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Look Before You Treat: Increasing the Cost Effectiveness of Eradication Programs with Aerial Surveillance

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Abstract

Most successful invasive species eradication programs were applied to invasions confined to a small area. Invasions occupying large areas at a low density can potentially be eradicated if individual infestations can be found at affordable cost. The development of low cost aerial surveillance methods allows for larger areas to be monitored but such methods often have lower sensitivity than conventional surveillance methods, making their cost-effectiveness uncertain. Here, we consider the cost-effectiveness of including a new aerial monitoring method in Australia's largest eradication program, the campaign to eradicate red imported fire ants (*Solenopsis invicta*). The program previously relied on higher sensitivity ground surveillance and broadcast treatment. The high cost of those methods restricted the total area that could be managed with available resources below the level required to prevent ongoing expansion of the invasion. By increasing the area that can be monitored and thereby improving the targeting of treatment and ground surveillance, we estimate that remote sensing could substantially reduce eradication costs despite the method's low sensitivity. The development of low cost monitoring methods could potentially lead to substantially improved management of invasive species.

Keywords:
automated monitoring, cost-effectiveness, broadcast pesticides, spread model, eradication.

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Introduction

Programs to eradicate and suppress invasive species can prevent substantial economic and environmental damages (Mack et al. 2000) but also can have a high cost and often fail. Most successful eradication programs were applied to small invasions and relied on “brute force” application of broadcast treatment to potentially occupied locations with minimal prior surveillance (Simberloff 2009). This approach is cost-effective where the potential area of infestation is known and broadcast treatment has high mortality. In such circumstances, one or a small number of treatment applications in all potentially occupied locations can remove all individuals without incurring large surveillance costs or the risk that surveillance will fail to detect all individuals. After discovering black-striped mussels (*Mytilopsis sallei*) in a northern Australian marina, the entire marina was poisoned with a high mortality treatment method that removed all individuals without the need to detect them all, which would probably have been infeasible (Bax et al. 2002). This “brute force” treatment approach is less suitable for larger invasions because of the high costs of treating all potentially occupied locations, particularly when treatment must be applied repeatedly over the same area to remove all individuals there.

Surveillance can substantially reduce the area requiring broadcast treatment for invasions that are patchily distributed. Searching large areas and focusing treatment only on those areas with confirmed or likely infestations avoids the need to repeatedly treat all potential areas of infestation. The cost-effectiveness of this strategy depends on the cost and sensitivity of surveillance. An important recent advance in invasion management is the development of surveillance methods involving automated detection and classification of targets, including wireless sensor networks (Hu et al. 2009) and remote sensing (Göktoğan and Sukkarieh 2014; Bryson et al. 2014; Turner et al. 2003). These automated monitoring methods can have a substantially lower cost per hectare than conventional methods involving intensive use of trained personnel. However, automated surveillance methods often have lower sensitivity than conventional methods and therefore are likely to detect fewer individuals in the areas searched. This can reflect the use of imperfect pattern recognition algorithms to distinguish invasive individuals from surrounding objects (Göktoğan and Sukkarieh 2014) and larger distances between sensor and target with automated monitoring methods than with conventional methods. Aerial surveillance often involves image capture from several hundred feet above the ground, much further than the distances between pest organisms and conventional visual and trapping based sensors (Turner et al. 2003; Hung et al. 2012). Infestations missed by lower sensitivity automated surveillance methods can expand before they are eventually detected and removed, increasing pest-related damages and future treatment costs. These additional costs may potentially outweigh the lower operating costs of automated monitoring methods, leaving it an open question whether such methods are beneficial in eradication programs.

Tradeoffs between surveillance sensitivity and treatment costs have been an ongoing focus of research. Epanchin-Niell et al. (2013) applied an equilibrium modelling approach to determine the sensitivity of surveillance that minimizes the sum of surveillance costs, pest-induced damages and treatment costs. An application of this approach to gypsy moth management in the USA (Epanchin-Niell et al. 2013) provided insights into the tradeoff between increased knowledge from monitoring and removal of individuals with available knowledge. Efficient management strategies for addressing tradeoffs of this form also were considered in other recent studies (Baxter and Possingham 2011; Bogich et al. 2011; Haight and Polasky 2011; Hauser and McCarthy 2009; Homans and Horie, 2011; Horie et al. 2013). Baxter and Possingham (2011) found that when general areas of infestation are known with a high degree of confidence, an efficient management strategy is to intensively monitor those areas ("focused searching"). In contrast, larger areas should be monitored, including areas with low likelihoods of pest occurrence, if pests are already widespread, knowledge of the pest's distribution is poor, or if the aim is to restrict expansion of the invasion boundary. The typically low likelihood of pest occurrence near an invasion's boundary reflects that pest densities and occurrence likelihoods usually decline outwards from an invasion's epicentre (Leung et al. 2010). Management strategies for efficiently addressing the risk of boundary expansion were considered by Chadès et al. (2011). They determined circumstances where control efforts should be focused on the invasion edge to progressively restrict the invasion's extent over time (an "outside-in" strategy).

The case study we consider focuses on Australia's largest eradication program, the campaign to eradicate red imported fire ants (*Solenopsis invicta*). A key feature of this case study is that the area that might contain fire ants is too large to be treated in its entirety with broadcast methods because of prohibitive cost. The high cost of this strategy reflects that multiple applications of treatment would be required within a short period to achieve a high probability of removing all individuals. Without a lower cost monitoring method, eradication of the fire ant invasion would not be feasible. The only readily available monitoring method with a lower cost than current used ground surveillance is remote sensing of fire ant nest mounds. The main disadvantage of this method is its low sensitivity, which is less than half the sensitivity of ground surveillance. Our case study provides early empirical evidence on the cost-effectiveness of including in eradication programs automated monitoring methods that have both a low cost and low sensitivity. As in the analysis of Baxter and Possingham (2011), we consider the combined application of low sensitivity surveillance for improving knowledge of the pest's distribution and higher sensitivity surveillance for assisting with the removal of individuals from known infestations. The higher sensitivity surveillance method we consider involves ground surveillance by trained personnel. We estimate eradication costs in scenarios with and without remote sensing to assess the potential cost reduction from introducing this surveillance method to the eradication program.

Materials and Methods

Case Study Background

The Australian fire ant eradication program, which is ongoing, commenced in February 2000. As in the U.S. campaign to eradicate fire ants, the Australian campaign relied primarily on broadcast bait treatment to achieve eradication, with much smaller areas searched. In most years of the program, >70% of resources were allocated to broadcast treatment, with 90% allocated over the first three years and 80% allocated in recent years. The main surveillance method used involved ground surveillance by trained personnel. Fire ant nests detected with this method were removed with the pesticide fipronil injected directly into the nests. This removed the detected colonies with certainty but left undetected colonies untreated. Surveillance with odour detection dogs is undertaken in the program and has important advantages over other available monitoring methods, including a high probability of detecting immature fire ant colonies that cannot be detected with visual methods. The main disadvantage of sniffer dog surveillance is its limited availability, reflecting substantial animal training periods required. Currently, a maximum of 40 dogs are potentially available to the program, which allows for only 80 hectares to be searched per day with this method, a small area compared to the area potentially containing fire ants.

The failure to eradicate fire ants led to a change in strategy involving increased surveillance with infrared remote sensing of fire ant nest mounds (QDAF undated). The method has a lower cost than previously used ground surveillance and therefore can be applied over a larger area. Remote sensing was applied for 2-3 years and ceased being used in 2015. The sensitivity of the method achieved prior to its cessation was approximately 0.38 (Table 2), which is < half the sensitivity of ground surveillance (0.80) and <half the mortality of broadcast treatment (Table 2). However, unlike broadcast treatment, remote sensing provides information on colony locations that can improve targeting of treatment. Remote sensing was used primarily in non-urban areas because of the low effectiveness of citizen monitoring there, reflecting relatively low human population densities. Citizen monitoring is the primary surveillance method in urban areas, reflecting its higher sensitivity than that of remote sensing in such areas (Keith and Spring 2013). Citizen monitoring, which also occurs in rural locations, provides “background surveillance” that can detect fire ants over large areas of land without actively searching those areas. Many of the detections of fire ants made in the eradication program were made with this method (Keith and Spring 2013). These detections trigger broadcast treatment and active surveillance in the immediate vicinity of detection points to delineate and remove local clusters of infestation.

Approximately $300 million has been spent on the Australian fire ant eradication program to date. The current annual funding available for surveillance and treatment of fire ants is between $11 and $12 million/year (precise information is not available on the share of the total program budget currently allocated to surveillance and treatment).

Overview of methods

To assess the cost-effectiveness of including a new aerial monitoring method in Australia’s fire ant eradication program, we develop a simulation-based model of fire ant spread and control and apply the model to compare different management strategies. The model has three components, a spread model for generating potential future states of the invasion; a knowledge model for recording knowledge of the invasion, and a strategy model for determining actions based on current knowledge.

The spread model includes initial locations of fire ant colonies, reproduction rates, dispersal distances and probabilities of establishment at different locations. Values for these parameters were drawn from distributions estimated with a recent application of the model of Keith and Spring (2013). These distributions were based on the entire history of fire ant detections and control actions since the eradication program commenced and were validated using a simulation-based method, as explained in Keith and Spring (2013, Supporting Information). The model of Keith and Spring (2013) also included methods for updating parameters as spread occurs and new information is obtained through implementing management actions. The updating methods have a high computational cost that precludes their use in our study because of the large number of parameter updates required. It was therefore necessary to apply an approximation of the original updating method of Keith and Spring (2013) that has a lower computational cost. This approximation method is described in the Spread Model and Knowledge Model sections below, and is briefly summarised here. The approach involves generating 50,000 alternative maps of fire ant colonies using the method of Keith and Spring (2013). Each colony is represented as a point on one of these maps, and the map of all colony points was overlayed on a 1-ha grid. We computed the average number of fire ant colonies in each grid cell by summing colony abundance across each of the 50,000 maps and dividing the summed value in each cell by 50,000. This average abundance map (the “expectation map”) represents initial knowledge about fire ant locations in our analyses. The expectation map is revised periodically during a simulation as spread occurs from untreated locations and ants are removed in treated locations. Further revision of expectations is required because initial knowledge of fire ant locations is imperfect, in the sense that the expectation map differs from the true locations of fire ants. These true locations are not known but for the purposes of the analysis are specified as one of the 50,000 potential maps determined with the method of Keith and Spring (2013), adjusted periodically to account for spread and removals by treatment. The computations involved in updating expected fire ant locations to account for spread, treatment and surveillance activity are described in the next two sections (“Spread Model” and “Knowledge Model”).

The current surveillance strategy applied by the eradication program is a form of adaptive cluster sampling (Thompson and Seber 1996). Nests detected by passive surveillance trigger active surveillance within a specific distance (100 m.) of detected nests. Any new detections made during active surveillance expand the area searched by a radius of 100 m. and this process continues until no more nests are found. The main modification to this “sampling-only” process made in the current fire ant control strategy is to include broadcast treatment in the immediate vicinity of detection points, with surveillance conducted immediately beyond treated areas. This modification takes account of the higher nest removal rate of broadcast treatment compared to the main alternative removal method, which involves pesticide injections directly into detected nests. Nest injections remove only detected nests but immature nests cannot be detected because they are subterranean. The latter nests can be removed by broadcast treatment because foraging individuals from immature nests take the poisoned baits into the nests (Lofgren et al. 1975). The current eradication strategy allows for treatment to be applied in locations most likely to be occupied and for searching to occur where it provides greatest confidence of delineating the spatial extent of individual infestations.

The management strategies we consider involve the same general approach as the modified adaptive cluster sampling approach of the eradication program, with a few differences. The manager’s approach determines where to apply surveillance and treatment based only on their proximity to the nearest known individual fire ant colony. Under our approach, the placement of management actions is based on a spatially explicit model of fire ant spread. Another difference is that the placement of actions is based not only on the likelihood of occurrence of fire ants at different locations but also the proximity of those locations to the estimated invasion boundary. It may be advantageous to apply greater management effort to infestations near the estimated invasion boundary than infestations further from the boundary to reduce the risk of the boundary expanding (Chadès et al. 2011). To jointly consider both the expected abundance of fire ants at different locations and the proximity of infestations to the invasion boundary, these two invasion attributes are computed on a grid representation of the study region. Each square grid cell (“site”), is 1 hectare in area. The estimated abundance of fire ant colonies in each site and the proximity of each site to the estimated invasion boundary are periodically updated as management actions are taken, observations are made, and pest spread occurs, leading to adaptive changes in the placement of management actions. The estimate of fire ant abundance at a specific site takes account not only of the site’s proximity to the nearest known infestation point, which is the only information considered in the current management strategy, but also the site’s proximity to other, more distant infestation points that may add to the site’s expected abundance. Spatially, the form of management strategy we consider involves extending the three control methods (broadcast treatment, remote sensing and ground surveillance) outwards from known points of infestation, identified with passive surveillance or previous active surveillance. Broadcast treatment is applied in the immediate vicinity of detection points and surveillance is applied beyond the treated area. The rationale for surveying the perimeter of treated areas is to ensure that treatment was applied far enough to remove all nests, reflecting that when a nest is detected, it is not immediately known whether the nest is part of a larger infestation. The total areas covered by each control method reflects the allocation of program funding between the methods. A proportion of the program budget is allocated to locations near the estimated invasion boundary, as determined by a separate control variable. The values of the different control variables are optimized to a limited extent by evaluating with simulation many different combinations of values of the variables. The comparison is made in terms of the cost of achieving a pre-specified probability of eradication. Combinations that achieve this probability at lowest cost are reported for two scenarios, one in which aerial surveillance is available at a specific sensitivity, and the other in which aerial surveillance is not available.

Spread model

The spread model component takes as its starting point an estimate of the current locations of fire ants (both mature and immature colonies), made in a recent unpublished report to the National Red Imported Fire Ant Eradication Program (NRIFAEP) (Keith and Spring 2015). Spread predictions are based on previously estimated fire ant reproduction and dispersal rates (Keith and Spring 2015). These estimates of fire ant locations and spread parameters were validated using the simulation-based method of Cook et al. (2002), as explained in Keith and Spring (2013 Supporting Information). In addition to being the source of the invasion spread parameters used in our simulation model, the model of Keith and Spring (2013; 2015) was also the source of our estimated probabilities of fire ants being detected by members of the public ("passive surveillance detection probabilities") in urban areas. The probability of passive detections occurring in rural areas was set at a lower level in our analyses based on expert opinion due a lack of sufficient observations for inferring this probability.

The spread model generates from a population of nests Pop_i at time step i, a new population Pop_{i+1} at the next time step. This update involves four steps.

- Generate a set of reproductions from the existing population of nests $Birth_i$
- Remove from the population a set of nests $Death_i$ based on the set of treated locations $Treat_i$
- Generate a set of detections $Detect_{i,p}$
- Generate sets of detections $Detect_{i,a}$, $Detect_{i,r}$ based on the set of searched locations $Search_{i,a}$, $Search_{i,r}$ (for active search and remote sensing respectively)

The new population is then given by the following:

$$Pop_{i+1} = Pop_i \cup Birth_i \backslash Death_i$$

The set of reproductions is created by sampling from the spread distribution estimated with the model of Keith and Spring (2013, 2015). Reproduction is governed by the following parameters:

λ – the rate of reproduction

Pm_j – the probability of a given reproduction using the j^{th} mode of dispersal

$\sigma_{x,j}$ – controls spread distance in the east-west direction for the j^{th} mode of dispersal

$\sigma_{y,j}$ – controls spread distance in the north-south direction for the j^{th} mode of dispersal

γ_k – controls the chance of establishment in the k^{th} land class

It is also influenced by the following spatial information:

$Usage_{s,t}$ – The land usage class of the site at (s,t), where s is the X coordinate and t is the Y coordinate of the site.

$Habitable_{s,t}$ – An indicator value, 0 when the site at (s,t) is uninhabitable.

$Density_{0,s,t}$ – An initial estimate of the expected population density at (s,t).

$Method_{s,t}$ – The applicable treatment class for the site at (s,t).

Nests under 6 months of age are immature and do not reproduce. The number of reproductions for each mature nest is governed by a Poisson distribution with parameter λ.

The mode of dispersal for each reproduction is drawn from a discrete distribution with probabilities Pm_j. This then determines the value of the parameters for the dispersal kernel. The dispersal distribution in each direction is a two-sided exponential distribution with parameters $\sigma_{x,j}$ and $\sigma_{y,j}$.

$$x' = x + \delta x,\ y' = y + \delta y$$

$$\Pr(\delta x = \eta) = \frac{1}{2\sigma_{x.j}} e^{-\sigma_{x,j}|\eta|}$$

$$\Pr(\delta y = \eta) = \frac{1}{2\sigma_{y.j}} e^{-\sigma_{y,j}|\eta|}$$

Where (x', y') is the location of the new nest, (x, y) is the location of the parent nest and $(\delta x, \delta y)$ is the dispersal vector.

The probability that a given dispersal results in a new nest is governed by the establishment probabilities γ_k. The probability of establishment is related to the land class at the new location. If the new location lies outside the boundaries of the map, or in an uninhabitable area, the dispersal is ignored.

The set of nests $Birth_i$ is the set of all nests resulting from sampling from the reproduction and dispersal distributions as described above excluding those that do not successfully establish. The set of nests $Death_i$ is governed by:

β – the treatment mortality rate

$Treat_i$ – The set of sites treated by broadcast treatment

$Inject_i$ – the set of nests treated by injection

Immature nests can be killed by treatment, even though they are not detectable. Each nest in the set $Inject_i$ is added to the set $Death_i$. For each site in $Treat_i$, the nests on that site are added to $Death_i$ with probability β. The set of nests $Detect_{i,p}$, $Detect_{i,a}$, $Detect_{i,r}$ is governed by:

$\alpha_{p,k}$ – the sensitivity of passive surveillance in land class k

α_a – the sensitivity of active surveillance

α_r – the sensitivity of remote sensing

$Search_{a,i}$ – The set of sites searched by active surveillance

$Search_{r,i}$ – The set of sites searched by remote surveillance

Immature nests are considered undetectable, they will not be detected by any form of search. For each mature nest in land class k, it is added to the set $Detect_{i,p}$ with probability $\alpha_{p,k}$. For each mature nest in each site in $Search_{i,a}$, it is added to the set $Detect_{i,a}$ with probability α_a. For each mature nest in each site in $Search_{i,r}$, it is added to the set $Detect_{i,r}$ with probability α_r.

Knowledge Model

This component involves taking many potential maps of estimated fire ant locations estimated in a previous unpublished report to the NRIFAEP (Keith and Spring 2015) and computing the average of these maps ("the expected abundance map"). One of the potential maps used to compute the expected abundance map is the map used in the spread component of the model, and this map is considered to be the "true map" of the fire ant invasion for the purposes of the learning component of the model. Uncertainty about fire ant locations is reflected in differences between the 'true map" and the expected abundance map.

The goal of the knowledge model is to maintain maps $EPop_{i,s,t}$ and $ESpread_{i,s,t}$ of the agent's knowledge of the population of mature and immature nests respectively. These maps record an estimate of the expected number of nests on each site at time step i. The estimation involves four calculations.

- Accounting for reproduction and spread (calculates the map $ESpread_{i,s,t}$)
- Accounting for the results of treatment (calculates the maps $EDeath_{i,1,s,t}$ for mature nest deaths and $EDeath_{i,2,s,t}$ for immature nest deaths)
- Accounting for the results of search (calculates the map $EDetect_{i,s,t}$)
- Calculate new density map (calculates the map $EDensity_{i+1,s,t}$)

To account for spread, the following calculation is used. This generates from the existing knowledge of the invasion, the expected new nests founded at each location.

$$ESpread_{i,s,t} = 6\Delta t \sum_{j} \frac{\lambda}{\Delta x \Delta y} \int_{y(t)}^{y(t)} \int_{x(s)}^{x(s+1)} \int_{y(t')}^{y(t'+1)} \int_{x(s')}^{x(s'+1)} \gamma_{Usage_{s,t}} \cdot EPop_{i,s',t'} \frac{1}{2\sigma_{x.j}} e^{-\sigma_{x,j}|x'-x|} \cdot \frac{1}{2\sigma_{y.j}} e^{-\sigma_{y,j}|y'-y|} dx'\, dy'\, dx\, dy$$

The value of $ESpread_{i,s,t}$ estimates the expected number of new immature nests at site (s,t). Given the population of mature nests $EDensity_{i,s,t}$.

In order to reduce the required processing, the above calculation is only performed twice per year, hence the factor of $6\Delta t$.

The maps $EDeath$ are estimations of the expected number of nests removed by treatment and are computed using the following equations.

$$EDeath_{i,1,s,t} = Inject_{s,t} + \begin{cases} \beta \cdot (EPop_{i,s,t}, (s,t) \epsilon Treat_i \\ 0, otherwise \end{cases}$$

$$EDeath_{i,2,s,t} = Inject_{s,t} + \begin{cases} \beta \cdot (ESpread_{i,s,t}, (s,t) \epsilon Treat_i \\ 0, otherwise \end{cases}$$

Where $Inject_{s,t}$ is the number of nests injected on the site at (s,t).

The map $EDetect_{i,s,t}$ is an estimation of the expected number of nests based on the number of nests detected there. It mixes the results of each search method evenly.

$$EDetect_{i,s,t} = \frac{1}{n}\left(\frac{Detect_{i,p,s,t}}{\alpha_{p,Usage_{s,t}}} + \frac{Detect_{i,a,s,t}}{\alpha_a} + \frac{Detect_{i,r,s,t}}{\alpha_r}\right)$$

Where n is the number of search actions of any type undertaken in the time period, and $Detect_{i,p,s,t}$, $Detect_{i,a,s,t}$ and $Detect_{i,r,s,t}$ are the number of detections by passive surveillance, active surveillance and remote sensing respectively.

The following equation combines the results of the spread, treatment and search, into a new estimation of the population (this occurs on every 6th time step).

$$EPop_{i+1,m,s,t} = \frac{\max\left(EPop_{i,s,t} + ESpread_{i,s,t} - EDeath_{i,1,s,t} - EDeath_{i,2,s,t}, 0\right) + EDetect_{i,s,t}}{2}$$

In other years, the spread population is not updated (other than to remove nests killed by treatment, and so the following pair of equations is used.

$$EPop_{i+1,m,s,t} = \frac{\max\left(EPop_{i,s,t} - EDeath_{i,2,s,t}, 0\right) + EDetect_{i,s,t}}{2}$$

$$ESpread_{i+1,s,t} = \max\left(ESpread_{i,s,t} - EDeath_{i,2,s,t}, 0\right)$$

Strategy Model

This component takes a set of strategy parameters and generates actions in each step of the simulation. The available actions are

- Treat a site with the applicable treatment method
- Search a site with active surveillance
- Search a site with remote sensing
- Treat a detected nest with direct nest injection.

In order to model a variety of different budgets (which allow for different total areas of action) with the same strategy parameters, it is simplest to determine for each action type, a ranking methodology for sites based on a mixture of criteria. This allows the strategy to be agnostic to the particular budget level, by acting on sites beginning at the highest ranking, until no further budget for that action type remains.

By permitting the ranking method to vary between action types we can investigate strategies that use different actions for different purposes. Of particular interest was whether actions should be directed at areas of high expected nest abundance, or areas near the anticipated boundary of the invasion area.

The edge of the invasion is calculated by first identifying the smallest set of sites that will contain 90% of the expected population (according to $EPop_{i,s,t} + ESpread_{i,s,t}$), and identifying all sites in this set that are not surrounded on all four sides by other sites in this set. These sites form the boundary set. Alternative boundary sets could have been considered, such as the 99% boundary, which contains 99% of the expected population. It is more difficult to detect fire ant colonies along the 99% boundary than the 90% boundary because of a lower estimated density of fire ants at points along the 99% boundary. For this reason, there may be disadvantages in conducting surveillance closer to the estimated outermost boundary of the invasion. Our selection of the 90% boundary for the purposes of allocating surveillance effort reflects an assumption that it is likely to be more efficient to begin surveillance inside the outermost boundary and then detect the outer edge adaptively. This assumption is supported by previous research (Leung et al. 2010).

Direct nest injection is assumed to be an automated action rather than being determined by the strategy model parameters. Detection by any search method triggers direct nest injection if funding from the budget is available.

Each of the other methods is described by the following parameters:

μ_q – The proportion of the total monthly budget spent on method q

c_q – The cost of searching a site with method q

π_q – The emphasis parameter for method q

$\pi_q = 1$ will rank sites entirely based on their proximity to an estimate of the edge of the invasion whereas $\pi_q = 0$ will rank sites entirely based on their expected nest abundance. The general form of the score used for ranking sites is the following

$$score_{q,s,t} = (1 - \pi_q)\frac{EPop_{i,s,t}}{EPop_{i,avg}} + \pi_q \frac{1}{1 + d_{edge,i,s,t}/d_{edge,i,avg}}$$

Where $EPop_{i,avg}$ is the average density of nests over the map and $d_{edge,i,s,t}$ is the taxi-cab distance from the selected site to the nearest member of the boundary set in time step i. The taxi-cab metric was chosen for computational efficiency.

Treatment actions (that is, the application of broadcast treatment) have two specific attributes. Firstly, they can remove undetected nests, so the population for the purposes of ranking is the $EPop_{i,s,t} + ESpread_{i,s,t}$ rather than just $EPop_{i,s,t}$. Secondly, the cost can vary according to the broadcast treatment method type applicable at that site ($Method_{s,t}$), with some forms of broadcast treatment not being permitted under current guidelines in specific land types. The cost parameter for treatment actions thus has an additional index.

Under current administrative rules, remote sensing actions cannot be applied in urban areas. This is implemented in our strategy model by assigning a zero score for the remote sensing method in urban land areas.

These treatment and surveillance actions occur in the following order following the update of the population.

1. Treatment – Treat the highest scored sites (according to the treatment scoring methodology) until $\mu_t \cdot B$ has been spent on treatment
2. Passive Surveillance Treatments – Treat detected sites via direct nest injection
3. Ground Search – Search the highest scored sites (according to the ground search scoring methodology) until $\mu_g \cdot B$ has been spent on ground search
4. Remote sensing – Search the highest scored sites (according to the remote sensing methodology) until no budget is remaining.

Strategy parameter definitions the optimal parameter values are set out in Table 1, and the efficacy and cost of the different control methods are set out in Table 2.

INSERT TABLE 1 HERE

INSERT TABLE 2 HERE

The sensitivity of infra-red remote sensing to detect fire ant nest mounds is approximately 0.38 (Table 2) but this may be increased over the course of the eradication program. The method has achieved sensitivity in excess of 70% in a United States evaluation project (Vogt and Wallet 2008) but the areas searched were quite different from the areas in Australia that are at risk of infestation (David Oi, Research Entomologist, USDA, personal communication). We considered a conservative estimate of future remote sensing sensitivity of 0.38, which is the highest sensitivity reached to date, and a higher sensitivity of 0.50, based on expert opinion among fire ant management personnel about an achievable future sensitivity of the method. There is uncertainty about the transportation and personnel costs arising from the need to confirm false positive detections made with remote sensing. An estimate of these costs was provided by the eradication program based on preliminary false positive rates. The total cost of remote sensing is the sum of the direct costs of operating the infrared sensor and platform (approximately $15-$20/hectare), and the indirect costs in confirming nest detections (approximately $50-$55/hectare). These indirect costs include transportation costs in driving to locations with potential fire ant colonies, and time costs in confirming whether the detection points are fire ant colonies (R. Wylie, Manager Biosecurity Queensland Control Centre, pers. comm.).

Results

At the current budget of between $10 million and $11 million/year, eradication is unlikely to occur within 10 years, regardless of the availability of remote sensing at either of the two sensitivities considered. A high (90-95%) probability of eradication within this timeframe is possible by increasing the budget and resuming remote sensing. Optimal values of the eradication strategy parameters are set out in Table 3, and simulation outcomes for each optimal strategy in each scenario on remote sensing availability are reported in Table 4.

INSERT TABLE 3 HERE

INSERT TABLE 4 HERE

Eradication probabilities of 90%, and 95%, were estimated to be achievable by increasing the budget to $17 million/year, and $24 million/year respectively, if remote sensing resumes at the previously achieved sensitivity of 0.38. Smaller budget increases of $16 million/year, and $22 million/year respectively, are required to achieve those eradication probabilities if the sensitivity of remote sensing can be increased to 0.50. If remote sensing is not available, larger budgets of $24 million/year, and $30 million/year, are required to achieve eradication probabilities of 90%, and 95%, respectively. These results can alternatively be stated in terms of a reduction in the estimated cost of achieving eradication at the two levels of confidence. These cost reductions are $7 million/year, and $8 million/year, for achieving an eradication probability of 90% by resuming remote sensing at a sensitivity of

0.38, and 0.50, respectively. Similar cost reductions can be achieved if the aim is to achieve a 95% probability of eradication.

To achieve either the 90% or 95% eradication probability target, the optimal strategy is to allocate half the budget to broadcast treatment, 30% to remote sensing and 20% to ground surveillance. The only difference in strategy between the two eradication targets is in the spatial placement of remote sensing, with there being greater emphasis on applying remote sensing near the estimated invasion boundary at the higher probability target (Table 3). The consequences of applying sub-optimal combinations of strategy parameter values for the lower eradication probability target of 90% are illustrated in Figure 1.

INSERT FIGURE 1 HERE

Applying a suboptimal management strategy can substantially increase the estimated duration of the eradication program, with the largest increase occurring when too much treatment and remote sensing occurs near the estimated invasion boundary. The spatial placement of the three management methods is illustrated in figure 2 and figure 3.

INSERT FIGURE 2 HERE

The fire ant "expectation map" (figure 2) illustrates expectations about fire ant locations estimated using the method of Keith and Spring (2013) applied with more recent data (Keith and Spring 2015).

Initial treatment and surveillance effort is concentrated in areas with the largest estimated abundance of fire ants (figure 3).

INSERT FIGURE 3 HERE

The spatial pattern of management actions illustrated by figure 3 involves broadcast treatment occurring near an infestation point and higher sensitivity ground surveillance occurring around treated areas to delineate the infestation boundary. Lower sensitivity aerial surveillance search is placed around areas searched with ground methods to detect new areas of infestation that may have resulted from long distance movements. Aerial surveillance occurs only in rural areas under current restrictions on application of the method.

Discussion

We developed an empirical model of fire ant distribution and spread, and integrated this model with a decision model to determine optimal strategies for allocating an eradication program budget between three different control methods, including a new aerial surveillance method. The model also determined where to apply the three methods. Our main finding was that the resumption of aerial surveillance following its discontinuation in 2015 is likely to substantially reduce the cost of achieving a high probability of eradication. The reduction in cost is approximately $7 million/year or $8 million/year, depending on the sensitivity of remote sensing. We estimated that the program will require approximately 7 – 10 years to achieve eradication. The need for subsequent monitoring to confirm fire ant absence from the study region was not considered. For a program duration in the order of 7-10 years, annual cost savings of $7-$8 million/year arising from the resumption of remote sensing would be worth over $50 million. Cost savings would be larger if remote sensing were to be used to assist efforts to confirm fire ant absence following eradication. These savings substantially exceeds the likely cost of further development of the remote sensing method if this resumes with newer technology. The relatively low cost of remote sensing reflects that the method has already been successfully applied over several years in this eradication program and in the United States (Vogt and Wallet 2008).

Our analysis assumed remote sensing surveillance would resume immediately but further development of the method is likely to be required to achieve the higher sensitivity (0.50) considered in our analysis. Our finding that there are only modest cost savings from increasing the method’s sensitivity from 0.38 to 0.50 implies that it may be more cost effective to minimise the cost of further developing the method. This could be accomplished by resuming remote surveillance immediately at the previously achieved sensitivity of 0.38. However, further development of remote sensing could reduce the costs of operating the method, for example, by reducing the cost of false positives. Such a reduction in operating costs would allow for larger areas to be searched each year, potentially achieving eradication sooner and further reducing the total cost of eradication. Consultation with eradication program personnel indicated that between two thirds and three quarters of the cost of remote sensing is in confirming the identity of objects identified with the method as potential fire ant nests. This high cost reflects difficulties in distinguishing fire ants nests from other objects and high costs of transportation and labour in confirming the identity of detected objects. Further analysis is required to estimate the scope for reducing false positives and the resulting cost savings.

The main limitation of our approach was our inclusion of an approximation of a previously developed Bayesian method for updating knowledge of fire ant locations. We estimated the magnitude of errors arising from application of our approximation method instead of the original updating method. To do so, we compared the number of fire ant colonies estimated with the two methods for an example involving 50,000 initial fire ant maps, estimated with the model of Keith and Spring (2013, 2015). Our approximation method overestimated the number of fire ant colonies, with the magnitude of overestimation error being largest for locations with the largest estimated number of fire ants. This error affects the knowledge model (the expected number of ants at different locations) but not the actual number of ants. Most importantly, the error is unlikely to have influenced model outcomes or the study’s findings. This reflects that our approximate updating method did not influence relative expected abundances across sites, and therefore did not influence management choices, which are based on relative abundances rather than absolute abundances across sites.

As in previous studies that integrated an empirical distribution model and a decision model aimed at eradicating or suppressing an invasion (Giljohann et al. 2011; Hauser and McCarthy 2009), we found that most management effort should be focused on sites with a high probability of pest occurrence (in our case, a high expected density of pests). The only qualification of this finding was that some aerial surveillance should occur near confirmed detection points in close proximity to the invasion boundary, beyond the area that would be searched in sites of equal expected pest density in areas more distant from the invasion boundary. This finding, which is similar to that of Hauser et al. (2016), reflects the importance of perimeter surveillance in reducing the risk of expansion of the invasion boundary. While aerial surveillance near the boundary improved outcomes, we found that applying broadcast treatment in those locations worsened outcomes because of the low likelihood that fire ants exist there and the fact that treatment provides no information on fire ant presence. Conducting substantial treatment near the invasion's boundary is unlikely to remove fire ants or provide information for delimiting the invasion.

Conclusions

The main aim of this study was to provide early empirical evidence on the cost-effectiveness of including low cost automated monitoring methods to assist in eradicating patchily distributed biological invasions occupying a large area. The development of automated monitoring methods for biological invasion management is still in its early stages, and guidance is required on whether to attempt to develop such methods, and in what circumstances to do so.

The main disadvantage of the method we considered was its low sensitivity compared to existing monitoring methods. We found that the low cost of aerial surveillance, which was around one quarter the cost of ground surveillance, compensated for the method's low sensitivity by allowing for a much larger area to be area monitored each year. This allows for improved targeting of higher cost control methods required to eradicate individual infestations, including ground surveillance and multiple applications of broadcast treatment. Even low sensitivity aerial surveillance can readily detect larger infestations, allowing for their removal with intensive ground surveillance and treatment.

Our analysis provided useful insights on how automated monitoring methods can efficiently be integrated with other control methods. In our case study, the most efficient strategy for applying the different control methods involved the application of aerial surveillance at larger distances from known infestation points than the other methods. This takes advantage of the lower cost of aerial surveillance which increased its capacity to find remote infestations. Once detected with remote sensing, infestations can then be delineated and removed with a combination of ground search and broadcast treatment. Although our case study focuses on a single species, our methods can readily be applied to other invasion management problems in which invaders can be detected with multiple search methods having different combinations of cost and sensitivity.

Our case study demonstrates that if automated monitoring methods have a sufficiently low cost per hectare, their inclusion in pest eradication programs can substantially reduce total eradication costs even if the methods have much lower sensitivity than available monitoring methods. This provides grounds for optimism that lower cost monitoring methods will allow for eradicating of larger invasions for which eradication was previously deemed to be infeasible.

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Tables

Table 1: Strategy parameter definitions

Parameter	**Meaning**
Total treatment and surveillance budget	Total funding for management actions taken in the simulations: 1. Initial responses to passive detections (non-discretionary). 2. Treatment actions, ground search and remote surveillance.
Treatment budget allocation	The proportion of the budget (remaining after response to passive detections) spent on treatment actions.
Search budget allocation	The proportion of the budget (remaining after response to passive detections) spent on ground search. Any direct nest injections resulting from detections made during search are funded out of this search budget.
Remote surveillance allocation	The proportion of the budget (remaining after response to passive detections) spent on remote surveillance. Any direct nest injections arising from detections made during remote surveillance are funded out of this surveillance budget.
Edge population	An estimate of the edge of the invasion obtained by generating a boundary expected to contain a specific proportion of the population. This proportion is the Edge

	Population parameter
Treatment emphasis, search emphasis, Remote surveillance emphasis	The treatment/search emphasis determines the relative contribution of each of the two site attributes (expected fire ant abundance and proximity to the estimated invasion edge) considered in determining where to undertake treatment/surveillance actions each period. Values near 0 ignore the invasion edge, values near 1 prioritise the invasion edge over the expected nest density.

Table 2: Efficacy and cost of management methods

Parameter	Cost	Efficacy
Treatment method		Mortality
Ground (foot)	$239.86/ha	80%
ATV (quad bike)	$146.77/ha	80%
Aerial	$81.79/ha*	80%
Direct nest injection	$36/nest	96%
Search method		Sensitivity
Remote sensing	$72.00/ha	0.38[ǂ], 0.50
Ground (foot)	$277.88/ha	0.80[ǂ]
Citizen detection probability		
Urban areas	N.A.	0.535[†]
Rural areas	N.A.	0.10[††]

*Aerial treatment is combined with ground treatment at a ratio of 9:1 (aerial:ground) to account for areas aerial treatment cannot reach. The cost of pure aerial treatment is $64.22/ha.

[ǂ] Value achieved in trials of remote sensing (R. Wylie, Manager Biosecurity Queensland Control Centre, pers. comm.) and ground surveillance. Neither method detects immature colonies.

[†] Estimate made with method of Keith and Spring (2013) using updated data, reported in Keith and Spring (2015).

[††] Estimate based on expert opinion. It is approximately one fifth of the sensitivity of urban citizen monitoring, reflecting the much lower human population density in rural areas than urban areas.

Table 3: Optimal strategy parameter values

Parameter	**No remote sensing**	**With remote sensing**	
		90% eradication probability target	**95% eradication probability target**
Treatment budget allocation	50%	50%	50%
Search budget allocation	50%	50%	50%
Ground search	50%	20%	20%
Remote sensing	0	30%	30%
Edge population	0.90	0.90	0.90
Treatment emphasis	0	0	0
Ground search emphasis	0.5	0.3	0.3
Remote sensing emphasis	0	0.4	0.5

Table 4: Cumulative eradication probabilities under alternative remote sensing (RS) sensitivities for different 10-year eradication probability targets

Target probability of eradication within 10 years	**90%**		**95%**	
RS sensitivity	**38%**	**50%**	**38%**	**50%**
Years to eradication	**Cumulative eradication probability over time**		**Cumulative eradication probability over time**	
1	0	0	0	0
2	0	0	0	0
3	0	0	0.03	0
4	0.03	0.10	0.08	0.10
5	0.15	0.23	0.23	0.25
6	0.35	0.40	0.33	0.40
7	0.65	0.65	0.65	0.70
8	0.83	0.80	0.90	0.80
9	0.88	0.88	0.93	0.93
10	0.90	0.90	0.95	0.95
Minimum required budget ($ m./yr)	17	16	23	22

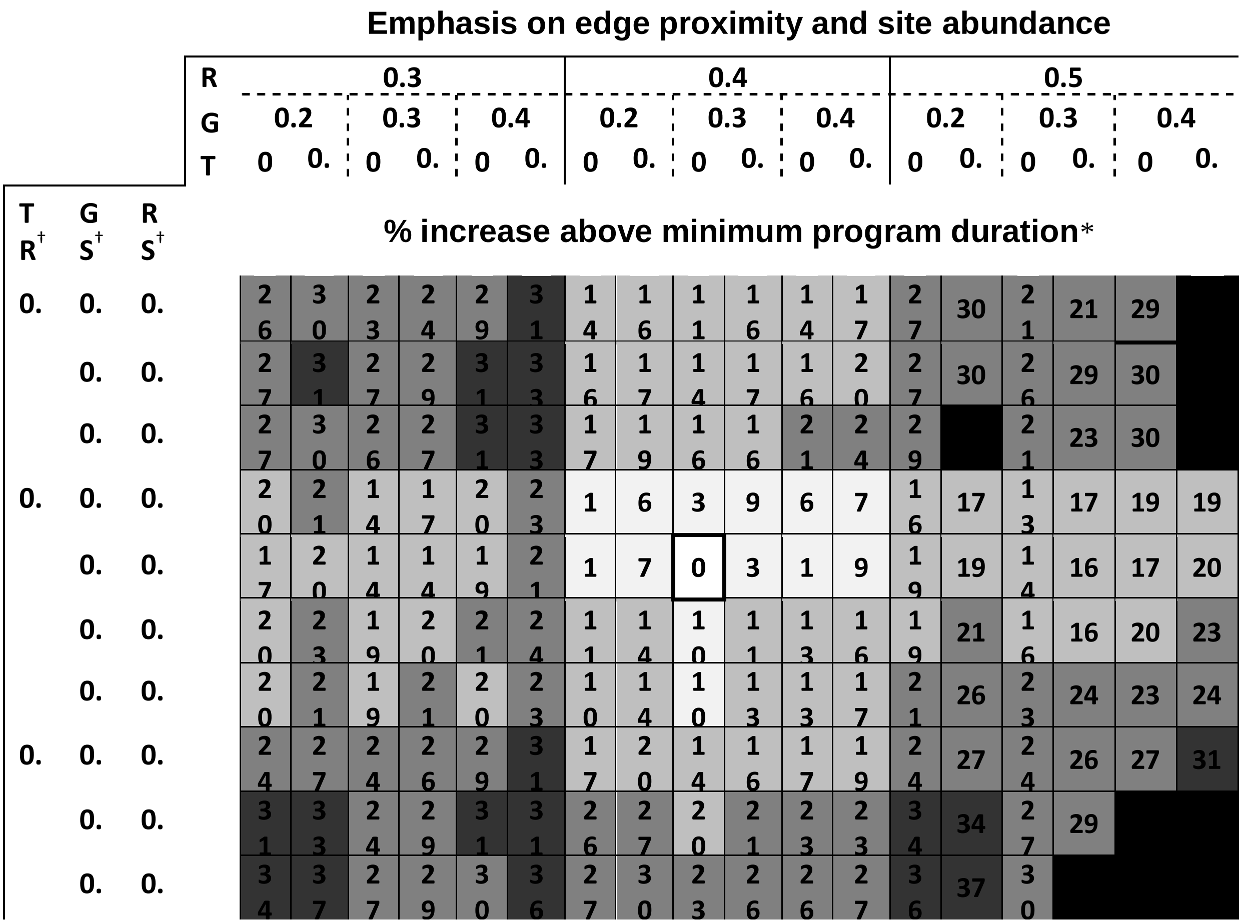
Figure legend

Figure 1: Sensitivity analysis for current remote sensing sensitivity (0.38) and eradication target probability of 90%. Darker shading indicates longer mean program duration compared to the minimum achievable duration. Control variable combinations that do not achieve eradication are shaded black.

Figure 2: Initial fire ant expectation map. Locations with more than 0.001 expected fire ant colonies are in orange. Urban areas are shaded white and pale grey, rural areas have darker shading.

Figure 3: Actions taken in first month within the 90% invasion boundary. Treated areas are in red, dark green areas illustrate ground surveillance, blue areas are

remotely sensed, the boundary estimated to enclose 90% of fire ants is illustrated in light green. Urban areas are shaded white and pale grey, rural areas have darker shading.



Emphasis on edge proximity and site abundance

% increase above minimum program duration*

			R	0.3						0.4						0.5					
			G	0.2		0.3		0.4		0.2		0.3		0.4		0.2		0.3		0.4	
TR†	GS†	RS†	T	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.	0	0.
0.	0.	0.		26	30	23	24	29	31	14	16	11	16	14	17	27	30	21	21	29	■
	0.	0.		27	31	27	29	31	33	16	17	14	17	16	20	27	30	26	29	30	■
	0.	0.		27	30	26	27	31	33	17	19	16	16	21	24	29	■	21	23	30	■
0.	0.	0.		20	21	14	17	20	23	1	6	3	9	6	7	16	17	13	17	19	19
	0.	0.		17	20	14	14	19	21	1	7	0	3	1	9	19	19	14	16	17	20
	0.	0.		20	23	19	20	21	24	11	14	10	11	13	16	19	21	16	16	20	23
	0.	0.		20	21	19	21	20	23	10	14	10	13	13	17	21	26	23	24	23	24
0.	0.	0.		24	27	24	26	29	31	17	20	14	16	17	19	24	27	24	26	27	31
	0.	0.		31	33	24	29	31	31	26	27	20	21	23	23	34	34	27	29	■	■
	0.	0.		34	37	27	29	30	36	27	30	23	26	26	27	36	37	30	■	■	■

† Proportion of program budget allocated to treatment (TR); ground search (GS) and remote search (RS)

* Result for each parameter set is based on an average of all simulations in which eradication occurred

Legend		
	⬜	1-10
	░	11-20
	▒	21-30
	▓	31-37
	■	Eradication not achieved within 10 years

Figure 1

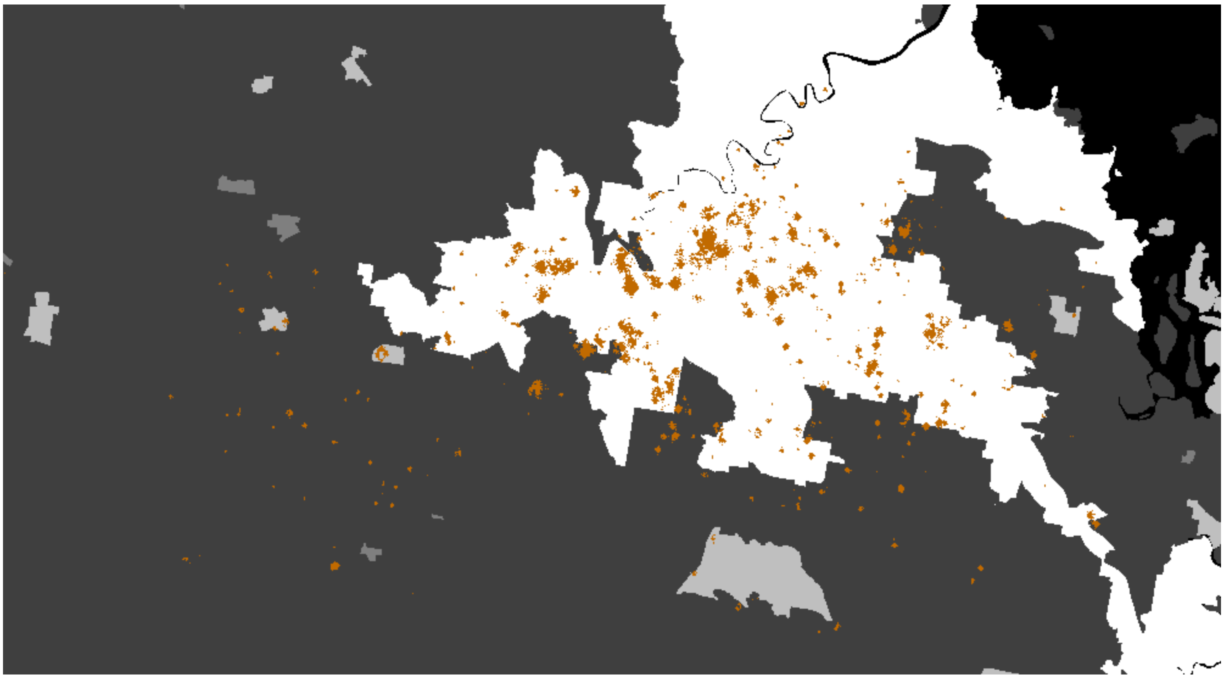


Figure 2

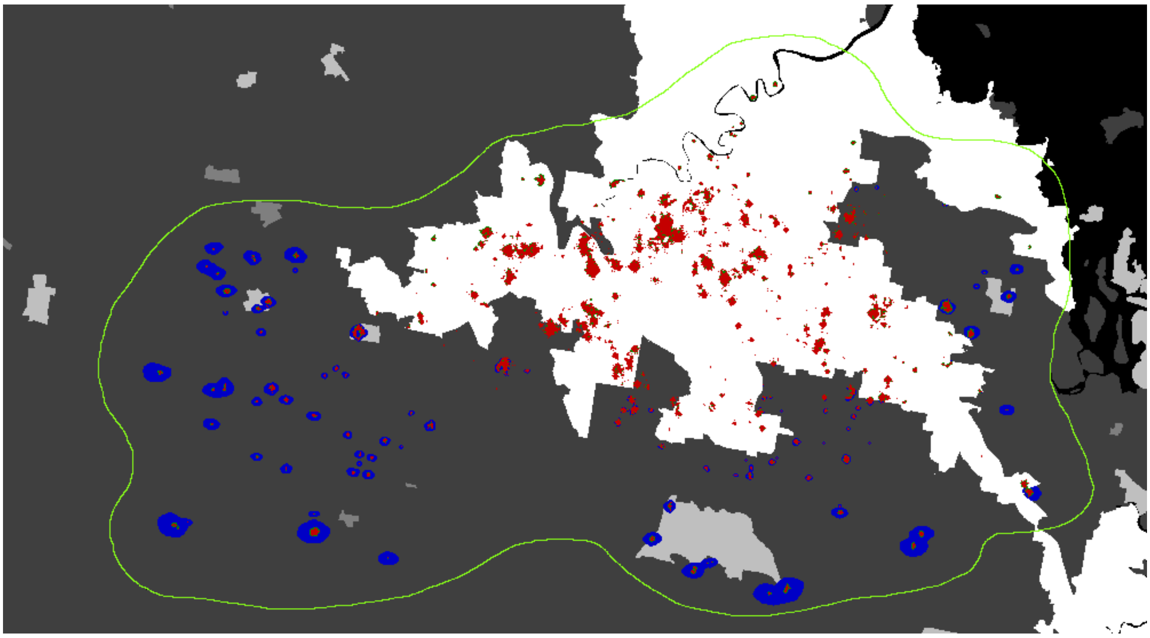


Figure 3