of P_J for the whole group. This optimal level for P_J is given by:

$$\begin{aligned} \frac{\partial Q_J}{\partial P_J} = & -D_{DJ} + D_{NJ} \left(1 - (1 - P_J)^{\frac{n(M-1)}{N-1}} (1 - P_F^*)^{\frac{n(N-M)}{N-1}} \right) \\ & - D_{NJ}(1 - P_J) \left(\frac{n(M-1)}{N-1} (1 - P_J)^{\frac{n(M-1)}{N-1} - 1} (1 - P_F^*)^{\frac{n(N-M)}{N-1}} \right) - \frac{dc(P_J)}{dP_J} = 0. \end{aligned} \quad (4)$$

This equation can be rearranged to:

$$\frac{\partial Q_J}{\partial P_J} = -D_{DJ} + D_{NJ} - D_{NJ} \left(1 + \frac{n(M-1)}{N-1} \right) (1 - P_J)^{\frac{n(M-1)}{N-1}} (1 - P_F^*)^{\frac{n(N-M)}{N-1}} - \frac{dc(P_J)}{dP_J} = 0. \quad (5)$$

211 If this equation does not have a solution $P_J \in (0, b]$, then $\frac{\partial Q_J}{\partial P_J} < 0$ for all $P_J \in (0, b]$
 212 and thus the payoff is maximised at $P_J = b$. These conditions on $\frac{\partial Q_J}{\partial P_J}$ and $\frac{\partial Q_F}{\partial P_F}$ usually
 213 have at most one solution, which would simultaneously maximise both payoffs, although
 214 this is not always true ($\frac{\partial Q_J}{\partial P_J} = 0$ occasionally have multiple solutions, some of which
 215 will be minima). The optimal solutions depend on the number of members M (i.e.
 216 $P_J(M)$ and $P_F(M)$) and consequently the payoffs are dependent on M (i.e. $Q_J(M)$
 217 and $Q_F(M)$).

218 The conditions for a coalition with $M \in [2, N - 1]$ members to form and be stable
 219 are:

- 220 1. No free-rider has the incentive to join, i.e. $Q_J(M + 1) < Q_F(M)$;

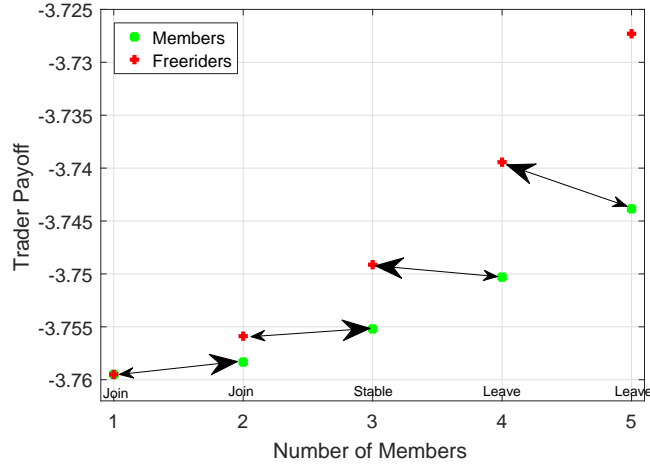


Figure 1. Visual demonstration of the stability conditions. The double arrowed lines highlight the payoffs which are compared in the stability conditions, with the larger arrowhead representing the larger payoff. A stable coalition occurs when a coalition size M only has larger arrowheads, which in this case occurs when $M = 3$. This Figure is a zoomed in version of Figure 2a.

221 2. No member has the incentive to leave, i.e. $Q_F(M - 1) < Q_J(M)$.

222 For the special case of $M = 1$, only the first condition is needed for a stable coalition,
 223 whereas for $M = N$, only the second condition is needed for a stable coalition. Stable
 224 coalitions are formed because coalitions smaller than \tilde{M} result in incentives for
 225 freeriders to join, increasing the coalition size, and coalitions larger than \tilde{M} result in
 226 incentives for members to leave, decreasing the coalition size. This is shown in Figure 1
 227 by following the larger arrowheads.

228 From here on, we investigate the number of assurance scheme members in a stable
 229 coalition (\tilde{M}) and the resulting level of biosecurity at the stable coalition as a measure
 230 of success of the scheme for a disease. As mentioned before, we measure biosecurity as
 231 the probability of avoiding infection ($1 - P_J$ and $1 - P_F$ for members and freeriders,
 232 respectively). Consequently we define overall biosecurity as the geometric mean of the
 233 probability of avoiding infection ($(1 - P_J)^{\frac{\tilde{M}}{N}} (1 - P_F)^{\frac{N - \tilde{M}}{N}}$); success is having overall
 234 biosecurity as close to one as possible. We will consider a local neighbourhood with
 235 large direct and neighbourhood costs to represent the buffer zones and movement
 236 restriction associated with *X. fastidiosus* as a baseline scenario. Other scenarios involve
 237 considering various direct and neighbourhood costs, which represent other pathogens,
 238 policies and economic factors, as well as the support given by government.

239 2.3. Numerical methods

240 Through all simulations, we consider there being 50 farms ($N = 50$), that the
241 neighbourhood costs are local ($n = 2$), that the probability of infection P_F, P_J is
242 between 0 and 0.1 ($a = 0, b = 0.1, d = 1$). This choice of parameters fits many scenarios
243 where the probability of infection is relatively low and hypothetically avoidable, which
244 applies well to more distant and uncertain threats like *X. fastidiosa* in the UK; whereas
245 for threats closer to home and more certain (like *X. fastidiosa* in southern Italy) would
246 need larger values of b and possibly a . The direct and neighbourhood costs for members
247 and freeriders are varied throughout to cover a variety of diseases and their
248 consequences, as well as to explore government support by reducing these cost for
249 members as an incentive for membership, but the default choices are
250 $D_{DJ} = D_{DF} = D_{NJ} = D_{NF} = 20$. This default choice of parameters of local damages
251 with direct and neighbourhood costs being large and equal fits the uncompensated
252 movement restrictions from *X. fastidiosa*, but other disease-farm-policy combinations
253 can have different direct and neighbourhood costs; in particular the 2001 FMD outbreak
254 in the UK could be seen to have very small direct costs and large neighbourhood costs
255 since culls were compensated, but wider movement restrictions were not.

256 The results in this paper are produced using the MATLAB function ‘fsolve’ (with
257 initial condition $(0.01 * b, 0.01 * b)$) to find solutions (P_J, P_F) that solves
258 $\left(\frac{\partial Q_J}{\partial P_J} = 0, \frac{\partial Q_F}{\partial P_F} = 0\right)$, noting that exterior solutions of $P_J = b$ and/or $P_F = b$ (i.e.
259 where member and/or freeriders have no biosecurity costs) are also considered and
260 compared for optimality. We use this solution of (P_J, P_F) to provide the optimal
261 payoffs Q_J and Q_F for a given coalition. We repeat this for all coalition sizes to get all
262 coalition payoffs and then determine which coalitions are stable by comparing payoffs
263 using conditions (1) and (2).

264 For simplicity, in our figures, we only show the largest stable coalition. Also, we will
265 assume that freeriders will join and members will not leave if the payoff is the same (i.e.
266 allow equality in the second condition for stability). Generally, this means we ignore all
267 but the largest trivial ‘stable’ coalitions (i.e. where members and freeriders provide no
268 biosecurity ($P_J = b$) for a range of membership size), although hypothetically there
269 might be cases where two or more non-trivial stable coalitions occur.

270 3. Results

271 3.1. Without government support

272 Figure 2 demonstrates how farmers' payoffs and biosecurity (measured as the
273 probability of avoiding infection) change with coalition size in the absence of
274 government support. Firstly, as the coalition gets larger, payoffs for both members and
275 freeriders increase, i.e. everyone benefits from a large coalition (Figure 2a). However,
276 payoffs for freeriders increase more than the payoffs for members, creating an incentive
277 to freeride that becomes larger with coalition size. This incentive to freeride is strong
278 and consequently only a small coalition of $\tilde{M} = 3$ members (out of a potential $N = 50$)
279 is stable. This low membership coalition results in the scheme providing little benefit in
280 terms of farmers' payoffs over the case where no coalition is formed ($M = 1$).

281 Figure 2b shows that as membership increases, the members will increase their
282 probability of avoiding infection. Increasing membership means each member has more
283 neighbours who are members to consider in their actions. Additionally, as coalition size
284 increases, the probability of avoiding infection of freeriders, also increases but to a
285 smaller degree. With more members the likelihood of a freerider experiencing
286 neighbourhood costs is reduced, consequently giving freeriders a greater incentive to
287 avoid direct costs from the outbreak and thus increase their biosecurity. Note, this
288 reduction in the likelihood of neighbourhood costs is due to both (i) the improvement in
289 biosecurity by each member and (ii) there being more members (with high biosecurity)
290 and less freeriders (with low biosecurity) as neighbours. From this, we can see that
291 overall biosecurity can improve greatly if a large coalition exists. However, since the
292 stable coalition from Figure 2a is $\tilde{M} = 3$, the corresponding improvement in overall
293 biosecurity from such a small coalition compared to no coalition ($M = 1$) is very small.

294 Figure 3 demonstrates that the the stable coalition size (\tilde{M}) and overall biosecurity
295 at the stable coalition varies with the magnitude of direct and neighbourhood costs.
296 These different direct and neighbourhood costs reflect the nature of the disease and the
297 regulatory and market consequences of an infection; for example, damaging endemic
298 diseases will likely have high direct costs and low neighbourhood costs, *X. fastidiosa* has
299 high direct and neighbourhood costs, and events like the 2001 UK Foot and Mouth
300 outbreak have high neighbourhood costs and lower direct costs since there were severe

301 movement restrictions and trade bans but with compensation for culls. Firstly, from
302 Figure 3a, when direct costs are low, the stable coalition size \tilde{M} is large, especially
303 when neighbourhood costs are also low. However, this region corresponds to low overall
304 biosecurity levels, with little to no biosecurity provided (Figure 3b). Conversely, from
305 Figure 3a, we find that when direct costs are high, there are higher levels of biosecurity
306 (set predominately by freeriders preventing increased costs) but with a small stable
307 coalition size \tilde{M} and thus the coalition has a negligible effect on the overall level of
308 biosecurity. However, from Figure 2, we see there is potential for considerable
309 improvement in biosecurity if the coalition would have been larger (but such a coalition
310 is not stable). Additionally, increasing neighbourhood costs results in lower biosecurity
311 since neighbourhood costs reduce the benefit of remaining disease-free and thus the
312 incentive for private biosecurity. Overall, we find that without government support,
313 assurance schemes provide little improvement in biosecurity as either membership is
314 high where members provide little in terms of biosecurity or membership is small.

315 3.2. With government support

316 Governments can support the assurance scheme by applying incentives for members
317 only that reduce members costs from an outbreak. These incentives could includes
318 monetary incentives like partial post-outbreak compensation or non-monetary incentives
319 like the relaxation of movement restrictions. This is simulated here as a policy that
320 reduces both direct and neighbourhood costs from outbreaks for members only by 20%
321 (Figure 4, we later consider a full range of reductions). First of all, Figure 4a shows that
322 reduction in costs increases the payoffs for members, which would mean freeriders would
323 be better off joining the scheme (compared to Figure 2a). As a result, membership
324 increases, resulting in a stable coalition size of $\tilde{M} = 48$ (out of 50). Additionally, the
325 reduction in costs makes a disease outbreak less costly for members and thus members
326 provide less biosecurity for any given coalition size than without government support (in
327 particular, with support the (stable) coalition of 48 members would have overall
328 probability of infection of around 0.025 (Figure 4b), whereas without support the
329 (unstable) coalition of 48 members would have an overall probability of infection of over
330 0.02 (Figure 2b)). However, this reduction in biosecurity is small compared to the
331 increase in biosecurity for all coalitions larger then 7 members as the larger coalition of

332 members incorporates the impact of neighbourhood costs on other members (compare
333 Figure 4b and $\tilde{M} = 3$ in Figure 2b). Overall, the incentive of a 20% reduction in
334 outbreak costs results in more than a 50% reduction in overall probability of infection
335 compared to no government support (from around 0.055 in Figure 2b and around 0.025
336 in Figure 4b). This shows that the assurance scheme has real potential in improving
337 overall biosecurity with government support, while also improving payoffs for both
338 members and freeriders.

339 Figure 5 shows the impact a 20% reduction of costs for members has on the stable
340 coalition size (Figure 5a) and overall biosecurity (Figure 5b) for a range of direct and
341 neighbourhood costs. Here we see that the stable coalition size (\tilde{M}) is large for most
342 values of direct and neighbourhood costs (Figure 5a), with regions with higher direct
343 costs or low neighbourhood costs resulting in the full 50 members. In the corresponding
344 full membership region in Figure 5b, we find that increasing neighbourhood costs results
345 in higher levels of biosecurity. Conversely, in Figure 3b and the regions of Figure 5b
346 where membership is not full (above the kinks in the contours), biosecurity levels
347 decrease as neighbourhood costs increases. Overall, there is considerable improvement
348 in biosecurity compared to Figure 3b, with the only region with no significant
349 improvement occurring where both direct and neighbourhood costs are small and so the
350 need for biosecurity is small.

351 For previous results, we considered a fixed level of support from a government to
352 incentivise membership (i.e. a 20% reduction of direct and neighbourhood costs for
353 members); now Figure 6 shows a government that can vary this level of support through
354 monetary and non-monetary incentives such that both direct and neighbourhood costs
355 are reduced proportionately. We find that for low direct and neighbourhood costs, a full
356 coalition is stable for all levels of support in these costs (left of Figure 6a) that provides
357 little biosecurity (left of Figure 6b). This is consistent with the result shown above
358 where there was no government support (from Figure 3). However, for higher levels of
359 direct and neighbourhood costs, increasing the levels of support from 0% (shown in
360 Figure 3, where there is a very small coalition) leads to a rapid increase in the stable
361 coalition size (as the contours are close together) until $\tilde{M} = 50$ is reached at a level of
362 support, in terms of reduction of outbreak costs, of just over 20%; all larger levels of
363 support lead to full membership.

364 From Figure 6b, for the case where there are larger direct and neighbourhood costs,
365 we have that overall biosecurity increases as the level of government support increases
366 until a peak is reached (signified by the lower white line) which corresponds with the
367 case where there is full membership of the coalition (i.e. the ‘50’ contour in Figure 6a).
368 This means the optimal level of government support to voluntary private schemes is
369 given by smallest amount that leads to full membership. When governments increase
370 their support beyond this optimal level, biosecurity decreases without any further
371 increases in membership. These results can be explained by recalling that reducing
372 private outbreak costs through incentives leads to less necessity for members to invest in
373 biosecurity for a given coalition (comparing Figure 2 and Figure 4), but this reduction
374 in overall biosecurity is more than compensated by the improvement in biosecurity that
375 comes from increasing the number of members in the stable coalition, resulting in a net
376 overall improvement in biosecurity. However, once a full coalition is achieved, further
377 incentives that reduce outbreak costs can only lead to members reducing their
378 biosecurity. In this case, there exists a level of support in these outbreak costs (around
379 65%) that results in the same level of biosecurity as the ‘no support’ case (top white
380 line in Figure 6b). This means that all levels of support below the top white line lead to
381 higher levels of biosecurity than without this government support (i.e. an improvement
382 in biosecurity), whereas too much support by reducing outbreak costs for members leads
383 to lower levels of biosecurity than without government intervention (i.e. worse
384 biosecurity). This suggests that there is a wide range of levels of government support
385 (with respect to reducing direct and neighbourhood costs for members only) that lead to
386 improvements in overall biosecurity (in this case, any reduction less than 65%), giving
387 evidence that this improvement that government policies can achieve is rather robust.

388 Government support could be more targeted than a broad reduction in all outbreak
389 costs for members simulated in Figure 6; some policies like (partial) post-outbreak
390 monetary compensation are often applied to direct costs only like culling infected
391 animals/plants, whereas non-monetary incentives like relaxing movement restrictions
392 are often easier to apply to uninfected neighbouring farms that have lower risks of
393 spreading the infection than infected farms. We explore this by considering reducing
394 neighbourhood costs only (Figure 7a) and direct costs only (Figure 7b) as incentives for
395 members. Comparing Figure 7a and 7b with Figure 6b, we find that there exists an

396 optimal level of support (i.e. the smallest reduction that gets full membership), below
397 which increasing support increases biosecurity and stable coalition size and beyond
398 which increasing support decreases biosecurity. In this case, a larger level of support in
399 direct costs only (Figure 7b, 65%) and neighbourhood costs only (Figure 7a, 30%) is
400 needed for the highest level of biosecurity, compared to 20% in Figure 6b. This means
401 that if only either monetary or non-monetary incentives are offered, a larger level of
402 (targeted) government support is needed to get full membership.

403 The targeted support simulated in Figure 7a and 7b leads to one major difference to
404 that of the broad support in Figure 6; that all levels of targeted support from
405 government to the coalition result in better biosecurity than in the case with no
406 government intervention. In other words, reducing direct or neighbourhood costs only
407 for members through monetary or non-monetary incentives leads to robust
408 improvements in biosecurity. For supporting neighbourhood costs only, this
409 improvement in biosecurity is generally true because of the following: (i) once a full
410 coalition is achieved, reducing neighbourhood costs for members reduces their
411 biosecurity and thus leads to decreasing levels of overall biosecurity (so zero
412 neighbourhood costs has the lowest level of biosecurity beyond the optimal); and (ii)
413 reducing neighbourhood costs to zero results in members setting their biosecurity to
414 consider (private) direct costs only (without neighbourhood costs, members behave like
415 freeriders), which has larger overall biosecurity than any non-zero neighbourhood costs
416 for a given direct cost (since neighbourhood costs undermine private efforts to prevent
417 outbreaks, Figure 3). Bringing (i) and (ii) together, reducing neighbourhood costs
418 beyond the optimal level leads to better overall biosecurity than the case with no
419 neighbourhood costs, which is better than the coalition with no government support.
420 There is no clear rationale as to whether reducing direct costs for members only will
421 always improve biosecurity since although argument (i) is generally true, there is no
422 clear reason for something like (ii) being true in general.

423 **4. Discussion**

424 Biosecurity-related assurance schemes are a potential method to get voluntary
425 biosecurity investment. If these schemes can achieve high membership, members
426 improve their biosecurity knowing it will be reciprocated, which can yield considerable

427 improvements. However, we find that without government support there is real
428 difficulty in getting farms to volunteer, resulting in little improvement in biosecurity.
429 These means that assurance schemes would have little impact without outside support.
430 Governments can provide support for a voluntary biosecurity-related assurance scheme
431 through policies that reduce direct and neighbourhood costs from outbreaks for
432 members to incentivise membership; this can be through monetary mechanisms like
433 post-outbreak compensation or non-monetary mechanisms like preferential regulatory
434 treatment. We have shown that reducing costs to members from outbreaks can be an
435 effective incentive to getting high membership, leading to high levels of biosecurity. This
436 means that government support can lead to a successful assurance scheme that has high
437 membership and significant improvements in overall biosecurity. Moreover, we find that
438 these improvements are robust, with a wide range of support leading to higher
439 biosecurity compared to the absence of government support, as well as more members
440 and improved payoffs for farms. This means there is a good degree of leeway around the
441 different strategies governments can use to achieve full membership with substantial
442 improvements in biosecurity. These strategies could broadly be seen as either: (i)
443 ‘monetary’ support through compensation to the scheme members for direct outbreak
444 costs or subsidises for their biosecurity actions; such support normally targets direct
445 costs; or (ii) ‘non-monetary’ support through preferential treatment for members that
446 would reduce the costs of complying with biosecurity inspections and regulations such
447 as preferential movement restrictions or testing requirements; such support normally
448 targets neighbourhood costs. Given we showed that reducing neighbourhood costs for
449 members would always lead to improved biosecurity, we see ‘non-monetary’ policies like
450 preferential movement restrictions for members as a robust strategy for preventing
451 disease outbreaks.

452 Our finding that partial post-outbreak compensation for costs conditional on joining
453 an assurance scheme often leads to higher levels of biosecurity is consistent with the
454 idea of partial post-outbreak compensation conditional on good behaviour improving
455 biosecurity (Barnes et al., 2015; Gramig et al., 2009; Hennessy and Wolf, 2018). In our
456 case, we find that the optimal level is the smallest amount of post-outbreak
457 compensation to get everyone involved, as further reductions reduce the private
458 incentive for biosecurity. The issue of post-outbreak compensation depends on legal and

459 historical precedent of how outbreaks are dealt with. For example, in the UK,
460 post-outbreak compensation is sometimes given for the culling of animals as a result of
461 animal diseases (like in the 2001 Foot and Mouth Disease outbreak), but there is no such
462 precedent for plant diseases like *X. fastidiosa* (Waage and Mumford, 2008; Wilkinson
463 et al., 2011). Additionally, post-outbreak compensation is normally only paid for culled
464 animals, meaning other costs like those from complying with movement restrictions do
465 not receive post-outbreak compensation, potentially creating a perverse incentive where
466 it becomes preferable for the individual farmers to become infected so that they can
467 receive compensation for culling, resulting in more disease spread (Barnes et al., 2015).

468 The examples given in this paper focus on a case where neighbourhood costs are
469 local. This is appropriate for diseases where the main costs are limited to areas around
470 infections such as the regulations around *X. fastidiosa*. However, there are several forms
471 of neighbourhood costs like trade bans following an outbreak that are more global. In
472 these cases, without near universal cooperation, assurance schemes will likely have no or
473 little benefit. The prospect for success is slim, although since cooperation has limited
474 impact, it also has little cost, so might lead to enough farmers cooperating to get a
475 critical mass for members to invest in biosecurity. This has similarities to an argument
476 for minimum membership requirements in some coalition games (Barrett, 2005; Finus,
477 2008; Carraro et al., 2009; Barrett, 2016), although this mechanism fails with any
478 membership fee (or at least any fee when membership is low enough for no investment
479 in biosecurity).

480 This model does not take into account the dynamics of an outbreak, and instead has
481 only one time step. However, once an outbreak is in effect and found, factors on the
482 ground can change rapidly, be it changes in the probability of infection as more farms
483 become infected, or shifts in factors like market conditions and regulations that change
484 the costs from infection. Additionally, using a stable coalition analysis is most
485 appropriate when decisions to join or leave coalitions and setting biosecurity levels are
486 made and changed quickly compared to that the disease state and other factors. These
487 limitations mean that our model is most appropriate for modelling before a disease is
488 known to be present, which is the case here where we focus on biosecurity actions as
489 preventing disease outbreaks. Conversely, the model is also appropriate to model
490 endemic diseases since endemic diseases have relatively constant disease prevalence and

491 other conditions have largely stabilised.

492 The model considers biosecurity amongst farms, looking at potential benefits of
493 biosecurity to the industry. However, not all farms are the same, they can have with
494 various sizes, business models, distribution of hosts, location and trading partners that
495 can influence disease risk. This heterogeneity could lead to cases where the optimal
496 level of government support might not be linked with full membership; that there could
497 be farms that are too costly or have too little impact on overall biosecurity.
498 Nevertheless, given the weaker-link nature of preventing disease outbreaks, this should
499 be less likely than other public goods.

500 There can be many more stakeholders to a disease outbreak than just farmers. For
501 example, the 2001 Foot and Mouth Disease outbreak in the UK had large negative
502 affects to other rural industries like tourism (FAO, 2002). For *X. fastidiosa*, the threat
503 that it could spread into the wider environment and cause massive damages to many
504 host species means that there are many stakeholders with a wide range of interests
505 outside of the horticultural industry who would want biosecurity improved, ranging
506 from those interested in protecting irreplaceable ancient or iconic woodland and trees
507 and species dependent on these, to a homeowner who picks cherries from a tree in their
508 garden. This might require other stakeholders having input into the scheme to get their
509 interests incorporated, and sometimes other stakeholders take the lead in forming or
510 supporting an assurance scheme. In particular, some assurance schemes are born out of
511 crises that alter the priorities of consumers and retailers. For example, Assured British
512 Meats (also known as 'Red Tractor') scheme in the UK was born from retailers and the
513 meat industry responding to the BSE crisis and the changes in food safety regulations
514 that followed (Fearne, 2000; Hobbs et al., 2002). Retailers can and have used their
515 market powers to set conditions on suppliers, which can include membership of an
516 approved scheme. Failure to meet these conditions can result in a lack of market access,
517 which reduces the value of the produce from firms that are not members; or conversely,
518 members can sometimes gain a premium on their produce (Fearne and Walters, 2004;
519 Hubbard et al., 2007). Both of these effects reduce down to retailers and consumers
520 rewarding membership/penalising non-membership which can result in a higher uptake
521 in scheme membership and improved biosecurity, much like government support does in
522 this paper. However, even without stakeholder input, the improved biosecurity from a

523 successful assurance scheme can yield substantial benefits to other stakeholders.

524 Overall, we have demonstrated that biosecurity-related assurance schemes by
525 themselves will have difficulty getting sufficient membership to yield any notable
526 improvements in biosecurity, and that incentives from government support to join are
527 needed for such improvements to be realised. In particular, we find that government
528 support by reducing costs from outbreaks can be an effective incentive for improvements
529 in biosecurity to something closer to a social optimum.

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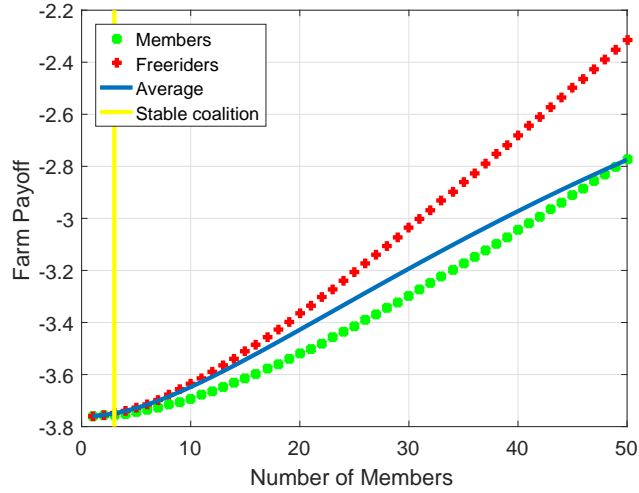
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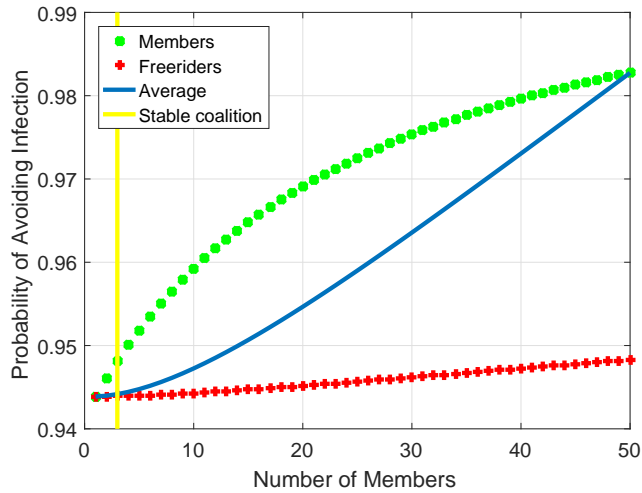
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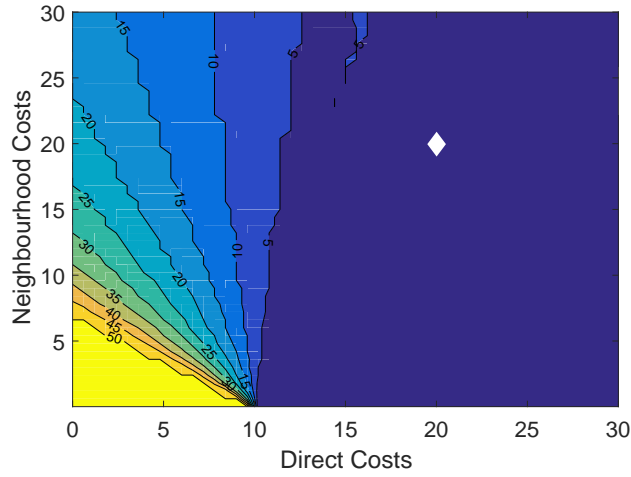


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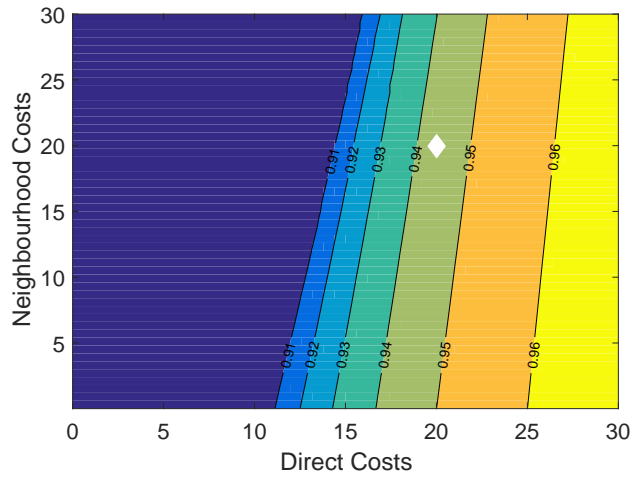


(b)

Figure 2. Without government support, a small stable coalition forms with little biosecurity. Profiles, as function of coalition size, of (a) farm payoffs and (b) the probability of avoiding infection, for both members and freeriders. The averages used is the geometric mean for the probability of avoiding infection ($1 - P_k$) and arithmetic mean for the payoff, noting that as membership increases, the more these averages are weighted towards members and away from the freeriders. Parameters: $D_{DJ} = D_{DF} = D_{NJ} = D_{NF} = 20$.

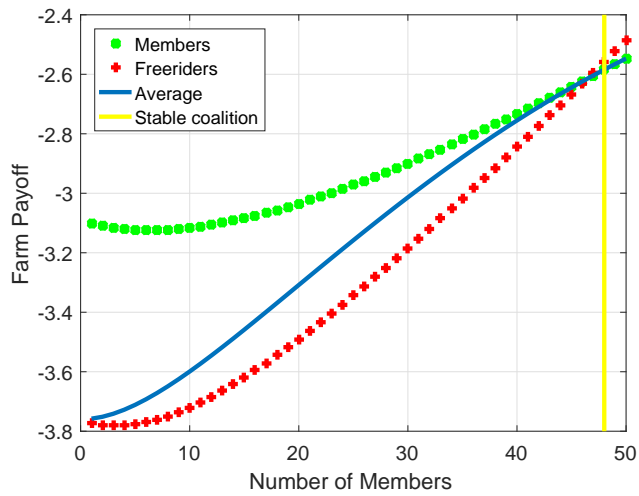


(a)

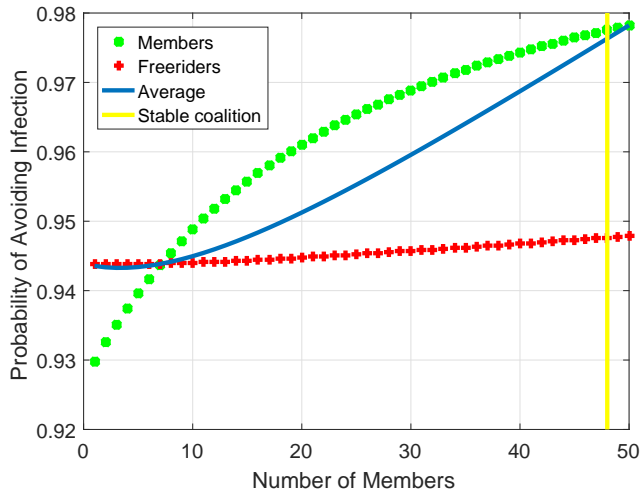


(b)

Figure 3. Across various direct and neighbourhood costs, without government support, either a small stable coalition or a large stable coalition forms, both with little improvement in biosecurity. Contour plots of (a) the number of members in the stable coalition and (b) overall biosecurity (taken as the geometric mean of the probability of avoiding infection $(1 - P_k)$ at stable coalition, i.e. where the yellow and blue lines meet in Figure 2b), against direct and neighbourhood costs. The white diamond marks the scenario in Figure 2. Parameters: $D_{DJ} = D_{DF}$ (x-axis) and $D_{NJ} = D_{NF}$ (y-axis) vary.

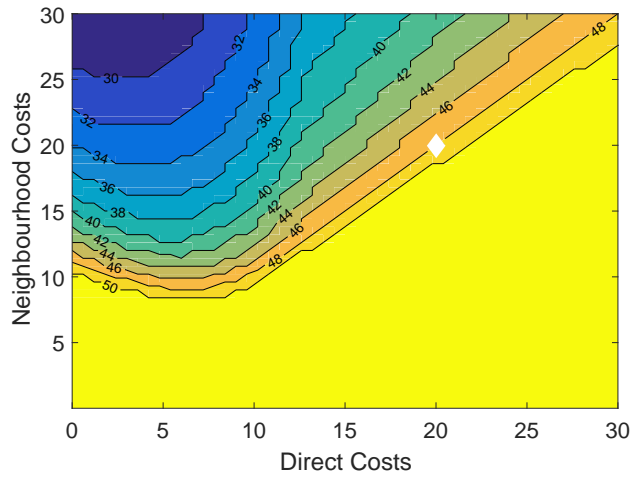


(a)

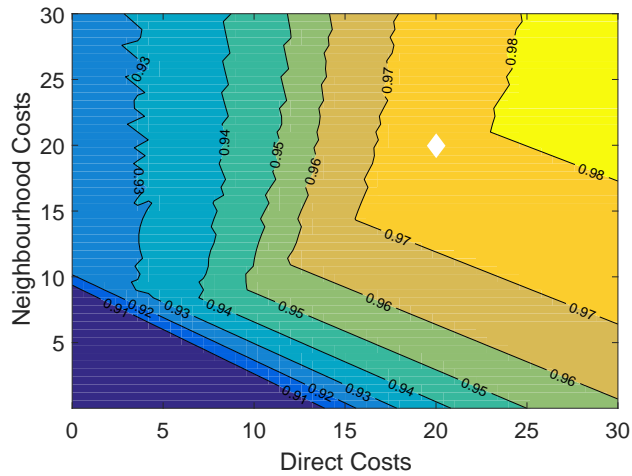


(b)

Figure 4. Government support leads to a large stable coalition with a large improvement of biosecurity. Profiles, as a function of coalition size, of (a) farm payoffs and (b) the probability of avoiding infection, for both members and freeriders, where members have both direct and neighbourhood costs reduced by 20%. Averages and lines have same meaning as Figure 2. Parameters: same as Figure 2 except $D_{DJ} = D_{NJ} = 16$.

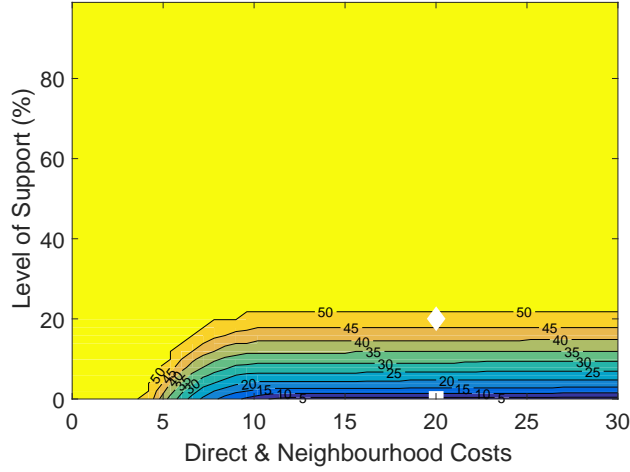


(a)

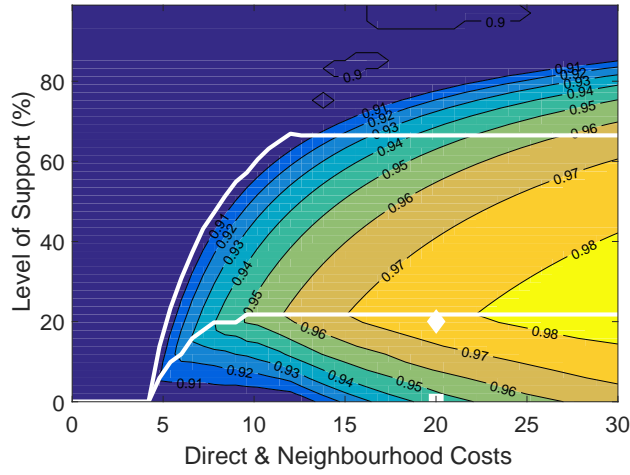


(b)

Figure 5. Across various direct and neighbourhood costs, with government support, a large stale coalition forms, often with substantial improvement in biosecurity. Contour plots of (a) the number of members in the stable coalition and (b) overall biosecurity, against direct and neighbourhood costs. Members have their costs reduced by 20%, just like Figure 4. The white diamond marks the scenario in Figure 4. Parameters: $D_{DJ} = 0.8 * D_{DF}$ (x-axis) and $D_{NJ} = 0.8 * D_{NF}$ (y-axis) vary.

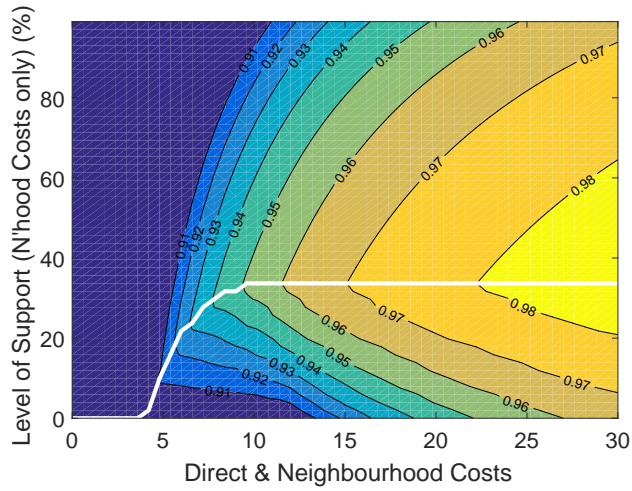


(a)

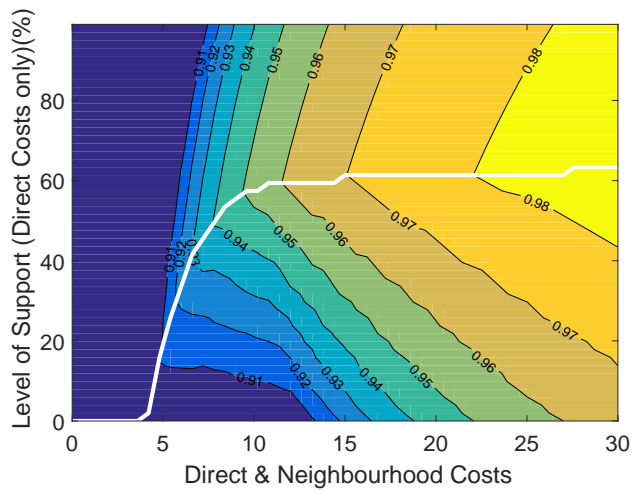


(b)

Figure 6. The level of government support that gives the best biosecurity is the smallest reduction that results in a full stable coalition. Contours of (a) the number of members in the stable coalition and (b) overall biosecurity, as a function of free-rider costs (x-axis) and reduction in costs members receive (y-axis, Figure 4 had a reduction of 20%). The bottom white line in (a) gives the level of reduction that maximises the probability of avoiding infection, whereas the top white line gives that reduction where the probability of avoiding infection is the same as with no reduction. The white diamond marks the 20% reduction in Figure 4, whereas the white square marks the ‘no incentive’ case in Figure 2. Parameters: same as Figures 2 and 4 except $D_{DJ} = D_{NJ}$ and $D_{DF} = D_{NF}$ vary.



(a)



(b)

Figure 7. With government support targetting direct or neighbourhood costs only, all levels of support lead to improved biosecurity. Contours of overall biosecurity where members (a) neighbourhood costs are reduced, and (b) direct costs are reduced. The white line corresponds to the reduction that maximises the probability of avoiding infection (the other white line in Figure 6b does not occur here). Parameters: same as Figure 2 except (a) $D_{DJ} = D_{DF} = D_{NF}$ and D_{NJ} vary and (b) $D_{NJ} = D_{DF} = D_{NF}$ and D_{DJ} vary.