



Australian Government
**Australian Bureau of Agricultural
and Resource Economics**

ABARE CONFERENCE PAPER 05.4

The emergence and failure of cooperation in the management of invasive species

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49th Annual Conference of the Australian Agricultural and
Resource Economics Society
Coffs Harbour, 8–11 February 2005

Invasive weeds and pests can impose significant commercial costs on the agricultural sector. Because the benefits of eradication largely accrue to individual landholders, the role for government intervention is likely to be limited. This paper uses a multi-agent system approach to model the role of negotiation and cooperation between individual landholders managing an incursion of an invasive species. The role for public intervention is explored when the total level of investment in eradication falls below the optimal level due to the biological characteristics of the invasive species, the institutional arrangements in place and high information and transaction costs.

ABARE project 2777
ISSN 1447-3666

Introduction

Invasive weeds and pests can impose significant commercial costs on the agricultural sector as well as causing environmental damage. Where environmental damage is likely to occur there is a clear case for government intervention to attempt to eradicate or contain the incursion, thereby minimising the cost imposed on the environment. Where an incursion requires the adoption of large scale border control measures or the establishment of quarantine boundaries there may also be a role for public intervention to limit the spread of the incursion.

In cases where an incursion has occurred on a relatively small scale and there are substantial commercial or private benefits associated with eradicating or otherwise managing the incursion, the role for government intervention is likely to be limited. For example, in Australia, community catchment groups have been established to facilitate cooperation between individual landholders, with limited public assistance. However, where the biological characteristics of an invasive species, the institutional arrangements in place, and the information and transaction costs impede such cooperation, there may be a role for more direct government intervention in incursion management.

This paper explores the role of negotiation and cooperation between individual landholders to manage an incursion of an invasive species, investigating the extent of the role for public intervention when the total level of investment in eradication falls below the optimal level due to high transaction and information costs.

The development of a model within a multi-agent system framework enables simulation of the interactive behaviour of landholders over time. This in turn makes it possible to investigate the extent of cooperation and the potential role for government in the eradication of an invasive species.

Multi-agent software

The model was developed using Cormas, a spatial natural resource and agent based simulation modelling framework based within the VisualWorks programming environment, which allows for the development of applications in the object oriented language, SmallTalk (CIRAD 2003).

A number of programming environments can be used to model multi-agent systems. Cormas was selected because it is a platform focused on the building of simulation models where individuals and groups of individuals share, or are located on, a common resource. The established library features, including a strong focus on the visualisation of agents and their behaviour, facilitate quick model development.

The Cormas development platform contains three modules. In the first module each of the entities within the system are created, and their interactions with other entities are defined. The second module coordinates the overall dynamics, particularly the sequence

of events. The third and final module enables the programmer to define the points of view from which the model can be observed.

The model is spatial in nature, with a grid of square cells representing individual plots of land, each of which is managed by a separate landholder. The invasive species spreads across the plots of land, driven by a cellular automata (CA) process. Landholders are assumed to behave in a way that maximises the net return to their land over time.

The incursion model

The growth of an invasive weed or pest is modelled as a logistic growth function. Let x , in the interval 0–1, be the proportion of the property infested with the following functional form:

$$x_{t+1} = x_t + \alpha x_t(1 - x_t)(x_t - \gamma) , \quad (1)$$

where α is a growth rate parameter and γ is a threshold parameter. The growth equation has two stable attractors at 0 and 1 and an unstable repeller at γ . For values of x_t greater than γ the density of the infestation will approach 1, at values below γ the infestation will die out.

The introduction of the invasive species from an external source is represented by a non-negative stochastic disturbance, ξ , added to the growth equation:

$$x_{t+1} = x_t + \alpha x_t(1 - x_t)(x_t - \gamma) + \xi_t . \quad (2)$$

For tractability it is assumed that ξ is distributed exponentially:

$$f(\xi) = \frac{1}{\beta} \exp\left(\frac{-\xi}{\beta}\right) , \quad (3)$$

noting that the distribution of ξ is truncated to ensure the density of the infestation is bounded by one.

Given the infestation will die out if the level of infestation is below the critical level γ , the stochastic disturbance term determines the expected inter-arrival time between when an incursion is eradicated and when it becomes reestablished.

Spread of the incursion

The spread of the incursion between properties is modelled as a CA process. It is assumed that the likelihood of the spread of the incursion to the i th property or cell

from its neighbours, $j \in J$, is a stochastic function of the density of infestation in the j th cell. We redefine the mean, β , of the stochastic disturbance ξ as a state variable:

$$\beta_{i,t} = \omega_0 + \sum_{j \in J} \omega_1 x_{j,t} , \quad (4)$$

where ω_0 is a constant or background contribution to the likelihood of infestation from a source outside the neighbourhood and ω_1 is the weight of the expected contribution from neighbouring properties.

The growth function is then modified so that the infestation density at property i is influenced by the infestation density of neighbouring properties $j \in J$:

$$x_{i,t+1} = x_{i,t} + \alpha x_{i,t}(1 - x_{i,t})(x_{i,t} - \gamma) + (\omega_0 + \sum_{j \in J} \omega_1 x_{j,t})\epsilon , \quad (5)$$

where ϵ is a random standard exponential variable.

The management problem

The property manager's problem is set out as simply as possible. Let s be a constant net annual return from the farm or other property enterprise. Let u_t be the discrete choice to eradicate or to not eradicate the invasive species at time t and c be the cost of eradication, which is independent of the level of infestation. The profit maximisation problem faced by the property owner is then:

$$\max_u \sum_{t=0}^{\infty} \frac{1}{(1 + \delta)^t} [s(1 - x_t) - cu_t] \quad (6)$$

subject to

$$\begin{aligned} x_{t+1} &= \begin{cases} +\xi_t & \text{if } u_t = 1 \\ x_t + \alpha x_t(1 - x_t)(x_t - \gamma) + \xi_t & \text{otherwise} \end{cases} \\ x_0 &= 0 , \end{aligned} \quad (7)$$

where δ is the discount rate.

The optimality condition, given by Bellman's equation, requires that the value function, $V(x_t, u_t)$, satisfies:

Table 1: **Parameter values**

α	growth rate parameter	1.0
γ	threshold parameter	0.5
ω_0	constant background contribution to the likelihood of infestation	0.0
ω_1	weight of the expected contribution from neighbouring properties	0.08
δ	discount rate	0.05
s	constant net annual return to land	\$500
c	constant cost of eradication	\$2000
u	decision to eradicate	[0,1]

$$V(x_t, u_t) = \max \left\{ s(1 - x_t) + \frac{1}{(1 + \delta)} E[V(x_t + \alpha x_t(1 - x_t)(x_t - \gamma) + \xi_t)], \right. \\ \left. s(1 - x_t) - c + \frac{1}{(1 + \delta)} E[V(+\xi_t)] \right\}, \quad (8)$$

where E is the expectations operator. The optimality condition simply implies that the expected increase in revenue from eradicating the infestation is greater than the cost. The increase in revenue depends inversely on the likelihood that the infestation will become reestablished and the rate at which the infestation will again reach its current level.

Uncertainty regarding the level of infestation in any given period means that this stochastic optimal control problem does not appear to have a tractable analytical solution. Rather, a numerical technique is required to find a solution.

The numerical collocation technique was chosen because it is ideally suited to this type of problem, which can be considered a variation of the asset replacement problem (Miranda and Fackler 2002). Essentially, the technique solves the problem for many different levels of infestation, generating a vector or matrix of optimal strategies. For a description of the collocation method see Miranda and Fackler (2002).

Optimal management

Using the CompEcon MATLAB toolbox developed by Miranda and Fackler (2002) the numerical solution to this problem identifies the critical infestation density x^* at which it is worth eradicating the incursion given the parameter values listed in table 1.¹

The critical infestation density x^* reflects the point at which it becomes optimal to invest in eradicating the infestation. Where the level of infestation is linked to the infestation of neighbouring properties and two or more neighbours choose to eradicate, both benefit from the action of this as it reduces the likelihood of the weed or

¹MATLAB is a registered trademark of The MathWorks, Inc.

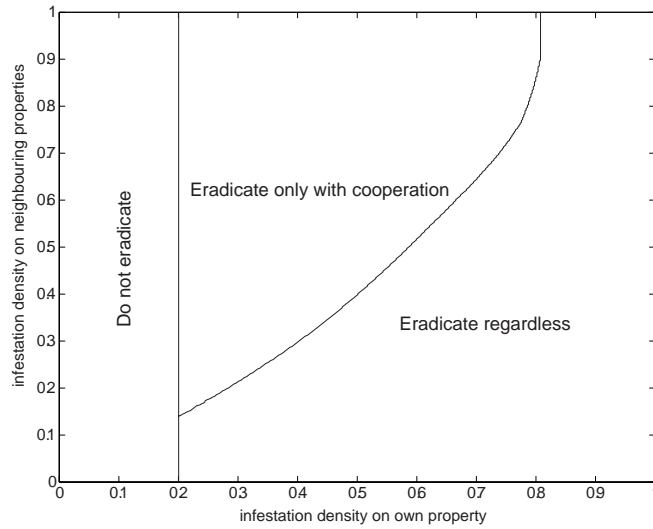


Figure 1: Eradication decision matrix

pest becoming reestablished on all properties. More precisely, the value of cooperative eradication is derived through an increase in the expected time before a new incursion becomes reestablished. Hence landholders have a greater economic incentive to eradicate if they cooperate.

This can be seen in the following numerical example where it is assumed that two neighbours are willing to jointly eradicate. Assuming that the landholder of neighbouring property j is also willing to eradicate, the landholder of property i will eradicate when the infestation density on his or her property is greater than or equal to 0.2004.

Relaxing the assumption that the landholder of property j is willing to eradicate it is possible to calculate the range of infestation densities on properties i and j at which the landholder of property i will choose to eradicate, even without cooperation from the landholder of property j . By combining these two cases it is possible to identify the region over which eradication will occur if landholders are able to negotiate with one another. Figure 1 shows the resulting eradication decision matrix for the two property case.

At infestation levels below 0.2004, the landholder of property i will not eradicate the incursion, regardless of the level of infestation on the neighbouring property j .

When the infestation density increases beyond 0.2004 it can be optimal to eradicate regardless of the action taken by one or more neighbouring landholders, or it can be optimal to only eradicate with cooperation. The region of cooperation captures the combinations of infestation levels where the benefits of eradication are outweighed by the potential for reinfestation unless one or more of the neighbouring properties also chooses to eradicate.

While both neighbours have an increased incentive to eradicate when the infestation on one property influences the level of infestation on the other, the expected return

from eradication to each landholder varies if the level of infestation on their respective properties is different. Those with lower levels of infestation are less likely to choose to cooperatively eradicate and remain a source for the continued spread of the incursion.

Development of the Cormas model

The incursion model and the model of optimal landholder behaviour presented in the previous sections were incorporated into an agent based model with a set of rules to govern the negotiation process between landholders. To start the initial incursion, four of the one hundred plots are assumed to have an infestation level of 0.6 at the beginning of the simulation. The value of 0.6 was chosen for the plots that represent the source of the incursion so that the level of infestation was above the threshold parameter below which it would die out.

In each time step, the infestation grows and spreads, and landholders are faced with a decision to eradicate or not based on the level of infestation on their property and on their neighbouring properties.² This decision is arrived at through an iterative procedure. At each time step t , a preliminary eradication decision is made based only on the level of infestation on each landholder's own property, not taking into consideration the infestation level on neighbouring properties. That is, for infestation levels below 0.2004 a landholder's preliminary eradication decision is to do nothing. For infestation levels above 0.8050 landholders decide to eradicate regardless of whether or not their neighbours cooperate. For all other infestation levels landholders are assigned a preliminary eradication decision of 'maybe'. Based on the infestation level at each of the plots with a decision of 'maybe', the threshold value — the level of infestation across neighbouring properties below which a landholder switches from 'do only with cooperation' to 'do regardless' — is obtained from the decision matrix.

By iterating over all plots of land until there is convergence, any landholder with a preliminary eradication decision of 'maybe' with neighbours that have low enough levels of infestation, or with neighbours who choose to eradicate even without cooperation is evaluated. If the level of infestation across the neighbouring properties is below the threshold value for a particular plot, the landholder chooses to eradicate.³ For more detail on how this cooperation algorithm was implemented see the pseudo code in appendix A.

The visualisation component of the Cormas development environment makes it possible to observe spatial patterns over time. The level of infestation at each plot of land is represented by gradation of colour so that the increasing intensity of an infestation can be graphically observed. A visualisation of the eradication decisions occurring in each time step was also constructed to observe spatial patterns in cooperative behaviour.

²Because of the grid based implementation, 8 neighbouring cells or plots contribute to the level of infestation.

³The method of negotiation implemented in this paper is one of many ways that a process of negotiation and cooperation could be represented.

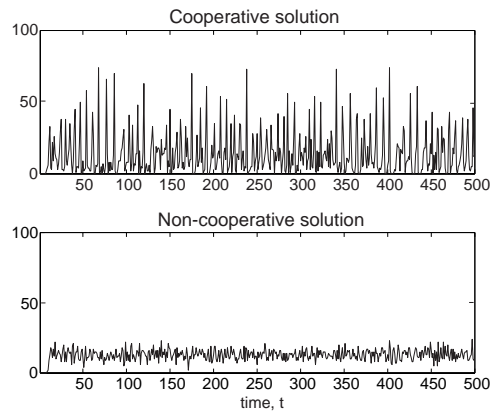


Figure 2: Number of cells/landholder plots eradicated

Simulation results

The results of the simulation depend on the assumption made about the willingness of landholders to cooperate with their neighbours. Two alternative scenarios were constructed to represent the extremes of this problem. In the first scenario it is assumed that there is no cooperation between individual landholders at all. That is, any landholder with an eradication decision of ‘maybe’ is assumed to not eradicate, regardless of the action taken by any neighbouring landholders. In the second scenario it is assumed that all landholders are willing to cooperate. That is, any landholder who has made a preliminary eradication decision of ‘maybe’ is willing to eradicate if sufficient cooperation from their surrounding neighbours can be obtained.

These scenarios represent the least optimistic and most optimistic situation. While they are not particularly realistic, they form a benchmark against which other, more realistic, scenarios can be compared and they enable estimation of the value of cooperation. More realistic scenarios could be constructed by assuming only a random proportion of landholders are willing to undertake cooperative action with their neighbours.

Each of the two scenarios were run on a 10 by 10 grid (that is, 100 plots each managed by a single landholder) over 500 time steps. The results presented in this section were obtained from a single simulation. Figure 2 shows the number of landholders that choose to eradicate in each time step. Much higher levels of joint eradication are obtained under the cooperative scenario, although it is interesting to note that the cooperative behaviour is not sufficient to completely eradicate the weed infestation entirely. The pattern of eradication under the cooperative scenario is highly variable over time, with peaks where more than 50 per cent of all landholders eradicate in a single time step, followed by short periods of time where very few landholders choose to eradicate. The level of joint eradication is much lower in the non-cooperative scenario, with fewer than 25 landholders choosing to eradicate in any one time step.

The total number of times landholders eradicated weeds on their properties were roughly similar for both the cooperative and non-cooperative scenarios. Despite this,

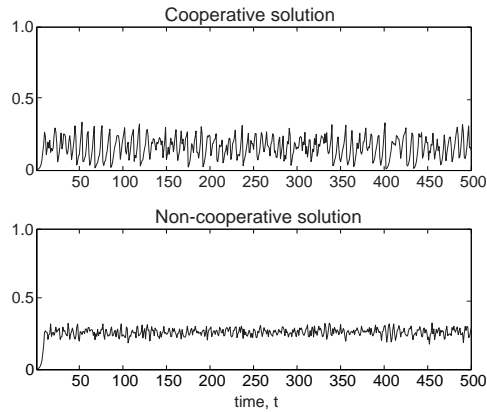


Figure 3: Average level of infestation across grid

the average level of infestation over the period is higher, and thus economic returns to the land lower, when landholders fail to cooperate compared with the scenario where they do cooperate (Figure 3).

Figure 3 shows the average level of infestation across the entire grid over the 500 time periods. The average infestation level over time is consistent with the eradication pattern observed in Figure 2. For the cooperative solution, infestation levels tend to peak at around 25 per cent before cooperative eradication lowers the overall level infestation. On average, the level of infestation across the grid for the entire time period is around 16 per cent for the cooperative scenario.

In contrast, the average level of infestation for the non-cooperative solution is less variable. Infestation levels across the entire grid are persistently around 25 per cent.

Discussion

The results presented in the section above reveal an outcome that is socially suboptimal if landholders are unable or unwilling to undertake cooperative weed eradication on their properties. Where landholders do not cooperate, the average level of infestation is, on average, higher than the cooperative scenario. This occurs despite the fact that roughly similar levels of expenditure are incurred on eradication activities.

The acquisition of information regarding the level of infestation on neighbouring properties is not costless, and neither is process of negotiation. These factors are likely to contribute to the failure of cooperative action and the resulting socially suboptimal outcome, despite the fact that individual landholders are operating to maximise their own net economic returns. Any action to reduce these information and transaction costs is therefore likely to facilitate increased cooperation and generate a better overall outcome.

The simulation framework enables estimation of the value of cooperation in economic

terms, which in turn provides a benchmark against which government action to increase the level of cooperation can be assessed. The simulation framework can also be used to investigate the tradeoff between the gains from facilitating cooperation against the associated cost. Given the likely diminishing marginal returns and increasing marginal costs associated with greater levels of cooperation, the optimal level of cooperation is likely to be something less than one hundred per cent.

Further work

The results presented in this paper represent a preliminary investigation of the role of landholder cooperation in the management of an invasive species such as a weed incursion. Several improvements will be made to increase the representation of the system including the incorporation of infestation density dependent eradication costs.

A number of extensions to the current modelling framework may also lead to further insights into both the rationale and role for government intervention in the management of an invasive species such as a weed incursion. For example, a ‘coordinating’ agent could be incorporated into the model who seeks to find groups of landholders that could benefit from collective eradication. The investigation of alternative negotiation strategies may also provide further insights.

Appendix A: Cormas model pseudo code

The following pseudo code describes the way in which the multi-agent model of landholder cooperation was implemented.

```

Initialisation {
    Set infestation levels to nil
    Load decisionMatrix
    Load thresholdVector
    Decide on scenario: cooperative, non-cooperative, intermediate
}

Step: t {
    Calculate growth and spread of incursion
    Look up preliminary eradication decision in decisionMatrix
    based only on own infestation level: yes, no, maybe
    If ‘maybe’, get thresholdValue from thresholdVector
    Iterate until convergence {
        convert ‘maybe’ to ‘yes’ where neighbourhood infestation <
        thresholdValue}
    For cooperative scenario {

```

```

    Assume all 'maybe' cells are 'yes'}
For non-cooperative scenario {
    Assume all 'maybe' cells are 'no'}
For intermediate scenario {
    Assume a proportion of all 'maybe' cells are 'yes' and the
    rest are 'no'}

Intermediate scenario only {
    No-to-Yes iteration until convergence {
        Convert 'maybe' assumed to be 'no' to 'yes' where
        neighbourhood infestation < thresholdValue}}
Intermediate and cooperative scenarios only {
    Yes-to-No iteration until convergence {
        Convert 'maybe' assumed to be 'yes' to 'no' where
        neighbourhood infestation > thresholdValue}}
Update infestation level based on stabilised eradication
decision
}

```

References

- CIRAD 2003, '*Cormas: Natural Resources and Agent-Based Simulations*'. Montpellier, France, (cormas.cirad.fr/indexeng.htm).
- Miranda, M. and Fackler, P. 2002, '*Applied Computational Economics and Finance*'. MIT Press, Massachusetts.