



Asymmetric public goods game cooperation through pest control



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ABSTRACT

Cooperation in a public goods game has been studied extensively to find the conditions for sustaining the commons, yet the effect of asymmetry between agents has been explored very little. Here we study a game theoretic model of cooperation for pest control among farmers. In our simple model, each farmer has a paddy of the same size arranged adjacently on a line. A pest outbreak occurs at an abandoned paddy at one end of the line, directly threatening the frontier farmer adjacent to it. Each farmer pays a cost of his or her choice to an agricultural collective, and the total sum held by the collective is used for pest control, with success probability increasing with the sum. Because the farmers' incentives depend on their distance from the pest outbreak, our model is an asymmetric public goods game. We derive each farmer's cost strategy at the Nash equilibrium. We find that asymmetry among farmers leads to a few unexpected outcomes. The individual costs at the equilibrium do not necessarily increase with how much the future is valued but rather show threshold behavior. Moreover, an increase in the number of farmers can sometimes paradoxically undermine pest prevention. A comparison with a symmetric public goods game model reveals that the farmer at the greatest risk pays a disproportionate amount of cost in the asymmetric game, making the use of agricultural lands less sustainable.

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1. Introduction

Land abandonment is a major issue for Japanese agriculture. There is evidence that global warming is impacting the geographic range, winter mortality, and number of generations per year of certain insects (Kiritani, 2006). In addition, the Japanese government's rice cropping restrictions in the 1970s brought about an increase in the prevalence of rice bugs, which reproduce in fallow fields (Kiritani, 2007). Rice bugs damage crops by sucking on the developing kernels of rice grains, causing a chalky discoloration at the head of the grain (Kiritani, 2007). As part of a plan to increase the rate of food self-sufficiency, the Ministry of Agriculture, Forestry and Fisheries releases annual statistics on the area of dilapidated farmland in Japan, as well as how much of that land can be restored. In the years 2011–2015 (the most recent years for which the statistics are available), the portion of land that can be restored has been steadily decreasing, while the portion of land that cannot has been increasing (MAFF, 2015).

Because pests can move from paddy to paddy, pest control is not just an individual issue of a single farmer but can potentially cause a public problem among farmers in the same geographical area. Inspired by this motivation, we consider a simple game theoretic model for pest control among farmers in order to study the conditions for the establishment of cooperation. In our model, farmers contribute to a collective fund (such as a local agricultural cooperative) that is used to control an active pest outbreak coming from an abandoned paddy. In particular, our model is a public goods game where the agents are *asymmetric* in their roles due to their different geographical positions from the pest outbreak. It is therefore worthwhile to study whether the asymmetry promotes or suppresses cooperation and to clarify the conditions under which such cooperation is established.

Asymmetric public goods games have not been studied as much as their symmetric counterparts. Hauert et al. (2004) and Sigmund (2010) listed various mechanisms for sustaining cooperation in public goods games, such as punishment (Boyd et al., 2003; Boyd and Richerson, 1992; Brandt et al., 2003; Fowler, 2005; Henrich and Boyd, 2001), reputation (Brandt et al., 2003; Suzuki et al., 2007), an outside option (Boyd and Mathew, 2007; Brandt et al., 2006; Fowler, 2005; Hauert et al., 2007; Sasaki et al., 2012), and

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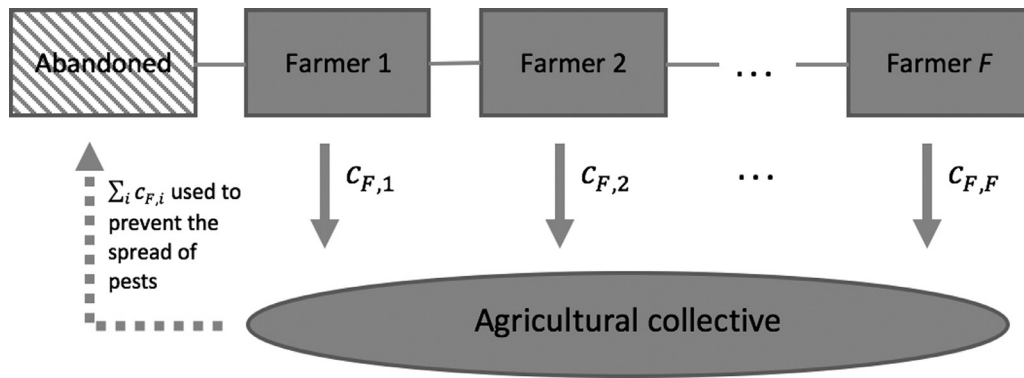


Fig. 1. The model for pest control. Each farmer pays an annual cost of his or her choice to an agricultural collective, which uses the farmers' money to prevent the spread of pests.

the effects of finite populations (Hauert et al., 2007; Sigmund et al., 2010). Archetti et al. (2011) provided a comparison between linear and non-linear public goods games. Recently, the effect of asymmetry in public goods games has started to draw attention. For example, Kun and Dieckmann (2013) showed that resource asymmetry greatly promotes cooperation. Vasconcelos et al. (2014) showed that inequality makes cooperation easier to achieve, but homophily, the tendency to imitate like agents, can lead to its collapse.

Our model addresses the increasing interest in applying ecological dynamics to the dynamics of social or human decision-making (Lee et al., (2015); Lee and Iwasa, 2014; Rodrigues et al., 2009; Satake and Iwasa, 2006; Satake et al., 2007; Suzuki and Iwasa, 2009). One of the key parameters in such systems is the *future discount factor*, which represents how much the human agents discount their future benefit. For example, Satake et al. (2007) have shown that a long-term management perspective (i.e. not discounting the future too much) is necessary to prevent deforestation and promote socially desirable land use.

The main goal of our paper is to see the effects of asymmetry on the realized level of cooperation as well as on the individual decision-making of each farmer. In particular, we derive the Nash equilibrium strategy of each farmer as a function of (i) the total number of farmers and (ii) his or her relative position from the abandoned paddy. We then use this to examine the conflicts between the farmers arising from asymmetry. We show how the farmers' decision-making is crucially affected by the future discount factor: if it is below a threshold value, then the farmers farthest from the abandoned paddy do not contribute.

2. Model

2.1. Pest invasion dynamics and discount factor

To model an asymmetric public goods game, we assume that there are initially F farmers cultivating their respective paddies at the one-dimensional lattice points $x = 1, 2, \dots, F$. At $x = 0$, there is an abandoned paddy with a pest infestation, directly threatening the frontier farmer (farmer 1). In each year $t = 1, 2, 3, \dots$, each farmer i pays a cost $c_{F,i}$ of his or her choice to an agricultural collective. The first subscript F represents the total number of farmers remaining in the game, and the second subscript i represents the farmer's distance from the abandoned land. The total sum held by the collective, $\sum_{i=1}^F c_{F,i}$, is used to prevent the spread of pests to neighboring paddies. We assume for simplicity that the pest can spread to at most one neighboring paddy each year, so that farmer 1 is at risk in year $t = 1$ but all the other farmers are safe that year. Fig. 1 summarizes our model.

The probability that pest control is successful is determined by a monotonically increasing function p of the amount of money held by the collective. (We discuss the precise form of p after this section.) If pest control is successful, each farmer reaps his or her harvest and gets revenue, which is normalized to unity throughout this paper. On the other hand, if pest control is unsuccessful, pests invade the frontier farmer's paddy, causing the frontier farmer to obtain no harvest and to abandon his or her land. (The premise behind this assumption is that pests are very expensive to eliminate once introduced.) That paddy is then infected with pests from the next year onward, acting as another abandoned paddy. Any paddy that is not on the frontier is safe from pests that year and yields a successful harvest, but its distance from the abandoned lands decreases by one.

Each farmer has a *yearly discount factor* of δ , where $0 \leq \delta \leq 1$. For simplicity, we assume the discount factor is the same for all farmers. This means that each farmer's benefit in year t is weighted by the factor δ^{t-1} . Observe that $\delta = 0$ corresponds to extreme nearsightedness (farmers only care about the current year), while $\delta = 1$ corresponds to extreme farsightedness (farmers care about all years equally). The average number of years the farmers care about is given by the infinite series $\sum_{t=1}^{\infty} \delta^{t-1} = 1/(1 - \delta)$, so, for example, $\delta = 0.8$ means that the farmers care about on average the next five years, including this year.

2.2. Pest control function

The pest control function $p(c)$ gives the probability that pest control is successful given an input cost c from the collective. We require that p be an increasing function with the properties $p(0) = 0$ (no effort, no prevention), $\lim_{c \rightarrow \infty} p(c) = 1$ (infinite effort, perfect prevention), and $p''(c) < 0$ (diminishing return). For ease of calculation, throughout this paper we assume

$$p(c) = \frac{kc}{1 + kc}, \tag{1}$$

where $k > 0$ is a fixed parameter that quantifies the *ease of pest control*.

Note that the parameter k determines the initial slope: $p'(0) = k$. Another way to understand k is that the cost needed for the probability of prevention success to be 50% is $c = 1/k$, and therefore $1/k$ measures the difficulty of pest prevention. Although p implicitly depends on k , we suppress this in our notation. Fig. 2 below shows a graph of this function for different values of k .

2.3. The farmers' strategies

Each farmer seeks to maximize his or her own benefit, defined as revenue from the harvests minus costs paid to the collective.

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