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Original Article

Managing Risk and Increasing the Robustness of Invasive Species Eradication Programs

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Abstract

Invasive species eradication programs can fail by applying management strategies that are not robust to potentially large but non-quantified risks. A more robust strategy can succeed over a larger range of possible values for non-quantified risk. This form of robustness analysis is often not undertaken in eradication program evaluations. The main non-quantified risk initially facing Australia's fire ant eradication program was that the invasion had spread further than expected. Earlier consideration of this risk could have led to a more robust strategy involving a larger area managed in the program's early stages. This strategy could potentially have achieved eradication at relatively low cost without significantly increasing known and quantified risks. Our findings demonstrate that focusing on known and quantifiable risks can increase the vulnerability of eradication programs to known but non-quantified risks. This highlights the importance of including robustness to potentially large but non-quantified risks as a mandatory criterion in evaluations of invasive species eradication programs.

Key words: invasive species, eradication, robustness

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1. Introduction

An increase in the transport of non-indigenous species with growth in international trade and tourism is increasing the number of biological invasions potentially warranting eradication. Successful eradication programs can provide substantial benefits by preventing damage to the environment, agriculture and human health and by eliminating the need for ongoing control (Pimentel et al. 2005). Many eradication programs fail because they commence too late, after too much spread has occurred or because of insurmountable logistical difficulties such as pest detectability problems (Simberloff 2009). Other eradication programs fail because of avoidable management errors. These include the application of ineffective treatment methods ('treatment failure') and the application of control efforts over an insufficient area to achieve eradication ('delimitation failure') (Panetta & Lawes 2005). The primary focus of this study is on these two forms of risk and how to optimally balance them in developing eradication and suppression strategies.

Avoidable management errors can reflect a lack of information about specific invasion attributes. Underestimating how far an invasion has spread, and the mortality of treatment methods, can lead to delimitation failure, and treatment failure, respectively. Two approaches for mitigating these risks are to gather more information and to apply eradication strategies that are less vulnerable ('more robust') to uncertainty (Moffitt et al. 2008; Davidovitch et al. 2009; Rout et al. 2009; Carrasco et al. 2010). The latter approach is of particular relevance when there are large costs in reducing uncertainty, such as the high cost of monitoring a large area to reduce uncertainty about an invasion's spatial extent. Robustness to uncertainty about a specific invasion attribute depends on the extent to which that attribute can take a worse value than expected without causing the eradication or suppression program to fail. Failure is typically defined relative to a specific performance standard (Rout et al. 2009), such as the risk of falling below a minimum required probability of eradication. Robustness is maximised when the worst 'tolerable' value of the attribute cannot be increased/decreased any further without causing performance to fall below its minimum required level.

Here, we demonstrate how a focus on addressing known and quantified risks of an eradication program failing can reduce the program's robustness to unknown or non-quantified risks. To do so, we focus on an eradication program facing both the known and quantified risk of treatment failure and the known but non-quantified risk of delimitation failure. In the program we considered, the first of these risks was addressed by applying large amounts of pesticide to known infestations. This reduced resource availability for addressing the potential, but non-quantified, risk of delimitation failure by reducing the resources available for expanding the area searched and treated. The implications of this reduction in the area managed were not estimated in quantitative terms because it was not known when the invasion commenced, or the frequency of long-distance dispersal events. In contrast, the risk of treatment failure was estimated based on past experience with the relevant treatment method. These circumstances are common, reflecting that it is often more difficult to estimate the boundary of an invasion than the mortality of treatment.

Our main aim is to demonstrate how a focus on addressing known and quantified risks can increase an eradication program's vulnerability to known but non-quantified risks that often receive less attention in program design. Our secondary aim is to assess the extent to which this adverse outcome can emerge as a by-product of commonly used eradication program evaluation methods. These include scientific evaluations of eradication feasibility and economic evaluations of program costs and benefits. To address these aims, we consider a case study focusing on Australia's largest eradication program, the campaign to eradicate red imported fire ants (*Solenopsis invicta*). We take the novel approach of comparing evaluations and management actions taken at different stages of the program with a previous reconstruction of the fire ant invasion. This reconstruction estimated that the program's failure to eradicate the invasion reflected delimitation failure (Keith & Spring 2013) and it provided estimates of the likely spatial extent of the invasion over time. This information allows us to estimate whether a more robust eradication strategy could have achieved eradication while the invasion was small enough to eradicate with available resources.

2. The Queensland Fire Ant Eradication Program

2.1 Background

The red imported fire ant (*S. invicta*, hereafter 'fire ants') is one of the world's worst invasive species (Lowe et al. 2000), with annual control costs and damages in the United States alone ranging from \$1 billion (Pimentel et al. 2005) to more than \$6 billion (Lard et al. 2006). The species was discovered in Australia in 2001 and an eradication program commenced soon after (Moloney & Vanderwoude 2002). There was severe uncertainty about how far the invasion had spread because the large infestations found when the invasion was first discovered implied that spread may have begun long before eradication efforts commenced. Further uncertainty arose from the possibility that fire ants made long-distance 'jumps', which are known to occur with this species (Porter et al. 1988). This uncertainty is likely to have been of pivotal importance in the program's failure to delimit the invasion. Delimitation has only recently been achieved despite prior expenditure of $300 million since the program commenced.

2.2 Eradication Strategies

The initial eradication strategy was adaptive in the sense that the locations searched and treated were modified as new detections were made. Delimitation was to be achieved by progressively expanding the searched and treated areas until the invasion's boundary is reached. Increasing the areas treated and searched each year increases the likelihood that more distant infestations will be detected if they exist, but this would have required a reduction in the number of rounds of repeat treatment, reducing the probability of eradication arising solely from the risk of treatment failure.

The initial eradication strategy was to apply broadcast pesticide baits ('baiting') over known infestations and nearby areas without searching those areas. Surveillance was carried out within a specific distance of treated areas to determine whether any infestations existed outside those areas. Any detections made with this approach triggered additional treatment and surveillance near detection points, resulting in a gradual expansion of the managed area (Figure 1).

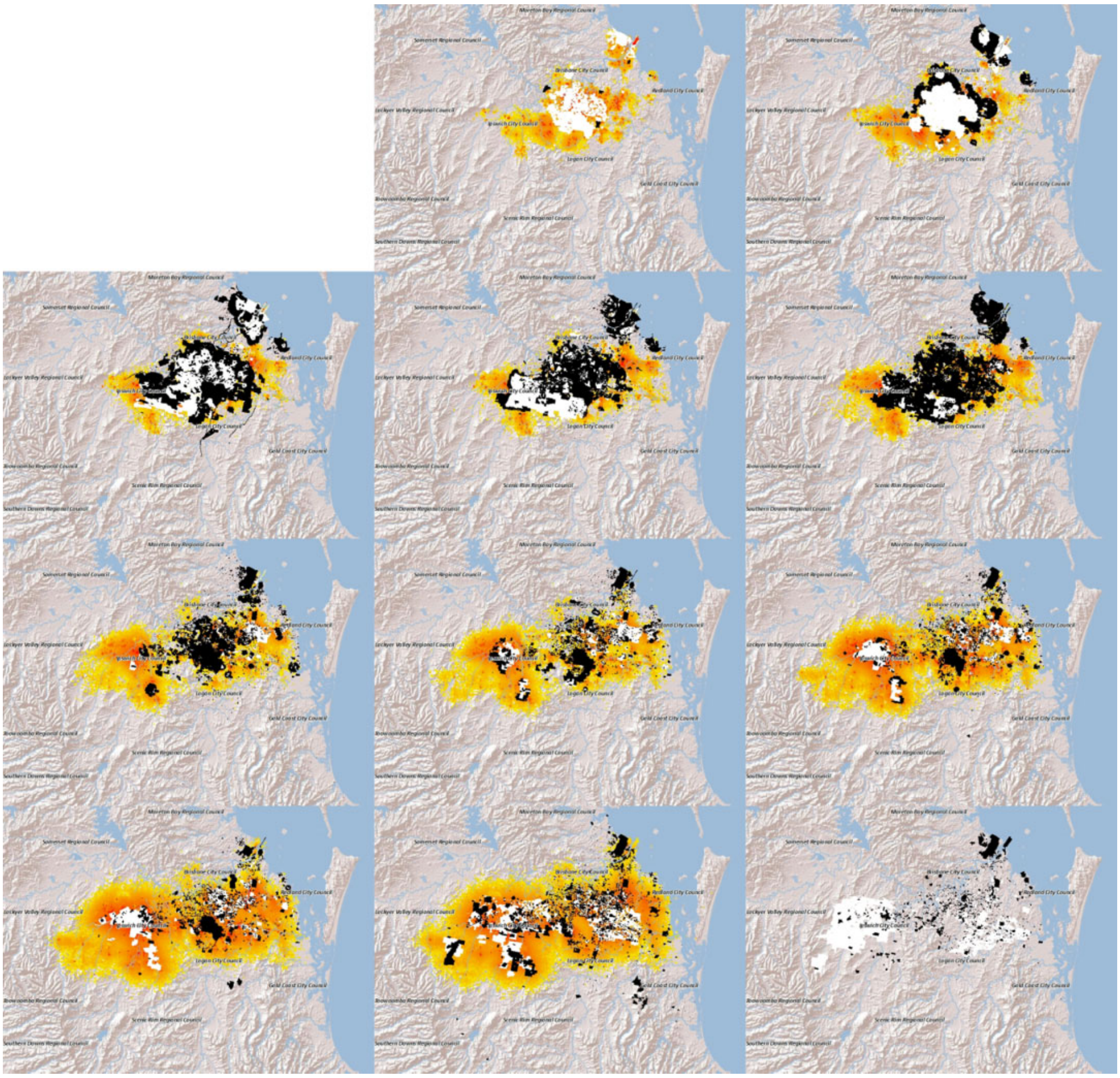
Baiting was initially applied at a frequency of three to four times per year for 3 years followed by 2 years of increased surveillance, as recommended by the program's Scientific Advisory Panel (SAP) (Queensland Parliament 2001). The SAP advised that this strategy could achieve eradication within 5–7 years (Queensland Parliament 2001). On this basis, the program received funding for 5 years.

The first few panels of Figure 1 illustrate the area baited and searched over the first few years of the program. Approximately 90 per cent of operational expenditures were allocated to baiting during this period, most of which involved repeated baiting over the same area. Repeated baiting is required to ensure that fire ant colonies are exposed to a sufficient level of pesticide over a sufficient duration for the colonies to die (McNaught et al. 2014). The high frequency of repeat treatments reflected uncertainty about the mortality of baiting in Australian conditions. Experience in North America indicates that baiting is between 80 and 95 per cent effective (Barr et al. 2005), but its efficacy in Queensland was uncertain when the eradication program began. Increasing the frequency of baiting reduced the risk of treatment failure. However, the reliance on frequent repeated baiting in known areas of infestation at the start of the program was a risky strategy because it reduced the rate at which the managed area expanded. This may have delayed the discovery of more distant infestations and thereby increased the risk of delimitation failure. This risk was mitigated by conducting surveillance around the perimeter of treated areas, reflecting that any detections there would have triggered an expansion of the treated and searched area that may have continued until delimitation was achieved. For this to have occurred, it was necessary that the invasion boundary was not expanding more rapidly than the area managed. Although the managed area did expand over time as new detections were made, it appears to have fallen increasingly short of the expanding invasion boundary over much of the program (Figure 1). This may have reflected insufficient perimeter surveillance in the first year of the program and significant surveillance gaps in the second and third years (Figure 1). It is possible that the invasion 'escaped' during those early years from areas where less surveillance occurred (Keith & Spring 2013).

2.3 Robustness of the Initial Eradication Strategy

The initial strategy focused primarily on removing areas known or likely to be occupied

Figure 1 Heat Maps for the Posterior Expected Number of Fire Ant Nests in Grid Cells 500 m by 500 m in December of Each Year 2000–2010, Overlaid on Maps of Searched and Treated Areas



Note: Brighter cells (yellows) have lower expected numbers of nests and darker cells (reds) have higher expected numbers. Colour classes are on a logarithmic scale. White indicates treatment only, and black indicates search. Areas where both search and treatment occurred are also in black.
Source: Keith and Spring (2013).

by fire ants. An alternative and potentially more robust eradication strategy was to conduct fewer rounds of repeat treatment at the start of the program, with the money saved being used to extend treatment and surveillance over a larger area. This could have allowed for a substantial increase in the managed area without significantly reducing baiting mortality because of the high mortality of a single round of treatment, even if this was conservatively estimated at 80 per cent. Any concern that baiting mortality was lower than 80 per cent could potentially have been resolved sooner by undertaking a controlled experiment at the program's outset rather than a 3-year intensive baiting program. The feasibility of such an experiment was demonstrated by its completion later in the program (McNaught et al. 2014). The importance of such an experiment reflects that it could have supported a large increase in the area managed when the invasion may have been small enough to be eradicated with available resources. For that reason, such an experiment is likely to have been consistent with the aim of developing a management strategy that optimally traded off a small increase in the risk of treatment failure for a reduction in the risk of delimitation failure.

2.4 Robustness of Later Eradication Strategies

The area managed increased substantially over time (Figure 1), with the expansion partly achieved by conducting fewer rounds of repeat treatment. The reduction in repeat treatments reflected increased confidence in the mortality of the broadcast treatment methods used (McNaught et al. 2014). The increased proportion of the program budget allocated to surveillance rather than broadcast treatment in later years of the program (Figure 1) reflected a greater priority given to delimitation over removal of infestations from known or likely areas of infestation. Further increases in the area monitored occurred after 2012 following the introduction of a lower cost monitoring method involving aerial surveillance with infrared sensors (Standing Council on Primary Industries (SCOPI) 2012). At that time, a requirement for continuing the program was imposed by program funders, including the need to demonstrate that the invasion had been accurately delimited with a high level of confidence. To address this requirement, the program made a substantial investment in remote sensing of the invasion, focusing on areas likely to be near the invasion boundary.

These changes in program strategy are potentially more robust to the risk of delimitation failure than the initial strategy that focused primarily on broadcast treatment of areas known or likely to be occupied by fire ants. If the invasion boundary was accurately estimated, and if efforts to prevent further expansion of the boundary are undertaken, the main risk of program failure would stem from the risk of treatment failure in known areas of infestation. This represents a fundamental change in strategy, from minimising a known and readily quantified risk, to addressing the main known but non-quantified risk. Addressing the latter risk in our case study would slightly increase the risk that the program will fail because of insufficient treatment in known and likely areas of infestation. This reflects that by applying management efforts over a larger area each year to reduce the risk of delimitation failure, there would necessarily be a reduced frequency of repeat applications of broadcast treatment over the same areas. Increasing the interval between successive rounds of treatment over the same area would increase the risk that any colonies not removed in the previous round of treatment would reproduce before they are removed. If the average likelihood that an established colony will produce a new colony before the founding colony is removed exceeds 1, eradication would not be achieved. If this likelihood is close to 1 at the current level of program funding, any reduction in the frequency of broadcast treatment could lead to the program failing to achieve eradication in the future. The fire ant program evaluations conducted to date indicate that current program funding is probably insufficient to achieve eradication unless the sensitivity of remote sensing is increased (Hafi et al. 2014). This implies that even if a new eradication strategy is introduced that is more robust to the risk of delimitation failure, the strategy would probably fail without a budgetary increase.

2.5 Potential Institutional Barriers to the Development of Robust Eradication Strategies

Biosecurity institutions include the rules governing evaluation of publicly funded eradication programs (Cook et al. 2010; Liu et al. 2012). These rules can determine whether robustness is considered in developing eradication strategies. In Australia, robustness is not a mandatory evaluation criterion. To be eligible to receive funding from the Australian Government, a proposed eradication program must provide benefits greater than costs and have a realistic chance of succeeding (Council of Australian Governments (COAG) 2012). The first of these criteria is determined with cost–benefit analysis (CBA) and the second criterion typically is determined with evidence from a scientific advisory panel (COAG 2012). Neither of these criteria requires evidence that a proposed eradication strategy is robust to specific forms of uncertainty. This raises the question of whether currently used evaluation methods, when used to compare a pre-determined set of alternative eradication strategies, are likely to select the most robust strategy from those alternatives.

The program's robustness to uncertainty about the invasion's spatial extent was not considered in the initial scientific and economic evaluations of the program. The primary concern of the initial scientific evaluation was to ensure that sufficient rounds of repeat treatment would be applied to known areas of infestation to remove the infestations with a high degree of confidence (Natural Resource Management Ministerial Council 2002). There is no record that any consideration was given to trade-offs between increasing confidence in removing known infestations and increasing confidence in accurately delimiting the invasion.

The initial economic evaluation applied CBA to determine whether the program's benefits were likely to exceed its costs. Benefits were estimated using a predictive model of fire ant spread (Kompas & Che 2001; Scanlan & Vanderwoude 2006). Costs were estimated by the fire ant eradication program management agency. Monte Carlo simulation analysis was used to estimate eradication benefits. This approach considered a degree of known epistemic uncertainties, but not gross uncertainty, including uncertainty about initial fire ant locations. The study estimated that eradicating fire ants was worth approximately $8.9 billion, or $2.8 billion in present value terms, over a 30-year period. This was compared with an estimate of eradication cost made by the invasion management agency of $109.6 million, resulting in a mean net present value (NPV) of the benefit–cost ratio of approximately 25 to 1. With such a high estimated NPV, the program was approved and eradication efforts commenced.

A review of the eradication program conducted in 2012 (Hafi et al. 2014) estimated that two alternative approaches could potentially achieve eradication, one involving an increase in surveillance sensitivity and the other involving an increase in the total area managed per year. The two approaches may have substantially different levels of robustness to uncertainty about the invasion's spatial extent because of the large difference in the areas searched and treated each year. Despite this potentially large difference in a critical form of robustness, no program evaluation conducted to date has considered this form of robustness as a criterion for continuing the program and/or modifying the prevailing eradication strategy.

The large difference in estimated probabilities of eradication between some of the strategies evaluated in the second CBA of the program implies that the fire ant invasion was close to a threshold, at which small changes management parameters can cause the invasion to switch from expansion to decline. Evidence for the existence of such a threshold included a reduction in the estimated probability of eradication from 0.75 to 0 if surveillance sensitivity is reduced from 0.7 to 0.4 (results for the latter simulations are not reported here). Additional evidence for such a threshold is given by the impact of reducing the proportion of the budget allocated to treatment from 0.20 to 0.10, which resulted in a large reduction in estimated eradication probability from 0.89 to 0.23. Invasions are contagious processes involving birth, death and movement, and these parameters have threshold values that determine whether the invasion will expand or contract. The aim of eradication programs is to change one or more of these parameters sufficiently to cause the population/s to decline until eradication is achieved. Programs operating close to threshold conditions, as indicated by a high sensitivity of estimated eradication probability to changes in management variables, can be highly vulnerable to uncertainty about one or more invasion attributes. This vulnerability was demonstrated in the second fire ant program evaluation and highlighted the importance of including evaluation criteria focusing on the program's robustness to uncertainty about those attributes likely to have a large impact on program outcomes.

An indicator of robustness is the estimated duration of an eradication program. If a specific eradication strategy is estimated to achieve eradication much sooner than an alternative strategy, the program is likely to be more robust to uncertainty about how rapidly the invasion boundary is expanding. This form of uncertainty is substantial in the fire ant program because reproductive ants can make long-distance jumps (Porter et al. 1988) that accelerate expansion of the invasion boundary (Suarez et al. 2001). In the case of the fire ant invasion, the strategy with the highest potential NPV had the longest duration. This provides further evidence that standard CBA may produce rankings that conflict with those produced by robustness analysis.

3. Discussion

Eradication programs typically commence with substantial uncertainty about the state of the invasion, including how far it has spread. Uncertainty also commonly exists about the efficacy of control methods, such as the mortality of treatment and the sensitivity of surveillance. Such information gaps create uncertainty about the requirements for programs to succeed, and the likelihood of success.

It is common for information gaps to be larger for some aspects of an eradication program than other aspects. Information is often poorest for invasion state parameters such as the distances and directions over which the invasion has spread. Better information is commonly available for the efficacy of control methods because these can be evaluated in controlled trials, unlike the geographic extent of an invasion. In the case study we considered, uncertainty was most severe about how far the invasion had spread, and least severe for the mortality of broadcast bait treatment.

It can be tempting to focus on addressing known and quantified risks because of the greater knowledge about the extent to which these risks can be reduced. The fire ant eradication strategy we considered initially focused on how to remove known infestations. This reduced resources for addressing severe uncertainty about the invasion's geographic extent, and in doing so, it increased the program's vulnerability to this form of uncertainty. This was not considered in any of the program's evaluations, which were considered in developing the initial eradication strategy. Robustness evaluations involve explicit consideration of program performance in alternative scenarios involving different potential values for the non-quantified risk. This form of analysis could have been very useful in the case study we considered, by providing decision-makers with additional information and giving them an opportunity to decide whether any potential increase in robustness is worth the additional expense involved (for example, the longer time and cost required to eradicate known infestations when annual resource availability for those infestations is reduced). It is likely that these additional costs would have been modest in the case study we considered because a small reduction in the number of rounds of repeat treatment of the same areas would probably not have substantially reduced mortality rates.

Our findings demonstrate that a focus on known and quantifiable risks can increase the likelihood of a program failing due to known but non-quantified risks. A second finding was that reliance on scientific advice in developing eradication strategies, without considering trade-offs between different forms of risk, can be an institutional barrier to the development of robust eradication strategies. These findings highlight the importance of including robustness to non-quantified threats as a mandatory criterion in evaluations of invasive species eradication programs.

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