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; Geragthy 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).

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

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

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

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

The horticultural industry in the UK is developing a biosecurity-related assurance scheme to encourage voluntary investment in preventing disease outbreaks; in particular, they seek to prevent the plant pathogen *Xylella fastidiosa* from spreading to the UK (HTA, 2017; DEFRA, 2018). *X. fastidiosa* is a bacterial pathogen with a large number (300+) of plant hosts including olive, stone fruits, citrus, grapevine, oak, oleander, coffee and lavender (EFSA Panel on Plant Health, 2015; Sicard et al., 2018). It has spread across parts of Italy (where it is killing olive trees by olive quick decline syndrome), France and Spain (Sicard et al., 2018; Saponari et al., 2019; Brunetti et al., 2020). The trade in live plants is the major pathway for introducing many new plant pests and pathogens around the world (Brasier, 2008; Dehnen-Schmutz et al., 2010), including for *X. fastidiosa* in the UK (DEFRA, 2018). An outbreak of *X. fastidiosa* in the UK could have massive impact to ecosystem services and the environment, especially if the outbreak is of a strain that causes major damage to oak trees (DEFRA, 2018). For the UK horticultural industry, an outbreak of *X. fastidiosa* has more certain impacts, the costly 'draconian outbreak measures' (HTA, 2017). These measures are set by European Union regulations (European Commission, 2015, 2017) that include destroying all hosts immediately around an outbreak and enforcing a buffer zone[1] around an outbreak where no host can be moved for 5 years. This amounts to an effective cull (at personal expense) of all potential hosts within the buffer zone for those in the horticultural trade since 5 years is considerably longer than the lifespan of any plant in a plant nursery or garden centre. This means there can be large costs from regulatory compliance to those in horticultural trade from biosecurity failures that occur either on-site or off-site but within the buffer zone. However, there are real concerns around whether such biosecurity-related assurance schemes can get enough members to significantly reduce the likelihood of an outbreak of *X. fastidiosa* without governmental support to encourage membership (HTA, 2017). In other words, are additional incentives like compensation for culling, preferential regulatory treatment (e.g. allow scheme members to move less risky hosts within the buffer zone that would otherwise be prohibited) or other ways to reduce the cost for members from an outbreak needed for an assurance

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[1] The 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).

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

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

2. Methods

2.1. General assumptions

The model describes a set of N farms who decide on their preventative biosecurity, given that a disease/pest outbreak results in costs for that farm. Additionally, an outbreak on a farm will impose costs on n other neighbouring farms that are not infected. The number of neighbours (n) depends on the type of neighbourhood cost; for example, $n = N - 1$ would represent neighbourhood costs where one infected farm affects everyone, which is appropriate for trade bans and industry wide movement restrictions (like Foot and Mouth Disease), whereas smaller n represent neighbourhood costs that are more 'local' (like the movement restrictions and buffer zone regulations for *X. fastidiosa*). We assume that each farm will experience one of three mutually exclusive scenarios: (i) the farm experiences 'direct costs' if the farm is infected, which includes all private costs that are a consequence of infection, from the costs from the reduction in quantity and quality of yield to the costs of controls, movement restrictions, trade bans, post-outbreak compensation and regulatory compliance[2]; (ii) the farm experiences 'neighbourhood costs' if the farm is not infected but at least one 'nearby' farm is infected, which are associated with the consequences of a 'nearby' outbreak like trade bans, movement restrictions, controls and regulatory compliance; (iii) the farm experiences no outbreak costs if the farm is not infected and there are no 'nearby' infected farms. All farms experience some cost for their (preventative) biosecurity.

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

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

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

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

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

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

2.2. Payoffs

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

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

The final term of the payoff is the biosecurity costs, which we assume is a function of the probability of infection. We set the cost of biosecurity as $c(P_i) = \frac{\ln(b-a) - \ln(P_i - a)}{d}$, where b is the probability of infection where no biosecurity actions are taken, $a \geq 0$ is the probability of infection where unlimited biosecurity actions are taken, and d is the cost-effectiveness of biosecurity. This formulation is derived from rearranging $P_i = a + (b - a)\exp(-dc(P_i))$ from Bate et al. (2016)[3] which has the following desired properties: that biosecurity costs strictly increase as the probability of infection decreases in a continuous and smooth manner $\left(\text{so } P_i \in (a, b] \text{ and } \frac{dc(P_i)}{dP_i} < 0\right)$; that biosecurity costs grow to infinity as the probability of infection approaches a from above; and that biosecurity costs have diminishing returns with respect to the probability of infection $\left(\text{i.e. } \frac{d^2c(P_i)}{dP_i^2} > 0\right)$. With this formulation, we have a one-to-one relationship between the probability of (avoiding) infection and the cost of biosecurity. For simplicity we assume all infections are hypothetically preventable, given enough spending (i.e. $a = 0$), which means $P_i \in (0, b]$. Additionally, we have assumed that $c(P_i)$ (likewise, a, b and d) is independent of other P_j's; this means that outbreaks on other farms do not change the ability and cost to prevent outbreaks on the focal farm. This independence is most appropriate for cases where infection between farms within the single timestep is negligible, such as outbreaks dominated by distant trade (like *X. fastidiosa* in the UK) or by transmission in the wider environment.

Consequently, the expected payoff for a member is:

$$Q_J = -\overbrace{D_{DJ}P_J}^{\text{E(Direct costs)}} \overbrace{-D_{NJ}\overbrace{(1 - P_J)}^{\text{P(Avoid infection)}}\overbrace{\left(1 - (1 - P_J)^{\frac{n(M-1)}{(N-1)}}(1 - P_F^*)^{\frac{n(N-M)}{(N-1)}}\right)}^{\text{P(1 or more neighbours infected)}}}^{\text{E(Neighbourhood costs)}} - \overbrace{c(P_J)}^{\text{Biosecurity costs}}, \tag{1}$$

whereas the expected payoff for a freerider is:

$$Q_F = -\overbrace{D_{DF}P_F}^{\text{E(Direct costs)}} \overbrace{-D_{NF}(1 - P_F)\left(1 - (1 - P_J^*)^{\frac{nM}{(N-1)}}(1 - P_F^*)^{\frac{n(N-M-1)}{(N-1)}}\right)}^{\text{E(Neighbourhood costs)}} - \overbrace{c(P_F)}^{\text{Biosecurity costs}}. \tag{2}$$

For members, the effect of other members on their neighbourhood costs in (1) are incorporated into their decision, whereas all freeriders both members and freeriders are assumed to be exogenous to the focal farm's decision and so all other farms (and thus

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[3] Technically, Bate et al. (2016) used biosecurity effort 'u_{res}' instead of cost, but since biosecurity costs were proportional to effort, u_{res} and $c(P_i)$ are the same up to the rescaling of d

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

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

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

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 $\frac{dc(P_F)}{dP_F} \to \infty$ as $P_F \to 0$. 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:

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

This equation can be rearranged to:

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

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

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

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

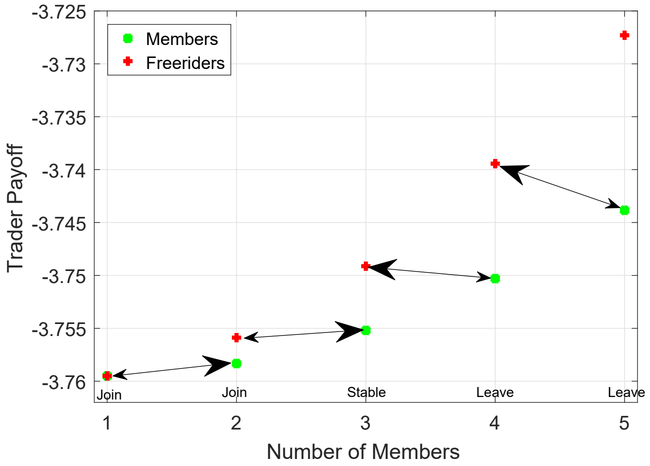

Figure 1. Visual demonstration of the stability conditions. The double arrowed lines highlight the payoffs which are compared in the stability conditions, with the larger arrowhead representing the larger payoff. A stable coalition occurs when a coalition size M only has larger arrowheads, which in this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

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

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

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

2.3. Numerical methods

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

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

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

3. Results

3.1. Without government support

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

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

Figure 3 demonstrates that the the stable coalition size ($\tilde{M}$) and overall biosecurity at the stable coalition varies with the magnitude of direct and neighbourhood costs. These different direct and neighbourhood costs reflect the nature of the disease and the regulatory and market consequences of an infection; for example, damaging endemic diseases will likely have high direct costs and low neighbourhood costs, *X. fastidiosa* has high direct and neighbourhood costs, and events like the 2001 UK Foot and Mouth outbreak have high neighbourhood costs and lower direct costs since there were severe movement restrictions and trade bans but with compensation for culls. Firstly, from Figure 3a, when direct costs are low, the stable coalition size $\tilde{M}$ is large, especially when neighbourhood costs are also low. However, this region corresponds to low overall biosecurity levels, with little to no biosecurity provided (Figure 3b). Conversely, from Figure 3a, we find that when direct costs are high, there are higher levels of biosecurity (set predominately by freeriders preventing increased costs) but with a small stable coalition size $\tilde{M}$ and thus the coalition has a negligible effect on the overall level of biosecurity. However, from Figure 2, we see there is potential for considerable improvement in biosecurity if the coalition would have been larger (but such a coalition is not stable). Additionally, increasing neighbourhood costs results in lower biosecurity since neighbourhood costs reduce the benefit of remaining disease-free and thus the incentive for private biosecurity. Overall, we find that without government support, assurance schemes provide little improvement in biosecurity as either membership is high where members provide little in terms of biosecurity or membership is small.

3.2. With government support

Governments can support the assurance scheme by applying incentives for members only that reduce members costs from an outbreak. These incentives could includes monetary incentives like partial post-outbreak compensation or non-monetary incentives like the relaxation of movement restrictions. This is simulated here as a policy that reduces both direct and neighbourhood costs from outbreaks for members only by 20% (Figure 4, we later consider a full range of reductions). First of all, Figure 4a shows that reduction in costs increases the payoffs for members, which would mean freeriders would be better off joining the scheme (compared to Figure 2a). As a result, membership increases, resulting in a stable coalition size of $\tilde{M} = 48$ (out of 50). Additionally, the reduction in costs makes a disease outbreak less costly for members and thus members provide less biosecurity for any given coalition size than without government support (in particular, with support the (stable) coalition of 48 members would have overall probability of infection of around 0.025 (Figure 4b), whereas without support the (unstable) coalition of 48 members would have an overall probability of infection of over 0.02 (Figure 2b)). However, this reduction in biosecurity is small compared to the increase in biosecurity for all coalitions larger then 7 members as the larger coalition of members incorporates the impact of neighbourhood costs on other members (compare Figure 4b and $\tilde{M} = 3$ in Figure 2b). Overall, the incentive of a 20% reduction in outbreak costs results in more than a 50% reduction in overall probability of infection compared to no government support (from around 0.055 in Figure 2b and around 0.025 in Figure 4b). This shows that the assurance scheme has real potential in improving overall biosecurity with government support, while also improving payoffs for both members and freeriders.

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

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

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

Government support could be more targeted than a broad reduction in all outbreak costs for members simulated in Figure 6; some policies like (partial) post-outbreak monetary compensation are often applied to direct costs only like culling infected animals/plants, whereas non-monetary incentives like relaxing movement restrictions are often easier to apply to uninfected neighbouring farms that have lower risks of spreading the infection than infected farms. We explore this by considering reducing neighbourhood costs only (Figure 7a) and direct costs only (Figure 7b) as incentives for members. Comparing Figure 7a and 7b with Figure 6b, we find that there exists an optimal level of support (i.e. the smallest reduction that gets full membership), below which increasing support increases biosecurity and stable coalition size and beyond which increasing support decreases biosecurity. In this case, a larger level of support in direct costs only (Figure 7b, 65%) and neighbourhood costs only (Figure 7a, 30%) is needed for the highest level of biosecurity, compared to 20% in Figure 6b. This means that if only either monetary or non-monetary incentives are offered, a larger level of (targeted) government support is needed to get full membership.

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

4. Discussion

Biosecurity-related assurance schemes are a potential method to get voluntary biosecurity investment. If these schemes can achieve high membership, members improve their biosecurity knowing it will be reciprocated, which can yield considerable improvements. However, we find that without government support there is real difficulty in getting farms to volunteer, resulting in little improvement in biosecurity. These means that assurance schemes would have little impact without outside support. Governments can provide support for a voluntary biosecurity-related assurance scheme through policies that reduce direct and neighbourhood costs from outbreaks for members to incentivise membership; this can be through monetary mechanisms like post-outbreak compensation or non-monetary mechanisms like preferential regulatory treatment. We have shown that reducing costs to members from outbreaks can be an effective incentive to getting high membership, leading to high levels of biosecurity. This means that government support can lead to a successful assurance scheme that has high membership and significant improvements in overall biosecurity. Moreover, we find that these improvements are robust, with a wide range of support leading to higher biosecurity compared to the absence of government support, as well as more members and improved payoffs for farms. This means there is a good degree of leeway around the different strategies governments can use to achieve full membership with substantial improvements in biosecurity. These strategies could broadly be seen as either: (i) 'monetary' support through compensation to the scheme members for direct outbreak costs or subsidises for their biosecurity actions; such support normally targets direct costs; or (ii) 'non-monetary' support through preferential treatment for members that would reduce the costs of complying with biosecurity inspections and regulations such as preferential movement restrictions or testing requirements; such suport normally targets neighbourhood costs. Given we showed that reducing neighbourhood costs for members would always lead to improved biosecurity, we see 'non-monetary' policies like preferential movement restrictions for members as a robust strategy for preventing disease outbreaks.

Our finding that partial post-outbreak compensation for costs conditional on joining an assurance scheme often leads to higher levels of biosecurity is consistent with the idea of partial post-outbreak compensation conditional on good behaviour improving biosecurity (Barnes et al., 2015; Gramig et al., 2009; Hennessy and Wolf, 2018). In our case, we find that the optimal level is the smallest amount of post-outbreak compensation to get everyone involved, as further reductions reduce the private incentive for biosecurity. The issue of post-outbreak compensation depends on legal and historical precedent of how outbreaks are dealt with. For example, in the UK, post-outbreak compensation is sometimes given for the culling of animals as a result of animal diseases (like in the 2001 Foot and Mouth Disease outbreak), but there is no such precedent for plant diseases like *X. fastidiosa* (Waage and Mumford, 2008; Wilkinson et al., 2011). Additionally, post-outbreak compensation is normally only paid for culled animals, meaning other costs like those from complying with movement restrictions do not receive post-outbreak compensation, potentially creating a perverse incentive where it becomes preferable for the individual farmers to become infected so that they can receive compensation for culling, resulting in more disease spread (Barnes et al., 2015).

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

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

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

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

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

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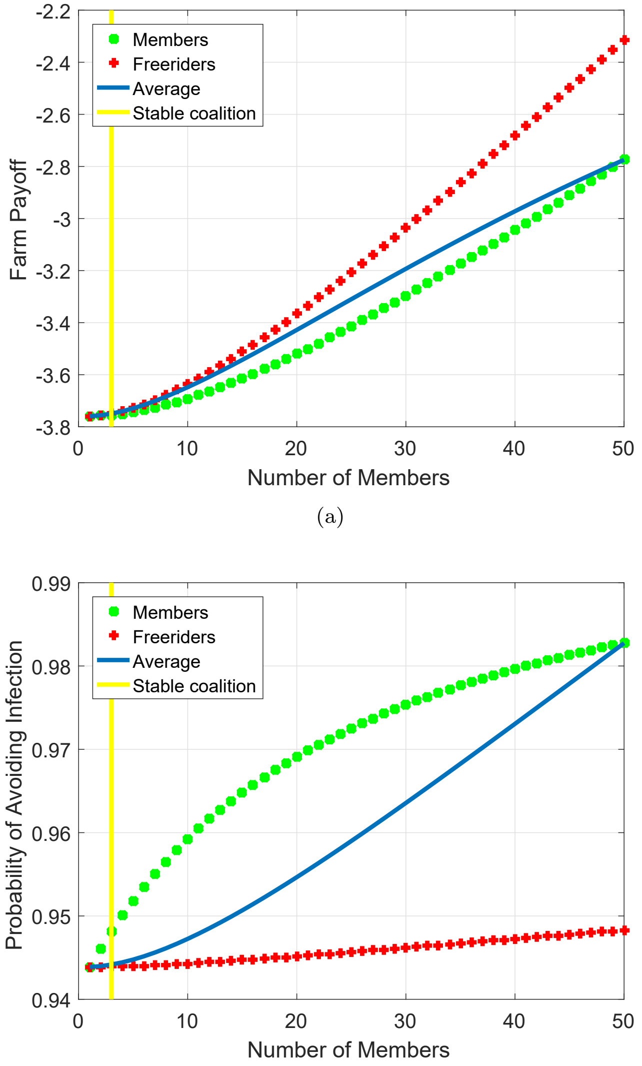
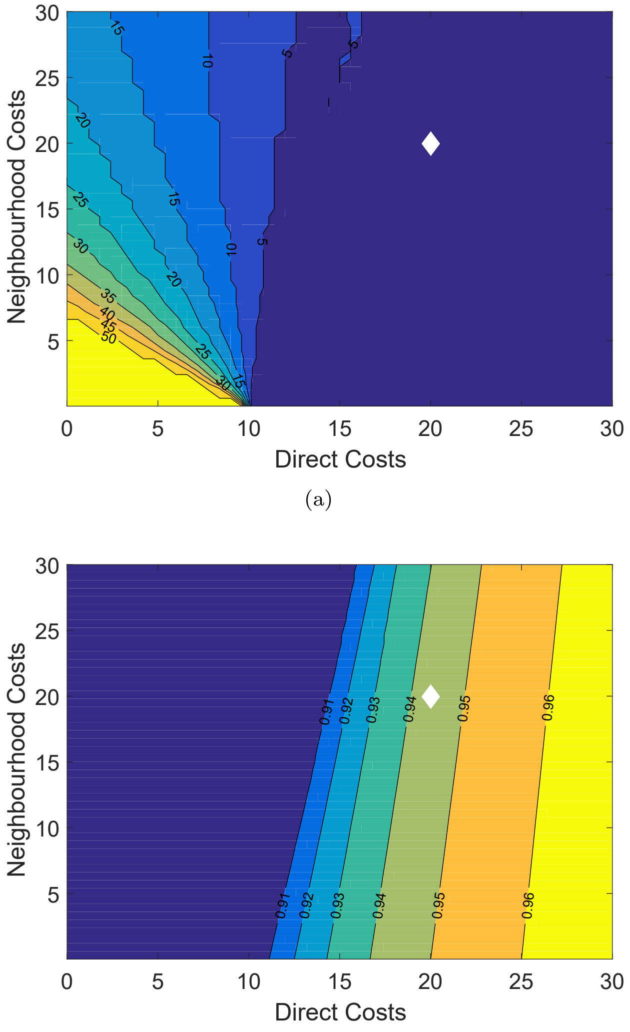


(a)

(b)

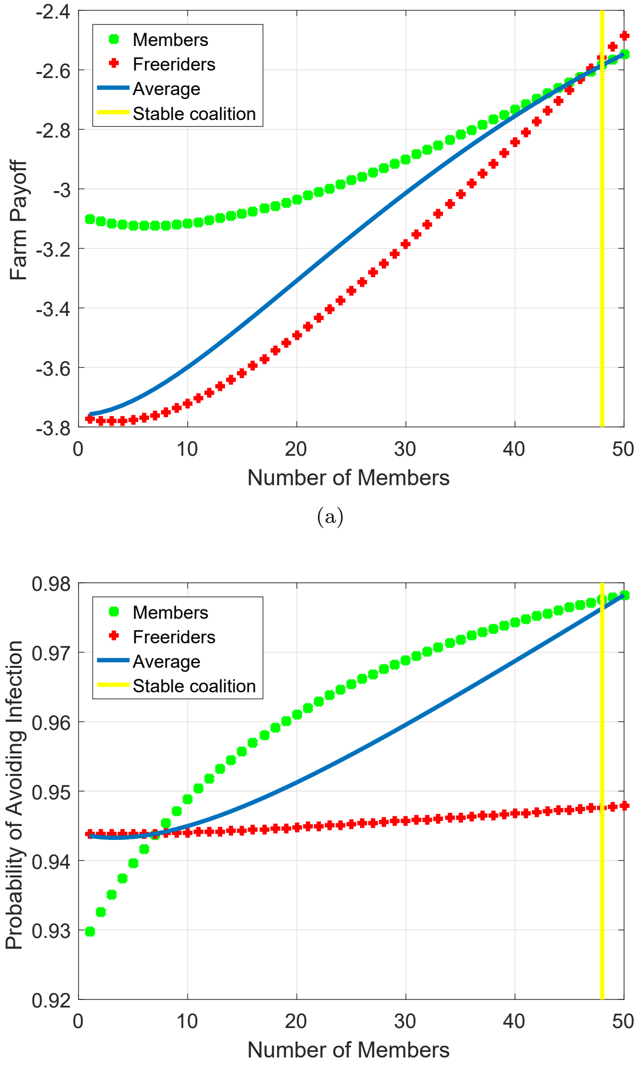
Figure 2. Without government support, a small stable coalition forms with little biosecurity. Profiles, as function of coalition size, of (a) farm payoffs and (b) the probability of avoiding infection, for both members and freeriders. The averages used is the geometric mean for the probability of avoiding 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)

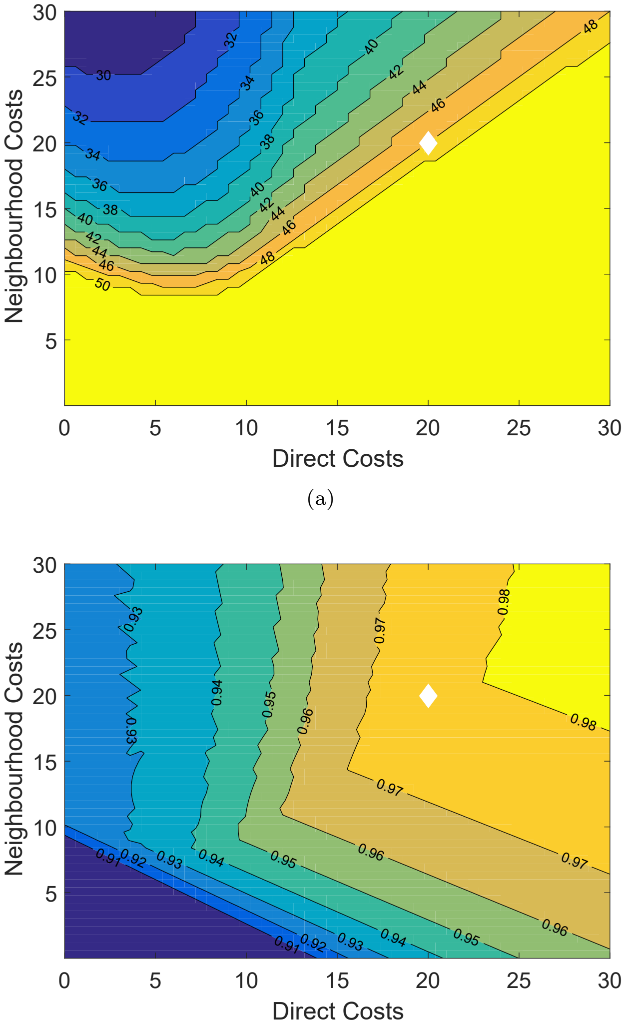
Figure 3. Across various direct and neighbourhood costs, without government support, either a small stable coalition or a large stable coalition forms, both with little improvement in biosecurity. Contour plots of (a) the number of members in the stable coalition and (b) overall biosecurity (taken as 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)

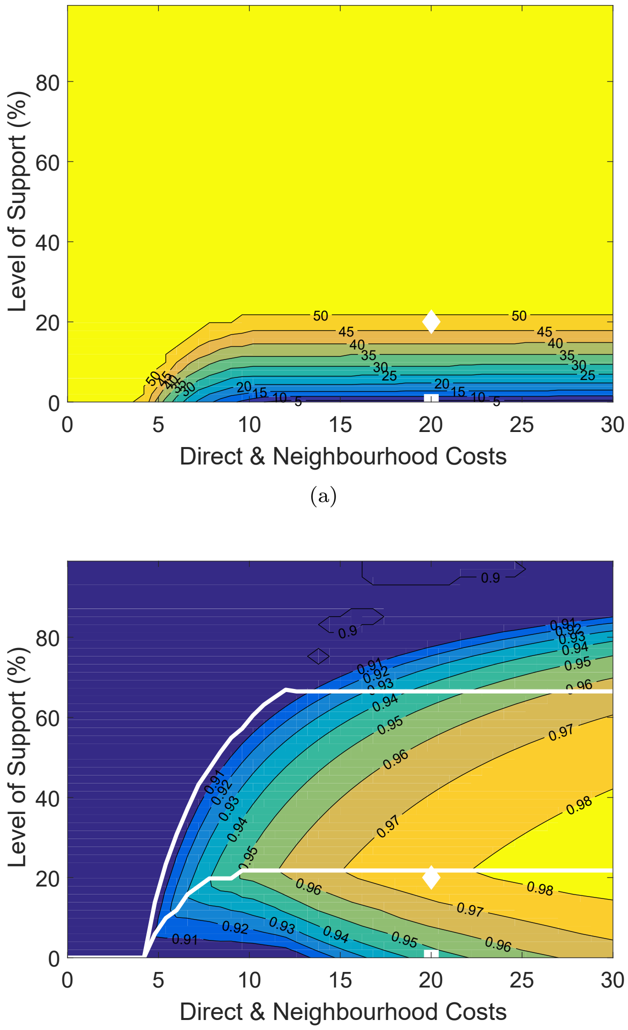
Figure 4. Government support leads to a large stable coalition with a large improvement of biosecurity. Profiles, as a function of coalition size, of (a) farm payoffs and (b) the probability of avoiding infection, for both members and freeriders, where members have both direct and neighbourhood costs 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)

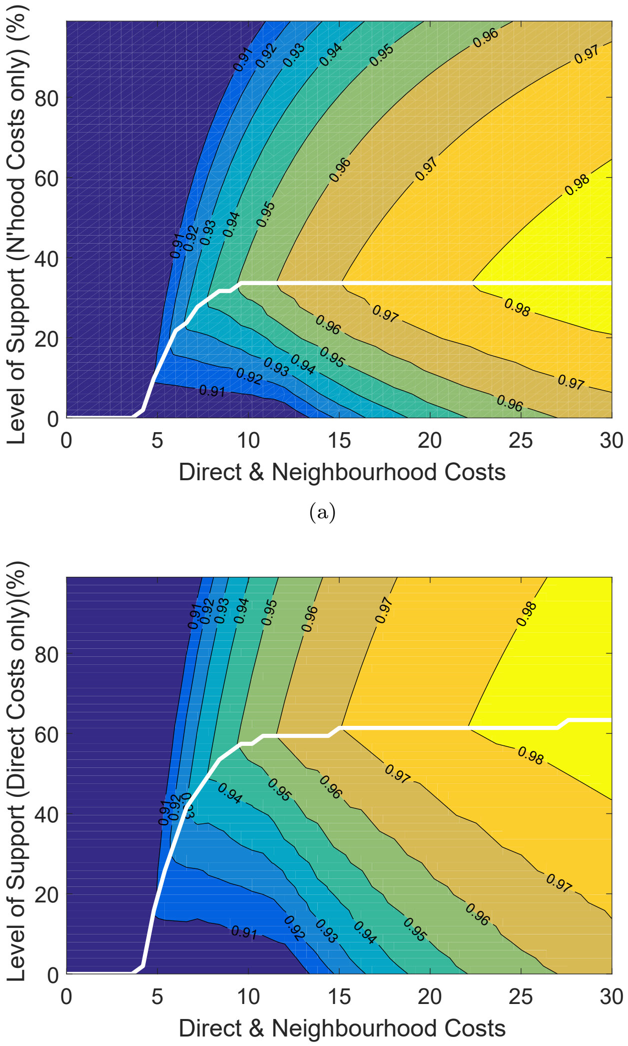
Figure 5. Across various direct and neighbourhood costs, with government support, a large stale coalition forms, often with substantial improvement in biosecurity. Contour plots of (a) the number of members in the stable coalition and (b) overall biosecurity, against direct and neighbourhood costs. Members 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.