# The biosecurity collective-risk social dilemma: Simulating the prevention of a rapidly spreading pest

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## Abstract

Protection against pest invasion is a collective-risk social dilemma. The overall protection in a region of actors depends on the biosecuring actions they each adopt. If too few take protective measures, then the entire region is at risk, since if a pest colonises one property it can quickly spread to neighbouring properties, causing catastrophic economic losses for all. In this paper, we introduce an experimental game—the biosecurity collective-risk social dilemma—for simulating the problem of collective pest management. In the game, four-player groups interact over a series of rounds. In each round, players must decide whether to pay a private cost to take biosecurity action to protect a value at risk. The game is based on a one-shot game-theoretic model of collective pest management developed by Hennessy (2008). According to the model, the incentive to biosecure increases as the invasion risk rises. The opportunity for actors to communicate with one another—so they may provide assurances that they will biosecure if others will do so too—should increase engagement in risk-reducing action. We tested these predictions in an experiment where we manipulated the risk of an outbreak occurring and whether group members could communicate on certain rounds. Consistent with the model, both a higher background risk and communication facilitated biosecurity investments. Communication was effective because it increased trust and provided opportunities to strategically coordinate biosecurity investment strategies. The results suggest additional effort should be directed to improving risk communication and ensuring biosecurity schemes include a strong element of communication.


*Keywords:* biosecurity · communication · collective-risk social dilemma · cooperation · fruit fly · risk

# 1 Introduction

Globalisation, by increasing trade and travel, has increased invasions of exotic agricultural pests and diseases and ecosystems threats, such as Myrtle Rust (Carnegie, 2015), Khapra beetle (Athanassiou et al., 2019), and red imported fire ant (Wylie & Janssen-May, 2017). Alongside exotic pests, farmers worldwide also face evolving endemic threats. The pesticides at their disposal to address these problems are becoming more restricted and many are no longer available (Dominiak & Ekman, 2013). Simultaneously, export market sensitivity to exotic pest risks and pesticide residues is increasing. There is mounting evidence that the standard response, where a farmer takes an individual decision to apply a pesticide, is no longer valid (Bagavathiannan et al., 2019; Garcia-Figuera et al., 2021). A farmer's decision to control a pest cannot be seen in isolation as there are spillover effects for neighbouring farmers and regions. A farmer who chooses to do nothing about a pest—because it is individually rational—imposes costs on their neighbours. Similarly, the efforts of proactive farmers may be dissipated if their neighbours shirk on pest management. For some pests, individual solutions are likely to be short-lived, expensive, or completely ineffective. The solution is cooperative integrated-pest management and area-wide management where coordinated efforts reduce pest populations at the regional level (De Lima et al., 2025; Florec et al., 2013; Tam et al., 2023; Tapsuwan et al., 2020). No pest exemplifies the need for cooperation between farmers more than the global struggle against endemic and exotic fruit flies—fruit flies devastate crops and close export markets, generating losses amongst large groups of farmers (Florec et al., 2013; Sultana et al., 2020; Tam et al., 2023). Export market closure can be triggered by a relatively minor fruit fly outbreak. Even short term export market closures can be very costly for producers of highly perishable products, as it can lead to a complete loss of the crop revenue.

## 1.1 Biosecurity as a public good

Biosecurity is a collective action problem or social dilemma involving a conflict between individual and collective interests (Bagavathiannan et al., 2019; Donaldson, 2008;

Garcia-Figuera et al., 2021; Hennessy, 2008). A social dilemma arises when a group of individuals must cooperate to achieve a shared goal. The collective best outcome arises when all individuals cooperate but because each person can benefit from the cooperation of others, there exists an incentive to defect. In the case of biosecurity, an individual who chooses to biosecure benefits their neighbours by reducing the risk of a pest outbreak that could spread to surrounding properties. Conversely, an individual who does not biosecure imposes costs on their neighbours by increasing this risk. Accordingly, an individual's protection from pest invasion depends on both their actions and those of others in the region. The risk they face is an *endogenous* collective risk—rather than an individual risk—that can only be reduced through cooperation.

Of the various types of social dilemmas, biosecurity is a public goods dilemma, wherein the public good is protection against exotic pest invasion and its provision requires cooperation between individuals who must adopt biosecuring actions that incur private costs. The dilemma arises because an individual's ability to benefit from low pest-invasion risk does not diminish the ability of others in the same affected region to enjoy those benefits (non-rivalry), and no individual in the affected region can be excluded from obtaining the benefits (non-excludable). These properties of the public good render it vulnerable to free riding. That is, a self-interested individual has an incentive not to biosecure, if they think that a majority of their neighbours will biosecure. In this way, they may obtain the benefits of the public good, without paying the costs of its provision. However, if each individual thinks this way, then the public good will never be supplied, resulting in biosecurity inefficiencies.

A valuable laboratory tool for simulating factors affecting the provision of public goods is the public goods game (for reviews, see Chaudhuri, 2011; Ledyard, 2020). In a typical game, there are groups of four players. In each of several rounds, players are endowed with a sum of money and must decide how much to contribute to a public account. Any money contributed gets multiplied by some factor before being distributed equally amongst the players, irrespective of whether they contributed to the public account. Although contributions are typically high on the first round, with players contributing around 50% of their endowment (Fehr & Gächter, 2002; Fischbacher & Gächter, 2010), they sharply decline over subsequent rounds. Contributions also decrease as group size increases because of a greater abundance of free riders (Isaac & Walker, 1988b). In general, public goods experiments reveal that the public good is more often than not undersupplied. Nevertheless, several factors have been shown to increase public good provision, including communication (Dawes et al., 1977; Isaac & Walker, 1988a), inclusion of a contribution threshold or provision point (Isaac et al., 1989; Suleiman & Rapoport, 1988), opportunities for reputation building (Milinski et al., 2002; Semmann et al., 2004), costly monetary punishments (Fehr & Gächter, 2002; Gachter et al., 2008), or social approval (Gächter & Fehr, 1999; Rege & Telle, 2004). The public goods game has therefore provided valuable insights into the conditions under which the provision of public goods is likely to succeed or fail, providing potential solutions for improving the provision of real-world public goods.

However, the public goods game is not an accurate experimental model of the biosecurity cooperation problem for two main reasons. First, in the public goods game, individuals must cooperate to obtain a collective gain—an increase in the welfare of all individuals. By contrast, protection against pest invasion requires individuals to cooperate to avoid a collective loss—a reduction in the welfare of all individuals triggered by an outbreak of pests. Second, the standard game is based on a linear summation public good, where the level of provision depends on the sum of individual contributions. By contrast, protection against pest invasion has been characterised as a weakest-link public good (Burnett, 2006; Hennessy, 2007; Perrings et al., 2002), where the level of provision depends not upon total contributions, but instead on the individual who contributes the least to biosecurity. In such cases, a single weak link can undermine the efforts of others, making overall protection dependent on the lowest contribution.

A prominent game-theoretic model of protection from pest invasion was introduced by Hennessy (2008). His model departs from the strict weakest-link assumption and instead considers strategic interactions between a group of beneficiaries, where individuals weigh the cost of biosecurity against the temptation to free-ride. Biosecurity is a risk-reduction public good in that pest freedom is risky—if a pest invades one property, it quickly spreads to all region's properties, reducing the welfare of everyone in the region—and contributions to the public good are concerned with reducing the risk that an incursion is established. In Hennessy's model, the public good is the joint endogenous probability of remaining pest free; conversely, the public bad is the probability of an incursion. Unlike a strict weakest-link model, the least motivated individual does not necessarily determine the overall level of provision. Instead, total contributions reduce the risk of pest invasion in a continuous, rather than binary, manner. Hennessy (2008) shows that typically the Nash equilibrium for this class of games leads to sub-optimal provision of biosecurity effort, which explains why pest prevention is an under-supplied public good associated with high levels of invasion (Burnett, 2006).

Improving biosecurity provision requires a better understanding of factors that promote or inhibit cooperation. An experimental game designed to study this problem could provide valuable insights. To our knowledge, no such game currently exists. This paper addresses that gap.

## 1.2 Biosecurity collective-risk social dilemma

Here we introduce an experimental game—the biosecurity collective-risk social dilemma (cf. Milinski et al., 2008)—that transports the theoretical model of Hennessy (2008) into an experimental economics framework. Hennessy's model—and our game by extension—applies to a variety of biosecurity situations where cooperation is required to prevent the entry of a pest into a region. However, in this paper, we frame our game in terms of the problem of a group of apple growers seeking to prevent a fruit fly outbreak.

The game involves groups of four players, each representing an apple grower in a region. It is played over multiple rounds, with each round representing a growing season.

In each round, players receive a crop profit and must pay a production cost, which is obligatory. They must also decide whether to pay an additional biosecurity cost to protect their profits, which is voluntary. Players are informed of the risk of an outbreak of fruit fly and must decide whether to invest in biosecurity based on this risk and their beliefs about other players strategies. Investments in biosecurity reduce the risk of pest invasion in a continuous manner—if all players invest, the risk is eradicated. At the end of each round, the possibility of an outbreak is simulated. If no outbreak occurs, a player's payoff is their crop profit minus production and, if applicable, biosecurity costs. If an outbreak occurs, crop revenue drops to zero, and the player incurs a net seasonal loss.

Hennessy's model assumes that the endogenous risk of pest invasion drives biosecurity actions—higher risk increases the incentive to biosecure. To test this, we compared biosecurity investments under two risk treatments—a low-risk and a high-risk treatment. We also included a base-case treatment without communication and a communication treatment in which players could interact via a chat interface in certain rounds. As previous work has shown that communication increases contributions in the public goods game (Brosig & Weimann, 2003; Sally, 1995), we expect a similar effect here, with communication providing a mechanism for fostering trust and coordinating biosecurity efforts.

## 2 Hennessy's (2008) model of biosecurity

The augmented version of Hennessy's (2008) model used in the experiment can be described as follows. He uses a lake as his motivating example, although the model is equally applicable to horticultural pests such as fruit fly. There are multiple firms in a region. If the pest colonises one of the firms, it will immediately reduce the welfare of all firms. There is some biosecurity action, such as field inspections, spraying, or trapping, that eliminates the risk of pest incursion and establishment. All firms benefit from the absence of the pest without rivalry. Non-acting firms cannot be excluded from the benefits. Biosecurity action has a private cost, as engaging in biosecurity effort requires management time and other resources. Each firm's decision depends on what they expect the others to do.

## 2.1 Formal description

Formally, the model is as follows. There are $N$ firms $i \in (1, 2, ..., N)$. Each firm derives a crop profit of $v_i - c_i^p$ and has a cost of biosecurity action of $c_i^b$. A firm that is affected by an incursion loses value $v_i$ but incurs production costs $c_i^p$. The risks that a firm will introduce the pest are independent, identically distributed Bernoulli random variables with realisations of 0 and 1. The probability that a firm is not the source of the incursion varies between $\sigma \in (0, 1)$ and 1. Parameter $\sigma$ can be viewed as the entry risk.

The expected profit for firm $i$ if no firms biosecure is $v_i\sigma^N - c_i^p$. If $k$ firms biosecure, it is $v_i\sigma^{N-k} - c_i^p$. The firm's objective function is:

$$\max[v_i\sigma^{N-k-1} - c_i^p - c_i^b,\, v_i\sigma^{N-k} - c_i^p] \tag{1}$$

That is, the firm compares the expected profit from biosecuring with that from not biosecuring. Biosecuring lowers the invasion risk but incurs a cost.

The marginal private payoff to biosecuring is:

$$\Delta = v_i\sigma^{N-k-1} - c_i^b - v_i\sigma^{N-k} \tag{2}$$

This captures the gain in expected profit from acting. The condition for action is that, $\Delta$>0. By defining $\rho_i = c_i^b/v_i$, the conditions for action become:

$$\sigma^{N-k-1}(1-\sigma) > \rho_i \tag{3}$$

A firm will choose to biosecure if the expected benefit exceeds the cost. Two factors influence this decision. First, the marginal benefit of acting increases with the number of other firms acting. Second, the incentive to act is stronger when $\sigma$ is low (high risk), and weaker when $\sigma$ is high (low risk).

## 2.2 A two-firm example

Consider the case where $v_1 = v_2 = 1$, $c_1^b = c_2^b = 0.4$, and $c_1^p = c_2^p = 0.2$—which mirror the incentive structure used in the experiment—with only two firms. Table 1 presents the expected payoff calculations, while Figure 1 illustrates the expected payoffs and protection probabilities for a subset of illustrative values of the entry-threat parameter. Figure S1 presents payoff matrices for a broader range of values of $\sigma$ (see Supplementary Figures).

Figure 1 shows how the incentive to biosecure increases as the entry-threat parameter decreases (i.e., as entry risk rises). There are two thresholds that divide the entry-threat parameter space into three qualitatively distinct regions, each characterised by a different payoff structure. The first is the dominance threshold, defined by $\sigma = v - c^b = 0.6$. To the left of this threshold ($\sigma \leq v - c^b$), the game is a coordination game with two pure strategy Nash equilibria: a risky equilibrium in which both firms do not biosecure and a safe equilibrium in which both firms biosecure. The Pareto optimal outcome arises when both firms biosecure, making the safe equilibrium *focal* (Schelling, 1980). As $\sigma$ decreases below 0.6—and the risk of an outbreak increases—the salience of the safe equilibrium becomes greater, making mutual biosecuring increasingly psychologically prominent. The theory predicts that in this region, the probability of an outbreak is sufficiently high that each firm knows that it is in their best interest to biosecure and that the other firm knows this too, which should lead to efficient provision of biosecurity.

To the right of the dominance threshold ($\sigma \geq v - c^b$), the dominant strategy for each firm is to not biosecure and mutual non-biosecuring is the unique pure strategy Nash equilibrium. There is a second threshold, the efficiency threshold, which is sensitive to the group size $n$, defined by $\sigma = (1 - c^b)^{1/n} =$ (e.g., 0.77 in the two-player case, 0.88 in the four-player case) that further divides this space. In between the dominance and efficiency thresholds ($v - c^b < \sigma \leq (1 - c^b)^{1/n}$), the game is a classic prisoner's dilemma where mutual biosecuring is the Pareto optimal strategy, yet each firm has an incentive to not biosecure if it expects the other firm to biosecure. The theory predicts that in this region, biosecurity will be under-supplied and associated with high levels of pest outbreaks.

Finally, in the region to the right of the efficiency threshold ($\sigma > (1 - c^b)^{1/n}$), the game no longer involves a social dilemma—mutual non-biosecuring yields higher payoffs than mutual biosecuring and is the Pareto optimal strategy. The theory predicts that in this region, the risk of an outbreak is sufficiently low that firms are better off not biosecuring.

### 2.3 Parameter values and predictions

For the experiment, we chose values of $\sigma = 0.9$ (low risk) and $\sigma = 0.8$ (high risk) for our risk manipulation. These correspond to the no-dilemma region—where mutual non-biosecurity is both individually and collectively optimal—and the prisoner's dilemma region—where non-biosecuring is individually rational, but mutual biosecuring is collectively optimal. The prisoner's dilemma region is of particular interest because it is the region associated with the greatest risk of biosecurity being under-provided, whilst the no-dilemma region provides a baseline for examining behaviour in the absence of a social dilemma.

The theory predicts mutual non-biosecuring in the two risk treatments, as not biosecuring is the dominant strategy and the unique Nash equilibrium in both cases. However, we know that the degree of cooperation in economic games is greater than predicted by standard economic theory. For example, experimental studies of the prisoner's dilemma find that a considerable fraction of players prefer to cooperate rather than defect (Kiyonari et al., 2000; Sally, 1995). Even in the low-risk treatment, players may misperceive the payoff structure and think that some degree of cooperation is warranted. Thus, we predicted a main effect of the risk manipulation: biosecurity investments—the fraction of group members choosing to biosecure—should be higher in the high-risk than the low-risk treatment.

Of critical interest is how the presence versus absence of communication influences biosecurity decisions. Communication affords the opportunity for trust building between players—it allows players to provide assurances to one another that they will cooperate if others are prepared to do so too. If each player is concerned not only about their own payoff, but also that of their co-players, then communication may turn the prisoner's dilemma payoff structure into an assurance game where mutual biosecuring and mutual non-biosecuring are both Nash equilibria. In other words, communication may turn the prisoner's dilemma into a coordination game like that which exists when $\sigma \leq v - c^b$. Which of these Nash equilibria players will coordinate on depends on each players beliefs about what the other players will do.

We predicted that biosecurity investments would be higher in the presence than the absence of communication. We also expected an interaction between the risk and communication manipulations—specifically, that communication would increase investments more in the high-risk than the low-risk treatment.

# 3 Experiment

Ethical approval was granted by the Human Ethics office at the University of Western Australia (UWA) (RA/4/1/6996).

## 3.1 Participants

Ninety-six participants (50% females; mean age = 20.72, SD = 5.26, range = 18 – 23) were recruited from the campus community at the University of Western Australia (UWA). Participants were recruited using the Online Recruitment System for Experimental Economics (ORSEE; Greiner, 2015).

## 3.2 Design

The experiment employed a 2 (risk: low vs. high) × 2 (communication: no communication vs. communication) × 15 (round: 1–15) mixed design: risk and round were within-groups factors, whereas communication was a between-groups factor. Participants were tested in groups of four players. Each group played two 15-round blocks, one under each risk treatment, with block order counterbalanced across groups. Groups were allocated randomly and evenly to the no-communication and communication treatments, resulting in 12 groups for each level of the communication factor.

## 3.3 Apparatus and procedure

Experimental sessions were conducted in the Behavioural Economics Laboratory at UWA, in the presence of the experimenter. At the start of a session, players were randomly seated at interconnected computer terminals running the Zurich Toolbox for Readymade Economic Experiments (z-Tree; Fischbacher, 2007), which was used to register and communicate their decisions during the experiment. The computer terminals were separated by privacy blinds to prevent player collusion. Participants read an information sheet before providing written informed consent. Sessions comprised three parts: a virtual lottery game, the biosecurity collective-risk social dilemma, and a post-game questionnaire.

### *3.3.1 Ex ante virtual lottery game*

Participants first completed a virtual lottery game (see Supplementary Virtual Lottery Game) taken from Tanaka et al. (2016). They were required to choose between playing for the monetary amounts under two different prizes. There were 35 games in total, separated into three play panels of 15, 15, and 5 games. For each game, players were informed of the odds of each prize and prompted to select their preferred prize. The game was included to permit estimation of participants' degree of risk aversion and loss aversion, using cumulative prospect theory (Tversky & Kahneman, 1992), so these estimates could be related with their decisions in the biosecurity collective-risk social dilemma.

### *3.3.2 Biosecurity collective-risk social dilemma*

Next, participants read the experimental instructions for the biosecurity collective-risk social dilemma (see Supplementary Experimental Instructions). The instructions informed each player that they own an apple orchard and are surrounded by three neighbours who also grow apples. They were told that each round of the game represents an apple-growing season and that seasonal revenues are earned on those rounds where no outbreak of pests occurs, whereas if an outbreak occurs, the pests spread quickly and infest all players' orchards, resulting in the loss of that season's revenue. Players were informed that they would have to decide whether to protect (at a cost) or not protect (at no cost) against a pest outbreak at the start of each season. They knew that if all players protected, the pest would be prevented with certainty. Once players had finished reading the instructions, they answered a series of control questions to ensure they understood the rules of play (see Supplementary Control Questions). When the experimenter was satisfied that the questions had been answered correctly, the game commenced.

At the start of the game, each player was assigned a pseudonym. During the game, each player's decisions were communicated to the other players under their designated pseudonym. The procedure for the no-communication treatment was as follows. Each round consisted of a protection-decision stage and a feedback stage. At the start of the protection decision stage, each player's operating account was endowed with a sum of money equal to the revenue generated by their orchard ($v$ = \$25). The decision they had to make— simultaneously and independently—was whether to protect or not protect their orchard against an outbreak of pests, where protection incurred a cost ($c^b$ = \$10). Players also knew that, regardless of whether they chose to protect or not, a seasonal production cost ($c^p$ = \$5) would be deducted from their account at the end of the round. Once all decisions were made, the possibility of an outbreak was simulated. The probability that the pest entered the system was calculated by (Hennessy, 2008):

$$p = 1 - \sigma^{N-k} \tag{4}$$

Where $N$ is the total number of players, $k$ is the number of players deciding to protect, and $\sigma$ is the entry risk parameter, which was set to 0.9 and 0.8 in the low-risk and high-risk treatments, respectively. Table 2 shows how these values of $\sigma$ translate into outbreak probabilities in the two risk treatments, as a function of the number of players choosing to protect. Players were fully informed of these probabilities before the game began. It can be seen from Table 2 that each player's decision to protect increases the probability that they are not the originator of pest entry $\sigma \in (0, 1)$. A random number $r \in$

(0, 1) was subsequently drawn from a uniform distribution to determine whether an outbreak occurred. If $r \leq p$, then an outbreak occurred and all $v$ were lost; otherwise an outbreak was prevented and all $v$ (minus expenses) were retained. The four possible revenue outcomes for each round are summarised in Table 3.

In the feedback stage, players were informed whether an outbreak occurred and which players chose to protect or not protect under their assigned pseudonyms. They were also told their revenue for the current round and the balance of their operating account, which represented the cumulative sum of the revenue obtained across all rounds completed so far in the current block. Upon entering the second block, the players operating accounts were reset to zero. Players were informed that their previously accrued earnings were not lost and would be paid at the end of the experiment in conjunction with any additional revenue acquired in the forthcoming block.

In the communication treatment, the procedure was the same as described above except that preceding the protection-decision stage on the first, sixth, and eleventh rounds of both the low-risk and high-risk treatments, players had the opportunity to communicate with each other via a chat terminal. Conversations lasted for two minutes (countdowns were visible to players) and during that time, players were free to discuss task-related and task-unrelated topics. Chatroom conversations were monitored by the experimenter and players were instructed not to use abusive language or offer side payments to induce cooperation.

#### *3.3.3 Ex post questionnaire*

Experimental sessions concluded with a brief questionnaire. Two self-report measures of risk and loss aversion were included to compare with the estimates from the virtual lottery game. To assess risk aversion, participants were asked to "Imagine you have \$40. With a probability of 50%, you will lose all \$40. You can avoid the risk by giving away \$20 of the \$40. Would you pay the \$20 to avoid the risk?". Responses (0 = no, 1 = maybe, 2 = yes) were used to classify participants as risk-seeking, risk-neutral, or risk-averse. To assess loss aversion, participants rated how well the statement "I generally hate to lose something more than I like to gain something" described them (1 = does not describe me at all, 7 = describes me perfectly).

Participants also completed general and situational trust measures. General trust was measured using the Generalized Trust Scale (Yamagishi & Yamagishi, 1994). The scale contains six-items (e.g., "Most people are trustworthy") and participants indicated the extent to which they agreed or disagreed with each statement (1 = strongly disagree, 5 = strongly agree). Situational trust was measured by asking participants how much they trusted each group member (1 = no trust, 5 = a lot of trust).

To identify player strategies, participants were asked to indicate which of six different factors was most important to their decision of whether to protect or not: (1) "I thought that other players would not protect, so I didn't see why I should either" (non contributor); (2) "I thought others would protect and I could benefit without having to protect myself" (free rider); (3) "I tried to avoid incurring monetary losses" (loss averse); (4) "I thought the other players would choose to protect, so I protected as well" (conditional cooperator); (5) "I thought that choosing to protect was the right thing to do, regardless of what other players decided" (moral cooperator); (6) "I didn't know what others were going to do and thought it was worth the risk of taking protective action" (worthwhile cooperator).

Experimental sessions lasted approximately 60 minutes. At the end of each session, participants were paid a $5 show-up fee and the outstanding balances of their operating accounts in cash. A 10% conversion was applied to the experimental profits to calculate the actual cash payments. For example, a player who earned $195 would receive $19.50. This conversion rate was explained in advance.

# 4 Results

## 4.1 Biosecurity investments

We begin by examining biosecurity investments in the different experimental treatments across successive rounds of the game. The top panel of Figure 2 shows the fraction of players choosing to protect, averaged across groups, as a function of risk, communication, and round. Since scores on the dependent variable represent proportions calculated by averaging over the binomial responses (protect vs. not protect) of individual players within groups, and then across groups, conventional parametric procedures based on a Gaussian distribution, such as Analysis of Variance (ANOVA), are not suitable for our data. Accordingly, we chose to analyse the data using a Generalized Linear Model (GLM). Using the *glm* package in R (family = binomial; weights = 4), we constructed and compared three nested models: one containing only the main effects of risk, communication, and round (main-effects model); a second containing the main effects and the two-way interactions (two-way interaction model); and a third containing the main effects, two-way interactions, and the three-way interaction (three-way interaction model). Model comparisons revealed that the three-way interaction model did not provide a better fit than the two-way interaction model, $\chi^2_{df=712} = 0.01$, $p = .915$, but the two-way interaction model provided a better fit than the main-effects model, $\chi^2_{df=713} = 29.21$, $p < .001$. Accordingly, we interpret the data in terms of the two-way interaction model.

There was a reliable main effect of risk, $\beta = 1.47$, $SE = 0.19$, $p < .001$, with investments being higher in the high-risk than the low-risk treatment, a reliable main effect of communication, $\beta = 0.88$, $SE = 0.20$, $p < .001$, with investments being higher in the communication than the no-communication treatment, and a reliable main effect of round, $\beta = –0.06$, $SE = 0.02$, $p = .001$, with investments decreasing gradually over rounds.

There was a significant risk × communication interaction, $\beta = 0.67$, $SE = 0.17$, $p < .001$, with communication yielding a greater increase in investments in the high-risk than the low-risk treatment. There was a significant risk × round interaction, $\beta = –0.05$, $SE =$

0.02, $p$ = .008, with investments being relatively stable over rounds in the low-risk treatment, whereas investments decreased over rounds in the high-risk treatment. Finally, there was a significant communication × round interaction, $\beta = 0.04$, $SE = 0.02$, $p = .032$, which arose because the benefits of communication increased gradually over rounds.

### 4.2 Outbreak frequency

We next examine how the frequency of outbreaks varied across the different treatments. The proportion of outbreaks, averaged over groups, as a function of risk, communication, and round is shown in the middle panel of Figure 2. Since the dependent variable is once again binomially distributed (no outbreak vs. outbreak), we analysed the data using the same procedure as in our preceding analysis. However, because the dependent variable comprises values of 0 or 1, rather than proportions, it was not necessary to specify weights for each observation. We again compared three models, a main-effects model, a two-way interaction model, and a three-way interaction model. Model comparisons revealed that the three-way interaction model did not provide a better fit than the two-way interaction model, $\chi^2_{df=712} = 0.04$, $p = .656$, which in turn did not provide a better fit than the main-effects model, $\chi^2_{df=713} = 0.24$, $p = .748$. Accordingly, we interpret the data in terms of the main-effects model.

The main effect of risk was nonsignificant, $\beta = -0.04$, $SE = 0.03$, $p = .180$, suggesting that the increased biosecurity investments in the high-risk treatment reduced the frequency of outbreaks to a level comparable to the low-risk treatment. There was also a significant main effect of communication, $\beta = -0.20$, $SE = 0.03$, $p < .001$, with fewer outbreaks occurring in the communication than the no-communication treatment. However, the main effect of round was nonsignificant, $\beta = 0$, $SE = 0$, $p = .892$.

### 4.3 Group payoffs

So far, we have shown that a high risk of an outbreak occurring, and the opportunity for communication between players, facilitate biosecurity investments. Communication also reduces the frequency of outbreaks. Next, we ask whether the risk and communication manipulations affected group payoffs. The bottom panel of Figure 2 shows the average total group payoffs as a function of risk, communication, and round. We again analysed the data using a GLM, this time specifying a Gaussian distribution for the dependent measure, and compared a main-effects model, a two-way interaction model, and a three-way interaction model. Model comparisons revealed that the three-way interaction model did not provide a better fit than the two-way interaction model, $\chi^2_{df=712} = 927.2$, $p = .472$, which in turn did not provide a better fit than the main-effects model, $\chi^2_{df=713} = 3568.1$, $p = .575$. We therefore interpret the data in terms of the main-effects model.

There was a reliable main effect of risk, $\beta = -7.03$, $SE = 3.15$, $p = .026$, with group payoffs being lower in the high-risk than the low-risk treatment. Thus, the price of the increased investments in the high-risk treatment was a reduction in total group payoffs. There was also a reliable main effect of communication, $\beta = 6.92$, $SE = 3.15$, $p = .029$, with group payoffs being higher in the communication than the no-communication treatment, but the main effect of round was nonsignificant, $\beta = 0.56$, $SE = 0.37$, $p = .125$.

### 4.4 Risk aversion, loss aversion, trust, and player strategies

We now examine whether player decisions were affected by their degree of risk aversion, loss aversion, and trust in their group members, as well as the dominant strategies driving their decision making.

We begin by examining the association between each individual player's biosecurity investments and their level of risk and loss aversion, as indexed by their preferences in the virtual lottery game, and their responses on the self-report items. For the analysis based on responses in the virtual lottery game, player's prize preferences in the three play panels were used to estimate the value of two parameters, using an augmented version of cumulative prospect theory (Tversky & Kahneman, 1992) incorporating the one parameter form of Prelec's (1998) weighting function (for a description of the parameter estimation procedure, see Tanaka et al., 2016). The two parameters were $\sigma$ and $\lambda$, which represent, respectively, the concavity of the value function, corresponding to the degree of risk aversion, and the degree of loss aversion (higher values of $\sigma$ and $\lambda$ correspond to greater degrees of risk and loss aversion).

The resulting individual parameter values were correlated with each player's biosecurity investments—averaged over rounds—in the low-risk and high-risk treatments separately. The correlation between risk aversion and biosecurity investments was negative in both treatments but nonsignificant: $r(94) = -.17$, $p = .108$ for the low-risk treatment, and $r(94) = -.01$, $p = .909$ for the high-risk treatment. Similarly, the correlation between loss aversion and biosecurity investments was nonsignificant in both treatments: $r(94) = .10$, $p = .358$ for the low-risk treatment, and $r(94) = -.00$, $p = .981$ for the high-risk treatment.

For the second analysis, based on responses to the self-report measures, the correlation between risk aversion and investments in the low-risk treatment was nonsignificant, $r(94) = .12$, $p = .228$. However, in the high-risk treatment, the correlation was significant, $r(94) = .23$, $p = .022$, suggesting that more risk-averse individuals invested more in biosecurity compared to those with risk-neutral or risk-seeking preferences. The correlations between loss aversion and biosecurity investments were negative in both the low-risk and high-risk treatments, but neither reached statistical significance: $r(94) = -.12$, $p = .252$, and $r(94) = -.06$, $p = .550$, respectively.

Overall, these findings suggest that risk aversion influences biosecurity decisions primarily under high-risk conditions, but its effect depends on the measurement method used—self-reported risk aversion was positively associated with biosecurity investments in the high-risk treatment, whereas the parameter-based measure did not capture this relationship. In contrast, loss aversion showed no significant association with biosecurity investments across either method.

Turning to trust, Figure 3 shows average participant responses on the general (left panel) and situational (right panel) trust measures for the no communication and communication treatments. Communication reliably increased both types of trust, albeit more so for situational trust, $t(94) = –5.56$, $p < .001$, than general trust, $t(94) = –3.19$, $p = .001$.

Finally, the strategies adopted by players are shown in the bottom panel of Figure 3. The dominant strategy adopted by players in both the no-communication and communication treatments—occurring in roughly equal proportions—was loss aversion. The proportion of players adopting the free rider, moral cooperator, and worthwhile cooperator strategies was comparable in the two treatments. However, the communication treatment was associated with a decrease in the non contributor strategy and an increase in the conditional cooperator strategy. This suggests that in the absence of communication, players had low expectations of cooperation from their group members, whereas in the presence of communication those expectations were increased.

To determine whether there were significant differences between the communication treatments in their strategy choices, a series of Fishers Exact Tests were performed. There was a significant difference between no-communication and communication treatments for the non-contributor strategy, $p = .006$, and the conditional-cooperator strategy, $p < .001$. All other comparisons were non-significant, $p = 1.000$ for all tests.

### 4.5 Contents of communication

To understand how communication improved cooperation, we undertook a text mining and sentiment analysis of the contents of group conversations in R (packages used: *snowball*, *syuzhet*, *tidytext*, *tidyverse*, *tm*, and *wordcloud*).

We imported the data and cleaned the text by removing special characters and whitespace before converting it to lower case. We then removed stop words (e.g., “the”, “and”) and stemmed words to their root forms.

Next, we constructed a word-frequency matrix. The top-left panel of Figure 4 shows a word cloud of the 100 most frequent words, with size indicating frequency. The top five words were “protect” (226), “round” (90), “risk” (73), “good” (58), and “yes” (45).

We used the AFFIN lexicon (Nielsen, 2011) to assign each word a sentiment score ranging from –5 (negative) to +5 (positive). The top-right panel of Figure 4 shows a sentiment-coded word cloud of the 100 most frequent words, with positive words in grey and negative words in black. It can be seen that the words "risk" and "outbreak" were the strongest contributors to negative sentiment, while "protect" contributed most to positive sentiment. Despite the higher concentration of negative words, the median sentiment score for the corpus was positive (1).

To understand the context of the top three words, we conducted a word-association analysis using a .15 correlation threshold to capture the most salient associations. "Protect" was not associated with any word, indicating that the context in which it was used was highly variable. Manual inspection revealed that it was largely used as a declaration to protect, to protect in a given situation (e.g., for a given risk level or round), or in the context of asking whether the group should protect, or whether a particular group member would protect.

"Risk" was strongly associated with "low" (.63) and "high" (.53), and more weakly with "part" (.21) and "tage" (.21)—terms referring to the low-risk and high-risk blocks. These associations arose because group conversations, especially at the start of each block, focused on the risk level. Groups recognised that different strategies were required in the low-risk and high-risk treatments, and the first round of communication in each block involved groups negotiating what actions should be taken, given the risk level. "Risk" also had associations with "take" (.3) and "reckon" (.24). These associations arose because statements involving the word "risk" were often made in the context of deciding whether the group thought ("*reckon*ed") they should "take" action to protect.

"Round" had associations with "two" (.22), "everi" (the root of "every"; .22), and "person" (.18), reflecting a common strategy amongst groups, which entailed rotating protection over rounds in pairs, such that two players would protect, and two would not protect, on one round, before switching on the next. Variants of this strategy involved rotating protection in one's (low-risk treatment) and in three's (high-risk treatment).

Another strategy in the high-risk treatment, again reflected in the association between "round" and "every", was to protect on every round. "Risk" also had associations with "first" (.16) and "next" (.17), which reflects the efforts of groups to coordinate who would protect "first" or "next" in the subsequent set of rounds, given use of an alternation strategy. Finally, "round" was associated with "last" (.29). This association arose in the context of announcements that over the forthcoming set of rounds, groups should repeat what they did over the "last" set of rounds.

Lower frequency negative words (e.g., "nasty", "traitor", "trick"), appeared when group members criticised players who had reneged on their pledges to protect. These instances were rare—most participants honoured their pledges. Lower frequency positive words (e.g., "cool", "glad", "happy") were associated with celebrations of successful group outcomes.

Finally, we used the NRC Emotion Lexicon (Mohammad & Turney, 2010; Nielsen, 2011) to classify words into eight emotion categories (anger, fear, anticipation, trust, surprise, sadness, joy, and disgust). Figure 5 shows the proportion of words falling into each emotion category. Anticipation had the highest proportion of words (22.5%), followed closely by trust (18.5%). This meshes well with our earlier results demonstrating that communication facilitates the building of trust between group members. Disgust had the smallest proportion of words (5.4%). Positive emotions (trust and joy) accounted for 32% of words, whereas negative emotions (disgust, fear, and sadness) accounted for 21% of words.

In sum, conversations revealed that groups used communication to set goals and coordinate strategies. While some naming and shaming occurred when players broke pledges, emotion analysis suggests trust was relatively high overall.

## 5 Discussion

In this paper, we introduced a novel experimental game—the biosecurity collective-risk social dilemma—for simulating the problem of collective pest management. Based on the game-theoretic model proposed by Hennessy (2008), the game serves as an experimental vehicle for testing its assumptions and examining the broader factors that influence self-organisation and cooperation in biosecurity contexts. According to the model, the incentive for a group of actors in a region to adopt biosecurity measures increases as the invasion risk rises. Furthermore, when biosecurity is at risk of being undersupplied, opportunities for communication may strengthen biosecurity efforts by allowing actors to reassure one another of their commitment to cooperation.

Using the game, we tested these predictions by co-manipulating the invasion risk and opportunities for communication. We also examined the link between player behaviour and psychological variables—including loss aversion, risk aversion, and trust—and sought to identify the dominant strategies in the game, comparing how they differed with and without communication. Finally, we analysed the content of communication to understand how players used it to coordinate their actions.

### 5.1 Overview of key findings

Consistent with Hennessy's (2008) model's predictions, both the risk and communication manipulations had an overall effect on collective biosecurity decisions—biosecurity investments were greater in the high-risk than the low-risk treatment, and with versus without communication. As predicted, there was also an interaction—communication had a stronger effect under high risk. Communication not only increased biosecurity investments, it also reduced the frequency of outbreaks and increased group payoffs.

Turning to the association between biosecurity investment decisions and psychological variables, the results with respect to risk aversion were mixed. Using the self-report measure, we find evidence that under conditions of high risk, risk aversion promotes biosecurity investments. However, using the parameter-based measure based on the virtual lottery game, we find no reliable association between risk aversion and biosecurity investments. Loss aversion, though the most commonly cited strategy, showed no reliable relationship with investment decisions. This discrepancy suggests that although individuals consciously perceive loss aversion as an important factor in their decision-making, it may not translate into consistent behavioural responses across players.

A key finding that sheds light on why communication was so effective is that players in the communication treatment reported higher levels of social trust in their group members than those in the no-communication treatment. This shift in trust was accompanied by reliable changes in two of the six self-reported strategies—specifically, a decrease in the non contributor strategy and an increase in the conditional cooperator strategy. These findings suggest communication increased trust and helped to establish a social norm of conditional cooperation.

These psychological changes brought about by the availability of communication are not the only reasons underpinning its effectiveness. The computational text analysis revealed that it was also used as a strategic coordination device. Groups typically negotiated strategies that were tailored towards the risk level and struck a balance between minimising collective biosecurity costs and maximising revenues. A popular strategy involved rotating biosecurity investments across rounds in pairs. Variants of this strategy included rotating investments individually in the low-risk treatment and in triplets in the high-risk treatment.

## 5.2 Implications of findings

Collective pest and disease management is of critical importance to Australian agriculture. Specific examples of long-standing collective pest management or area-wide management schemes include the Central Burnett QFly zone (Lloyd, 2007), and Vinehealth Australia (2025). These schemes are run by highly sophisticated industry organisations that manage communication with industry and the general public, as well as technical requirements for border protection and eradication (Kruger, 2017, 2021). These schemes engage in intensive communication about best practice, the extent of pest incursions, and regional border protection activities. Communications are to two groups—to commercial producers to advise them about incursions and export restrictions; and the general public, especially gardeners, to encourage them to reduce the risk of pest incursions.

Linking this study to those schemes, the communication simulated in the experiment was equivalent to that between commercial producers. It had the effect of increasing investments in collective biosecurity, thereby reducing overall risk. Communication during pest outbreaks and at other times tends to be formal and top-down from the coordinating organisation to producers. Our study indicates that there is also a critical role for communication between producers, possibly moderated by the coordinator. Indeed, a defining feature of the more effective area-wide management schemes for QFly is strong two-way communication, including frequent face-to-face interactions between producers and other stakeholders (e.g., crop consultants, researchers, and members of the public) to build trust. Regions with strong communication networks are characterised by high levels of participation and cooperation, whereas regions with weak networks are characterised by low levels of participation and greater free riding (Kruger, 2016a, 2016b). Although observational studies cannot confirm causality, our controlled experiment provides direct evidence that communication between producers is a likely causal driver of cooperation in area-wide management efforts and should be considered a core component of such programmes.

Turning to the risk manipulation, our results demonstrate the sensitivity of biosecurity collective action to the threat level. If the risk of an outbreak is low—or is perceived to be low—then this may lead to suboptimal levels of biosecurity effort. This novel finding has important implications for horticultural pest prevention and management in Australia and beyond. It suggests that additional effort should be devoted to investigating ways in which risk could be communicated better to avoid producers making pest management decisions based on distorted levels of perceived risk.

In an experiment, it is possible to communicate accurate risk measurements. Risk assessments change behaviour and given that a producer may have multiple biosecurity threats, they need to prioritise the allocation of management effort and resources. The risk concept that arises in this experiment and causes most conceptual difficulty to game participants is the joint probability of pest freedom—the idea that maintaining pest-free status depends not on individual action alone, but on the collective action of all producers. To our knowledge this is not a concept that is typically communicated by biosecurity organisations. A focus on this would highlight how potentially damaging free riding is not just in a single production season, but over many seasons if export markets are lost.

### 5.3 Potential limitations and future directions

One limitation of our current game is the binary nature of biosecurity decisions—players must choose either to biosecure or not. This contrasts with real-world biosecurity practices, where producers can calibrate their efforts depending on the level of perceived risk. Notably, some group strategies observed in the game—such as alternating cooperation in pairs across rounds—can be seen as an attempt to approximate partial effort. For example, producers facing low perceived risk might agree to spray only a portion of their crops. Our decision to simulate biosecurity in binary terms was intentional, aligning with Hennessy's (2008) model, which also treats biosecurity as an all-or-nothing choice. Nonetheless, extending the model and game to incorporate a continuum of effort would enhance their ecological validity and permit the observation of more nuanced strategic behaviour.

In this experiment, we examined the impact of risk and communication on collective biosecurity decision making. However, the game can readily be adapted to model the impact of other key variables. Hennessy's (2008) model, for example, makes specific predictions regarding the impact of heterogeneity in biosecurity costs and values at risk, the role of leadership, and the effect of large group interactions—where behaviour is expected to depart from that observed in smaller groups. Future work could extend the game to test these variables.

### 5.4 Conclusions

We introduced a novel experimental game—the biosecurity collective-risk social dilemma—for simulating the biosecurity collective action problem. We showed that the perception of risk and opportunities for communication influence biosecurity investments. Higher risk increased investments, while communication further enhanced biosecurity efforts by increasing trust, promoting conditional cooperation, and facilitating strategic coordination. These effects reduced the frequency of outbreaks and improved group payoffs. Together, the results provide empirical support for Hennessy's (2008) model, which predicts that biosecurity decisions are sensitive to entry risk and can be improved through communication. The results underscore the importance of effective risk communication and regular discussions between producers in real-world pest management schemes, and suggest new opportunities for strengthening biosecurity protections. Future iterations of the game could examine additional variables that promote or inhibit collective biosecurity efforts and draw out their implications for real-world practice.

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**Table 1**

Calculation of expected payoffs and protection probabilities for each combination of firm strategies.

| | | Firm 2 Strategy | |
|---|---|---|---|
| Firm 1 Strategy | Outcome | Biosecure | Not biosecure |
| **A** | | | |
| Biosecure | Expected Payoff | $\{\pi_1 = v_1 - c_1^b - c_1^p, \pi_2 = v_2 - c_2^b - c_2^p\}$ | $\{\pi_1 = \sigma v_1 - c_1^b - c_1^p, \pi_2 = \sigma v_2 - c_2^p\}$ |
| | Protection Probability | 1 | $\sigma$ |
| Not biosecure | Expected Payoff | $\{\pi_1 = \sigma v_1 - c_1^p, \pi_2 = \sigma v_2 - c_2^b - c_2^p\}$ | $\{\pi_1 = \sigma^2 v_1 - c_1^p, \pi_2 = \sigma^2 v_2 - c_2^p\}$ |
| | Protection Probability | $\sigma$ | $\sigma^2$ |

**Table 2**

*Probability of an outbreak of pests as a function of risk treatment and number of players choosing to protect.*

| | Number of players choosing to: | | |
|---|---|---|---|
| Risk treatment | Protect | Not protect | Probability of an outbreak |
| Low risk | 0 | 4 | 0.34 |
| | 1 | 3 | 0.27 |
| | 2 | 2 | 0.19 |
| | 3 | 1 | 0.10 |
| | 4 | 0 | 0 |
| High risk | 0 | 4 | 0.59 |
| | 1 | 3 | 0.49 |
| | 2 | 2 | 0.36 |
| | 3 | 1 | 0.20 |
| | 4 | 0 | 0 |

**Table 3**

*Payoffs on each round as a function of whether a player chooses to protect and whether an outbreak of pests occurs.*

| | Revenue outcome | |
|---|---|---|
| Player decision | No outbreak | Outbreak |
| Protect | $v - c^b - c^p$ = \$25 – \$10 – \$5 = \$10 | $v - c^b - c^p$ = \$0 – \$10 – \$5 = –\$15 |
| Not protect | $v - c^p$ = \$25 – \$5 = \$20 | $v - c^p$ = \$0 – \$5 = –\$5 |

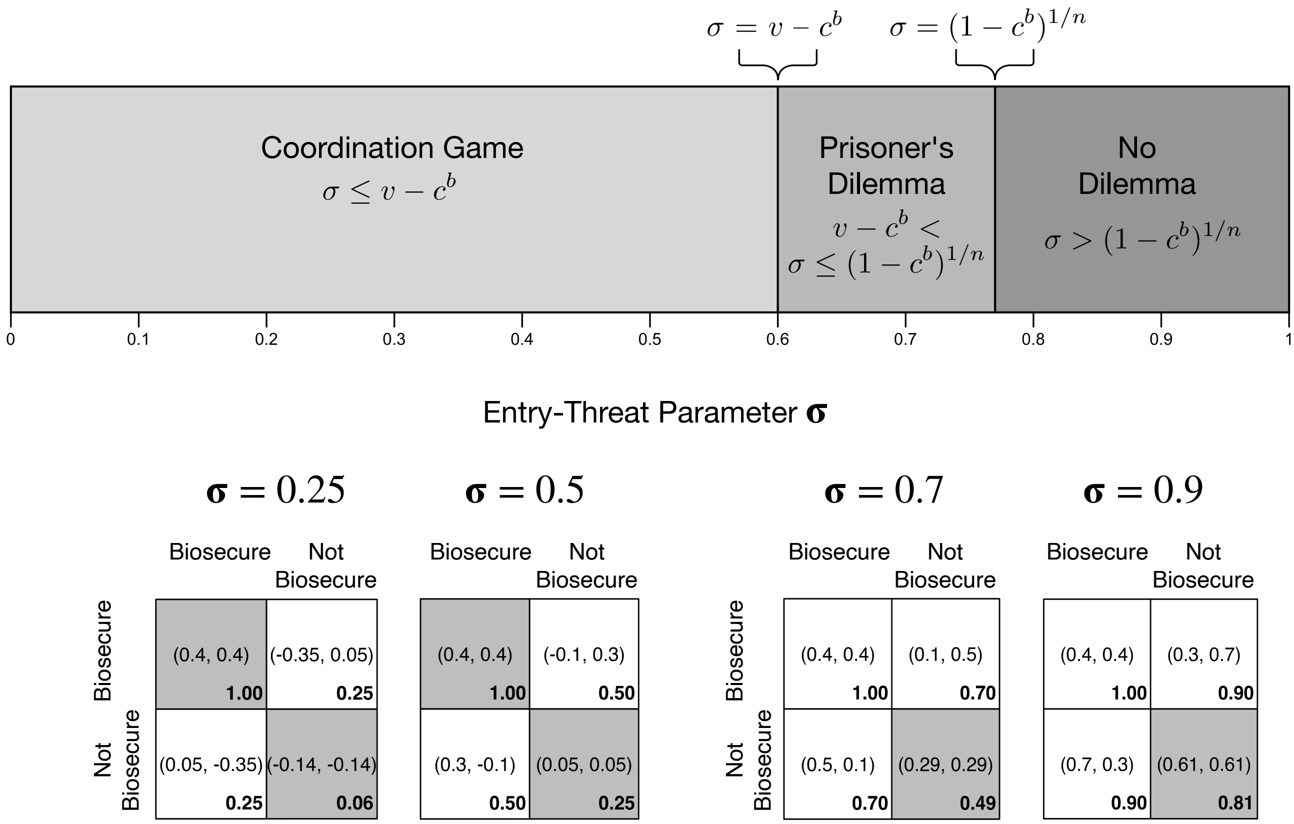


**Figure 1**

*The three regions of the entry-threat parameter space, each illustrated with one or more payoff matrices. In the matrices, bold-face values represent protection probabilities, and shaded cells represent pure strategy Nash equilibria.*

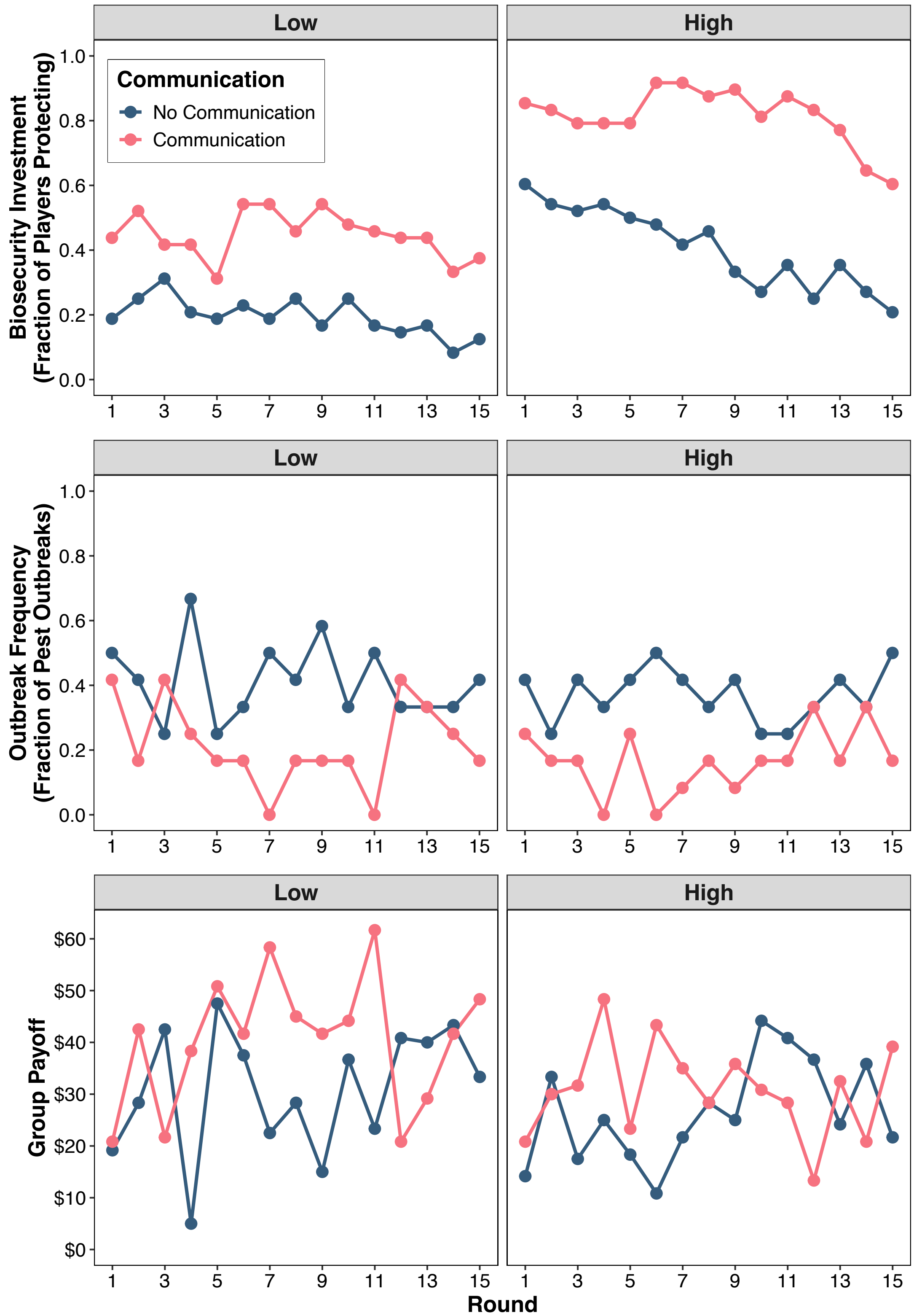


**Figure 2**

*Biosecurity investments (top panel), outbreak frequency (middle panel), and group payoffs (bottom panel) as a function of risk, communication, and round.*

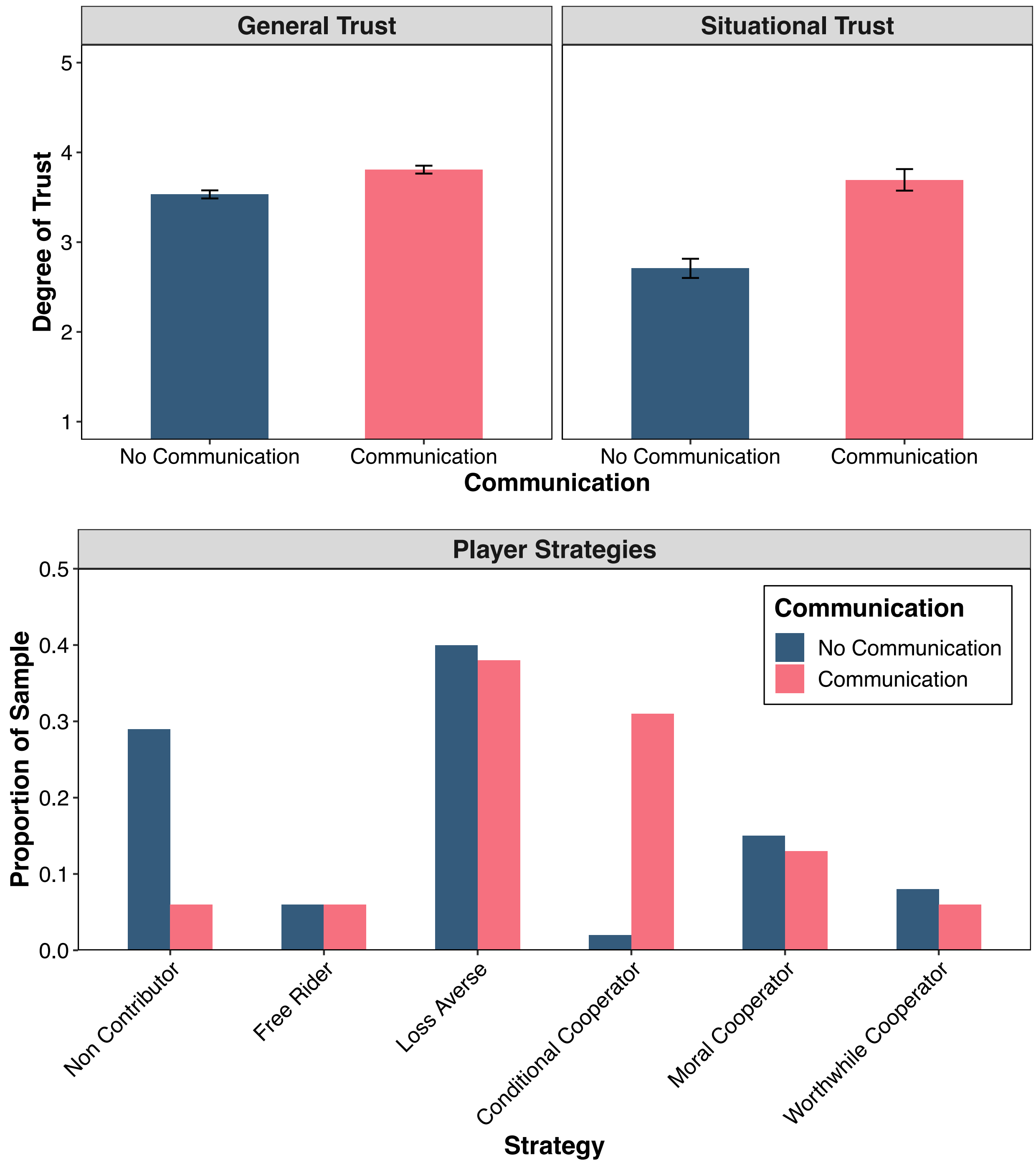


**Figure 3**

*General and situational trust ratings (top left and top right panels, respectively) and player strategies (bottom panel) as a function of communication.*


**Figure 4**

*Word clouds of the communication text corpus. The left cloud shows the 100 most frequent words, ignoring sentiment, whereas the right cloud shows the 100 most frequent positive and negative words.*

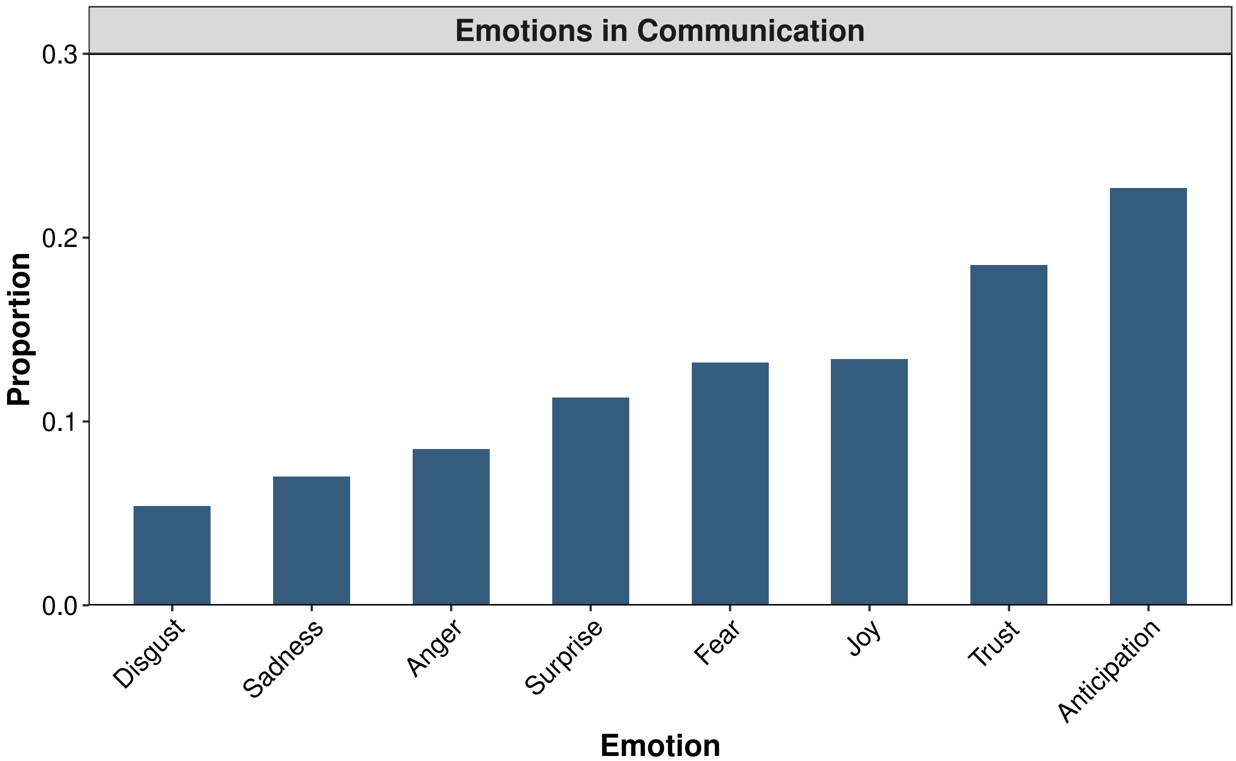


**Figure 5**

*Proportion of words in the communication text corpus associated with each emotion.*