NATIONAL
Fire Ant Eradication
PROGRAM

National Fire Ant Eradication Program Strategy: Proof of Freedom (PoF)

Authors' note:

Progressing this Proof of Freedom (PoF) strategy is somewhat complex as it relates an eradication strategy, a robust strategy for verifying eradication, as well as the scientific and quantitative methods required to conclude freedom from fire ants. To understand the strategic component of PoF, you must first understand how statistical modelling techniques are used to transform surveillance returns into certainty in freedom. All care has been undertaken to cite the relevant scientific material to help understand these techniques, and to summarize the relevant content from those sources as it relates to proving freedom from fire ants.

If you are not familiar with Bayes's rule, concepts of Bayesian updating, binomial probability, and issues related to imperfect detection, it is recommended to go straight to section 3.1 to understand probability and how it is applied in this situation. It is also highly recommended to read the scientific papers cited in this document, to genuinely help the reader understand the topic of freedom surveillance.

Thank you!

Queensland Government

Glossary

Term	Definition
Alternative baits	Baits that are currently not used by the Program
Clearance Zones	Divisions of the current geographic extent of the fire ant infestation in Australia, that are to be cleared of fire ants individually (CZ)
Community treatment	Supplemental treatment of fire ants by individual landowners, or small interest groups.
Clear / Clearance	Describing the state of, or process of, local eradication and confirmation of eradication within a CZ
Eradication	Complete, permanent removal of fire ants from an area
Isolated colonies	Observed colonies that do not imply the existence of more nearby colonies
Surveillance	Use of a particular method or technique to detect fire ants within a defined area. In most cases, refers to visual, ground-based inspection by humans, or detection dogs.
Treatment gap	Areas where treatments: 1) are not applied, 2) are applied inadequately,3) are not applied at the recommended frequency, which undermine the strategic ability to eradicate
Unsuitable habitat	More properly, non-habitat, or *unsuitable areas*; places or conditions whence fire ants cannot contribute to a sustained fire ant population.

1. The Road to Complete Eradication: Proof of Freedom

PoF is the final declaration of a pest eradication initiative—in this case the eradication of Red Imported Fire Ants (fire ants) from Australia, by the National Fire Ant Eradication Program (the program). PoF can only be declared upon attainment of meaningful, quantifiable evidence of the absence of fire ants. Such evidence comes in the form of knowledge of eradication treatments and a planned strategy, supplemented with active surveillance to demonstrate that fire ants have been eradicated.

As of 2022, eradication efforts have confined Australia's fire ant infestation to South East Queensland (SEQ). To demonstrate PoF, the program will pass through three phases: *eradication, clearance* (involving surveillance and eradication if detected), and final *PoF surveillance*. To be clear, the evidence for PoF is attained steadily throughout all three phases, but the mode of attainment is different in each phase. After each phase, a decision point for progression to the next phase is required (**Table 1**).

PoF can only be declared when surveillance demonstrates a very high probability that SEQ is free from fire ants.

Table 1. Phases of Eradication

Phase	Activity	Time period	Area incorporated
Phase 1: Eradication Treatment	Three rounds of IGR each year for two consecutive years	2 years	Clearance Zones (CZ) within the Eradication band
Decision point 1: No evidence of fire ants; Prior P(Freedom) > 0.5 established for Clearance Zones (CZ); Individual CZs declared "clear"			
Phase 2: Clearance	Surveillance only. If fire ants detected, revert to Phase 1, according to response protocols	5 years	CZs within the Eradication band immediately after treatment. Minimum 17% surveillance of area within each CZ.
Decision point 2: Target P(Freedom) reached in CZ; Individual CZs declared "clear"			
Phase 3: Final Proof of Freedom	Resourcing (FTE and bait stockpiles) maintained on standby basis; minimal "maintenance" surveillance. If fire ants are discovered, revert to Phase 1.	When overall P(Freedom) is very high	All cleared CZs
Decision point 3: Target Overall P(Freedom) is reached; program declares Freedom: Maintains agreements with contractors, but not budgeted			

PoF is the complete absence of fire ants and will result in the program ceasing all activities related to eradication. The exact moment of total eradication is unknown, and PoF will be achieved though surveillance (data) and statistical analysis / modelling to make informed evidence-based decisions.

In general, the PoF process is very simple: perform eradication activities over an area, survey to verify success, and retreat if necessary. The main issue then becomes determining how much surveillance is necessary to conclude success, which is the main objective of this document. However, surveillance to verify freedom from fire ants requires an effective, integrated eradication and containment strategy to be possible; it is not possible or reasonable to prove eradication of a large infestation if local, permanent eradication (herein referred to as "clearance") of small portions (herein termed "Clearance Zones") of the larger infestation are not probable. Therefore, in this document we describe two strategic processes:

1. How to execute an eradication strategy that allows for clearance of smaller areas, taking into account risk from reinfestation, and
2. How to use surveillance to infer clearance success, and eventually total eradication.

2. Clearance Zones (CZs)

The complete eradication of fire ants from Australia will occur sequentially through the partitioning of the geographic extent of the fire ant population into CZs - a coordinated process that commences from the outer areas first. The CZs system (*sensu* Anderson *et al.* 2017) is a *model* system used to stratify clearance surveillance and is depicted as a grid system overlaying the operational area (**Figure 1**). Each grid cell or CZ is 5km x 5km, or 2500ha, which is the minimum size to consider non-adjacent CZs as spatially independent in their infestation state. In this system, the local eradication of fire ants and verification of absence of fire ants within a CZ is called "*clearance*."

In general, fire ants are removed from individual CZs, and only after all CZs have been "cleared," can PoF be declared.

In the CZ system, all CZs belong to a local neighbourhood of nine CZs (the individual CZ plus the eight adjacent CZs), and to be "*cleared*," each zone must progress according to the following five rules (**Figure 2**):

1. All CZs commence as “*assumed infested*.”
2. All CZs must receive 2 years’ eradication treatment, immediately followed by 5 years’ intensive* “*clearance*” surveillance without a detection.
3. All CZs within the local neighbourhood must have received eradication treatment followed by 5 years’ intensive “*clearance*” surveillance without a detection
4. All CZs within the neighbourhood of an infested CZ must receive intensive “*clearance*” surveillance annually until the infested CZ has completed the eradication treatment and subsequent 5 years’ surveillance to confirm containment within the known infested CZ.
5. All detections during clearance surveillance reset that CZ to “assumed infested” whereby eradication treatment* re-commences.

All CZs must have either ongoing eradication treatment or ongoing surveillance until they are cleared, and no CZs can be “cleared” until all neighbouring cells have been cleared.

*Eradication treatment in response to a clearance surveillance detection is done in accordance with the detection response protocol, which is a standard treatment distance from the outermost known colonies.

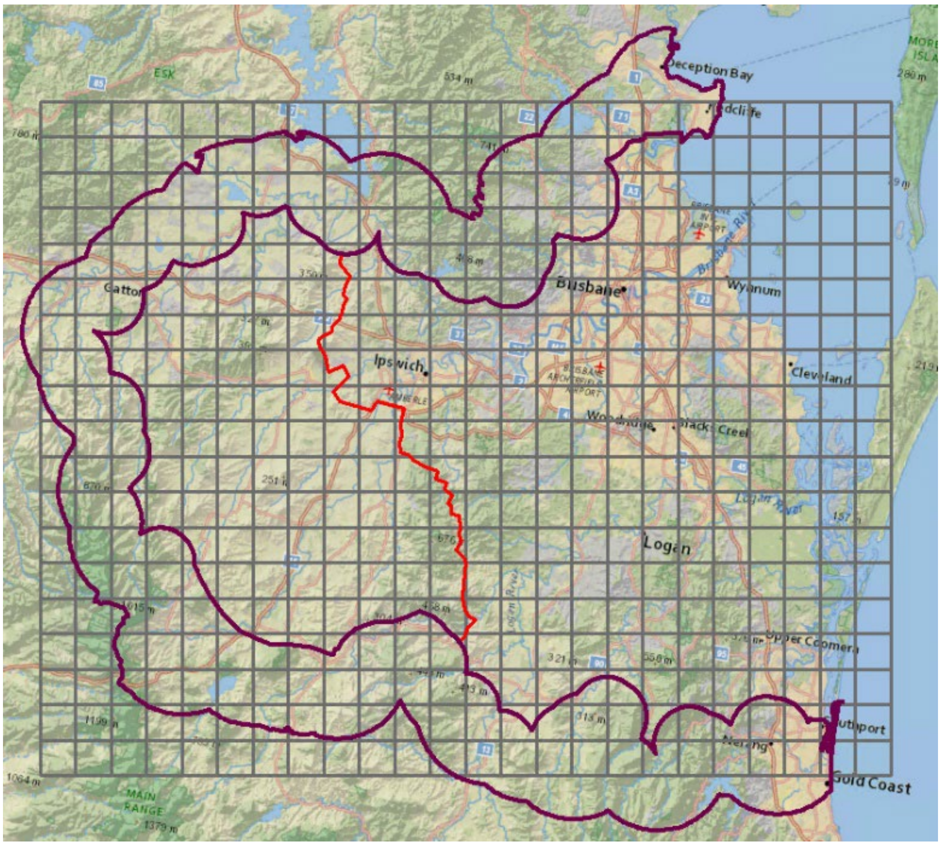

Figure 1. The Clearance Zone s

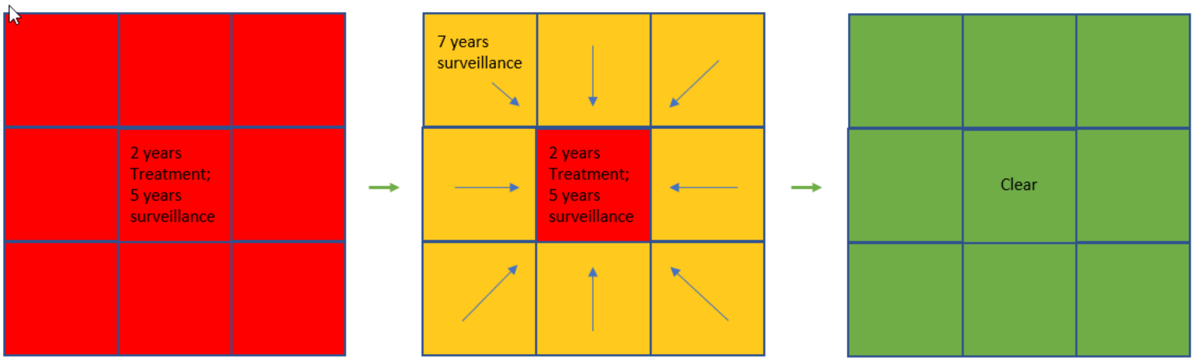

Figure 2. The clearance of a neighbourhood of CZs. Red cells are known infested.

In the CZ system, infestation status of each CZ affects the ongoing activities within its neighbours, but not in non-adjacent CZs. Again, this model is based on the view that an infestation within a 5-km CZ is a threat—via flight spread—to infest one or more of its neighbours, since an infestation could never be >2.5 km from the border of the nearest neighbouring (including those diagonally adjacent) CZ. Also, any infestation can never be < 5 km from the edge of the nearest non-adjacent (including diagonally adjacent) CZ.

This is important because this structure allows for a system where adjacent (including diagonally adjacent) CZs are not independent in their infestation risk—based on flight distances—while non-adjacent CZs (excluding diagonally adjacent CZs) can be treated as independent in their infestation risk. For a network of CZs, if as few as 1/9 of CZs remain infested, the worst-case scenario is that there are no CZs that are non-adjacent to infested CZs, i.e. all uninfested CZs are immediately threatened by infested CZs (Figure 3). Therefore, eradication treatment must occur in such a way that a target ≥ 90% of CZs are latently free from fire ants following treatment.

This 90% value corresponds to the initial expected success rate of eradication treatment (no gaps, 3 rounds / year, 2 consecutive years) on a per CZ basis, which is also the “prior” estimate of absence of fire ants in any individual CZ to be used when updating certainty in freedom according to Bayes’s rule. For an explanation of Bayes’s rule, prior expectations, and Bayesian updating, particularly as it relates to PoF, see **Sections 3 and 4**.

During post-eradication (“clearance”) surveillance, eradication failures are identified, and a responsive treatment is applied. Conservatively, if proper eradication treatment is carried out, we expect those failures to be approximately no more than 10% of CZs. However, for the purposes of having certainty in freedom, we can tolerate up to a 40% failure rate by having a conservative surveillance requirement for proving freedom (see Section 5 for freedom surveillance requirements). For more on this failure rate, please see Sections 4.1.

Further surveillance without a detection is then sufficient to update the within-CZ probability of freedom.

The distinction between an initial “prior” estimate of p(absence) and the final “posterior” estimate of p(absence) is important because the prior estimate merely establishes that there is some expectation of failure, while surveillance and subsequent estimates of freedom help pinpoint the exact locations of failures, while eliminating other CZs as potential failures. Surveillance is necessary to identify which CZs might be failures, and therefore require further eradication treatment. For final PoF targets and surveillance requirements, please see **Sections 3 and 4**.

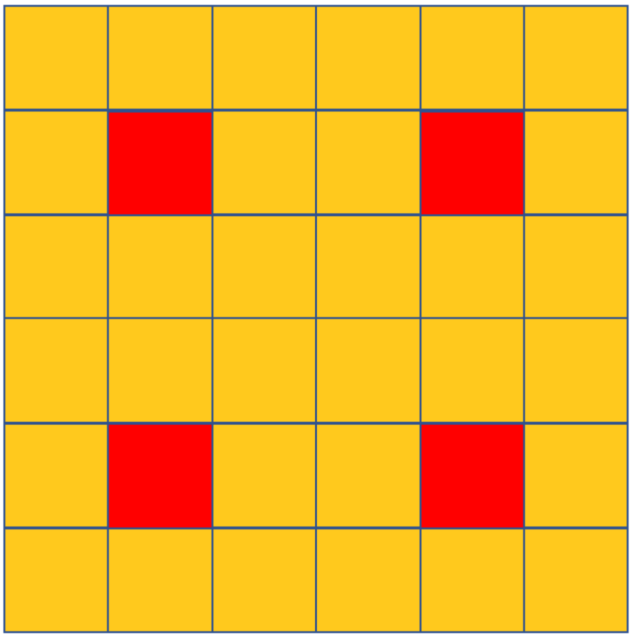

Figure 3. A network of infested (red) and uninfested (orange) CZs, where 1/9 of all CZs are infested, and therefore all CZs are infested or threatened by adjacent infestation.

3. Surveillance Requirements

A fire ant infestation, no matter how small, will spread if not destroyed. Following initial eradication treatment efforts, detection is essential to initiate further eradication treatment of remnant fire ant nests. As such, clearance surveillance serves two purposes:

1. Early detection of remnant fire ant colonies
2. Attaining evidence of absence of fire ants for containment / PoF.

Evidence of absence of fire ants comes in the form of non-detection from structured surveillance. Since we are primarily concerned with the presence or absence of fire ants, we state the following principles for surveillance:

1. The presence of an entire larger infestation is inferred from the detection of one or more colonies within that infestation.
2. The goal of surveillance is not to detect every colony within an infestation, but rather to simply detect one or more colonies.

Before determining the clearance surveillance requirement for early detection, and to reach some target certainty in absence of fire ants, we must first understand how prior expectation, imperfect detection, and scale of inference combine to infer the infestation status of a place.

3.1. Bayes's Rule for Estimating the Probability of Freedom: Priors, likelihoods, and posterior probabilities

Logically, we propose to use non-detections from structured surveillance to help infer absence of fire ants following eradication efforts. In almost all surveillance systems, detection is imperfect. In other words, it is possible to search for fire ants and not detect them, even if they are present. To conclude the probability of actual absence, given non-detection, it is most convenient to use Bayes's rule, which explicitly incorporates the effect of imperfect detection on inference from surveillance, and updates our level of certainty about the true state of a system, which we describe as a hypothesis. For example, a hypothesis that we can evaluate using Bayes's rule is the absence of fire ants from a place following an eradication effort. When evaluating the probability of absence given a non-detection, Bayes's rule takes the following form:

$$\mathrm{P(Absence\ |Non\text{-}detection)} = \frac{\mathrm{P(Non\text{-}detection\ |\ Absence) \times P(Absence)}}{\mathrm{P(Non\text{-}detection\ |\ Absence) \times P(Absence)\ + P(Non\text{-}detection\ |\ Presence) \times P(Presence)}}$$

3.1.1. Example Calculations Using Bayes's Rule

In the above equation, we can choose **as an example** to assign the following values to the terms:

P(Non-detection | absence) = 1 (100%) ; we assume zero ultimate false-positives; this is also known as the "likelihood" of observing the data

P(Non-detection | Presence) = 0.2 (20%); this is 1 – 0.8, where 0.8 is the detection probability given presence; this is also known as the "likelihood" of observing the data

P(Absence) = 0.9 (90%); this is what is known as the "prior" probability or baseline expectation of absence

P(Presence) = 0.1 (10%); this is 1 – the prior, or the prior or baseline expectation of presence

The resulting value is:

$$0.978 = \frac{1 \times 0.9}{1 \times 0.9\ + 0.2 \times 0.1}$$

or a 97.8% chance of absence, based on data *and* prior expectation.

Now consider a case where the same data are collected, but in a place we knew with 100% certainty there were no fire ants, such as at the bottom of the deepest trench of the ocean:

P(Non-detection | absence) = 1 (100%)

P(Non-detection | Presence) = 0.2 (20%)

P(Absence) = 1 (100%); again, this is what is known as the "prior" probability or baseline expectation of absence

P(Presence) = 0 (0%); again, this is 1 – the prior, or the prior or baseline expectation of presence

The resulting conclusion is:

$$1 = \frac{1 \times 1}{1 \times 1 + 0.2 \times 0}$$

or a 100% chance of absence.

You can see how the prior expectation is required for inference, and how it is incorporated into the convenient Bayes's rule.

Bayesian updating is the algorithm for using Bayes's rule to explicitly and serially update our level of certainty about a hypothesis. In first case described above, we "update" our certainty in absence from 90% to 97.8%. If we were to repeat the search, we can now substitute the updated certainty into the prior certainty of Bayes's rule:

$$0.996 = \frac{1 \times 0.978}{1 \times 0.978 + 0.2 \times 0.022}$$

We have serially "updated" the certainty in absence to 99.6%. Wintle *et al.* (2005) demonstrated that the above updating algorithm can be simplified by exponentiating the likelihood **P(Non-detection | Presence)** by the number of time to be updated *n,* where in the above case *n* = 2:

$$0.996 = \frac{1 \times 0.9}{1 \times 0.9 + 0.2^2 \times 0.1}$$

In the simplified algorithm posed by Wintle *et al.* (2005), the exponentiated likelihood is a constant. In our system, we intend to use continually changing likelihoods, based on continually changing hypotheses, which we will discuss in the next sections. Therefore, the Wintle *et al.* (2005) algorithm is not directly applicable to our PoF process without some additional modifications.

3.1.2. Spatial scaling and hypothesis-variant estimation of P(Non-detection | Presence)

In **Section 3.1**, we demonstrated Bayesian updating of certainty in absence based on prior expectation and negative surveillance returns. However, it's **critically important** to understand that ***all terms*** in the simple model above relate only to the area searched. In other words, if a detection rate of 80% for visual inspection is used, the inspection method dictates that it can ONLY apply to area inspected. We are likely only to inspect a fraction of an area about which we are to make inference. This is *sampling*. In the simplest case, where the hypothesis is that a single colony is present and the objective is detective one or more colonies (*according to Section 3: surveillance rule 4*), the detection rate for some search effort—and therefore the inference from such effort—is proportional to the *amount* of the area of interest that is searched. For example, if we are to infer absence of fire ants over a 2500-ha area, we must consider how much of that area is searched, and not simply use the per-unit detection rate of 80%.

However, following eradication treatment, our hypotheses about the state of an infestation change through time to reflect the amount of spread that has occurred since the conclusion of eradication treatment. In other words, as time passes, our hypothesis about the infestation progresses from, "*There are fire ants present,*" to, "*Fire ants have been present for a number of years, and have been increasing in local population size and distribution commensurate with known fire ant biology.*" This directly impacts the likelihoods in Bayes's rule, as time passes and the hypotheses change, according to the following rules and assumption:

1. Following eradication treatment, all remnant infestations will grow from a single undetected colony, which is the lowest detectable infestation size.
2. All infestations grow at a reasonably well-modelled rate and shape
3. There are no "*isolated*" colonies detected after a year of spread
4. All surveillance methods have imperfect detection
5. Detection error can be described with *sensitivity* and *specificity*. These figures are assigned to **individual objects**. Sensitivity is the chance of detecting a single object, or the proportion of objects expected to be detected. Specificity is equal to 1 *minus* the false positive rate.
    a. For our purposes, we assume the false positive rate is negligible.
6. If there is no bias in detectability between objects to detect, then the probability of detecting at least one object increases with the number of objects available to detect. This is modelled by the complement to the binomial probability mass function evaluated at zero: 1- [p(0) = choose(n, 0) p^0 $(1\text{-}p)^{n-0}$], where *n* is the number of objects available, and *p* is the detection rate. Therefore, the probability of detecting one or more object of candidate size *n* and detection rate *p* simplifies to 1-[$(1\text{-}p)^n$].
7. **The detector must encounter the object during surveillance**. For example, the individual fire ant mound **must** be within the range of the detector to be detectable and included.
8. The probability of identifying a single object is the Encounter Rate multiplied by the Detection Rate. That is, the chances you are in a correct location to detect the fire ant mound, multiplied by the chances of you seeing it.

These rules and assumptions allow us to infer absence given negative surveillance, while considering

1. We are partially sampling the landscape
2. Our detection methods are imperfect
3. Population growth of fire ants makes non-detection increasingly unlikely.

In other words, we allow that the probability of detecting one or more colonies increases as an infestation age and increases in size. Following initial eradication treatment efforts, we essentially hypothesize that an undetected, unobserved remnant infestation has an age of zero years, and a minimal population size of one, which is the most conservative and hardest-to-detect state. Each year, the hypothesis is updated to reflect an undetected, unobserved infestation that one year older and has one years' additional growth and spread. Since each new hypothesis has a new population size and distribution, each new hypothesis must carry a new probability of detecting one or more colonies—and therefore a new likelihood of observing zero colonies—for any given surveillance effort. These values are essential terms in Bayes's rule for updating certainty in a hypothesis.

3.1.3. Estimating P(Non-detection | Presence) for a growing infestation

Infestation spread and surveillance simulations are required to estimate the chances of detecting one or more colonies in a growing infestation. Colonies in a spreading infestation are not uniformly distributed; they are clumped (**Figure 4**.). Because of the clumpiness of colony distributions, analytical estimates of the chances of detecting an infestation can be difficult for any given surveillance effort (see McCarthy *et al.* 2012). This is because, as we stated in Section 3.1.1, the detector must encounter a colony to detect it, and the possibility of encountering any number of colonies depends on the clumpiness of those colonies. If we apply a model system of "surveillance grids" to a growing infestation, we could estimate the surveillance effort required to detect one or more colonies of a growing infestation.

The central limit theorem that would allow us to use a binomial approximation of the chances of successful sampling (our goal in this exercise), relies on virtual sampling *with replacement; however*, we are unlikely to sample our grid of surveillance cells with replacement, i.e. if we are to sample five cells, they are likely to be five different cells, with no repeats. This constitutes sampling *without replacement*, where every sampled cell is immediately removed from the candidate set, and the marginal chances of detecting an infestation, should it exist, increase. So, because of clumpiness of growing infestations, and because of sampling without replacement, surveillance simulations are required to estimate the chances of detecting one or more colonies in a growing virtual infestation.

In our spread simulations, we only consider the case of "natural" spread via flight, which is the most common and most reliably modelled case. It is true that occasional long-distance flight dispersals may happen under the rarest of circumstances, as well as human-assisted movements, which do pose a real risk to containment and eradication. However, the purpose of this modelling exercise is not to measure absolute risk of spread. Rather the purpose is to have a means to estimate the relationship between the age of an infestation and the expected detection rate, and thereby have a reliable figure to include in the Bayesian updating of PoF. In other words, accounting for long-distance dispersals, including human assisted movement, says very little about whether an infestation should be eminently detectable at its origin. If an infestation should be detected, and is not, that non-detection adds evidence that the infestation in fact does not exist, regardless of whether a long-distance dispersal occurred. The aim is to have accurate estimates of detection error for a typically spreading infestation, whereby non-detection can be used to conclude some certainty in absence.

3.1.3.1. Methods: Simulating Spread

A critical value for modelling spread is the potential distance any newly-mated fire ant queen is expected to fly—and establish—from its original colony. Observing flight distances and survival is very difficult, considering:

- The size of a fire ant queen
- Establishing the location of the parent nest.

A published study on flight distances (Helms & Godfrey (2016) suggests distances of between 2.8 km and 4.2 km, with the average somewhere between 540 m and 810 m. Importantly, this flight distance is straight-line, level flight, and does not include flight ascending to mating height, maintaining mating altitude, or descending to the ground. These results are consistent with previous empirical studies (Markin et al. 1971, summarized in Tschinkel 2013) showing that the majority of successfully establishing queens land very close (≤ 400m) to the original nest, while an ever decreasing, yet noticeable, proportion establish up to 1.6 km away, decreasing at a rate that would mean ≥99.9% of establishments would be within 3.5 km of the original nest.

Wylie *et al.* (2021) also report that, at the Port of Gladstone—which is one of the only isolated fire ant infestations in history with genetic analysis performed on >70% of the population—the average distance flown was 420 m, and ranged up to 1.2 km.

The second critical value is the reproductive rate of newly established monogyne fire ant colonies. Tschinkel (2013) summarizes many studies to arrive at the rate of roughly 1.5 progeny / established colony / year, for an average of six years.

Therefore, to simulate spread, we created a computer program that, starting with a "seed" of a single colony, create at random 0, 1, 2, or 3 new colonies, and virtually disperse the new colonies towards a random direction, at a distance (km) drawn from a random Gaussian kernel distribution where we set the parameter $\sigma = 0.8$ (**Figure 5**). For every time step, every existing colony underwent the same process. We ran 100 simulations each for 5 generations, which are notionally years. Table 2 is drawn from the results of those 100 simulations.

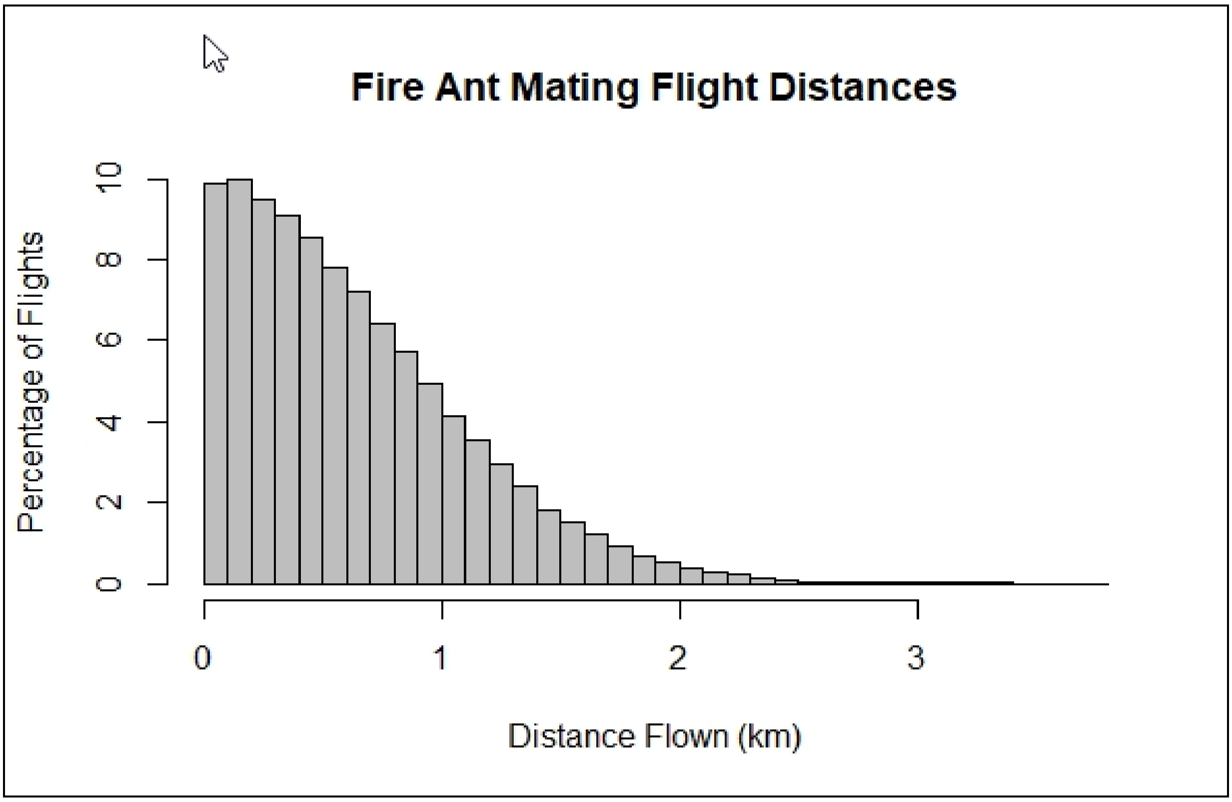

Figure 5. Simulated distribution of 100,000 fire ant mating flight distances, drawn randomly from a Gaussian kernel distribution where $\sigma = 0.8$, and the distance unit is kilometres.

It is important to note that the above simulation does not account for human assisted movements, or extreme cases of long-distance, wind-assisted flights, but rather to construct a reasonable scenario to help predict the detectability of a typical, outwardly spreading infestation.

3.1.3.2. Methods: Simulating Surveillance

For each of 100 spread simulations generated (described in Section 4), we overlayed a network of cells depicted in **Figure 4**. Instead of using 25 cells being 1 km x 1 km (100 ha) each, 169 "surveillance" cells were created (13 cells x 13 cells) approximately 14.8 hectares each (ex. **Figure 6a**), each represents a single day's effort for a single ground-based field crew conducting 100% visual surveillance.

25 levels of virtual search effort were defined as displayed on the y-axis of **Table 3** as the number of 15-ha grids to be virtually surveyed. For each of the 25 levels of effort,15,000 random allocations of cells were virtually searched. For example, spread simulation #1, the effort level of 10 cells searched (≈ 150 ha), 15,000 sets of 10 cells were generated, drawn without replacement from the candidate set of 169 cells. Therefore, there were 100 spread simulations x 25 effort levels x 15000 random allocations = 37.5 million random search allocation generated.

Then, for each of the 37.5 million search allocations, the number of simulated colonies encountered by the search was extracted, should it have occurred in each of the five years of every spread simulation, and estimated the probability of positively identifying ≥ 1 of those colonies encountered, according to the binomial probability mass function described in **Section 3.1.1**Rules and Assumptions #6, where $p = 0.8$, which is our best estimate of the detection rate for ground-based visual surveillance (Wylie *et al.* 2021), and n = the number of nests encountered virtually. **Figure 6b** shows an example of a single such extraction, where the simulated spread is in year two, and the search allocation 7 x 15-ha searches (105 ha total).

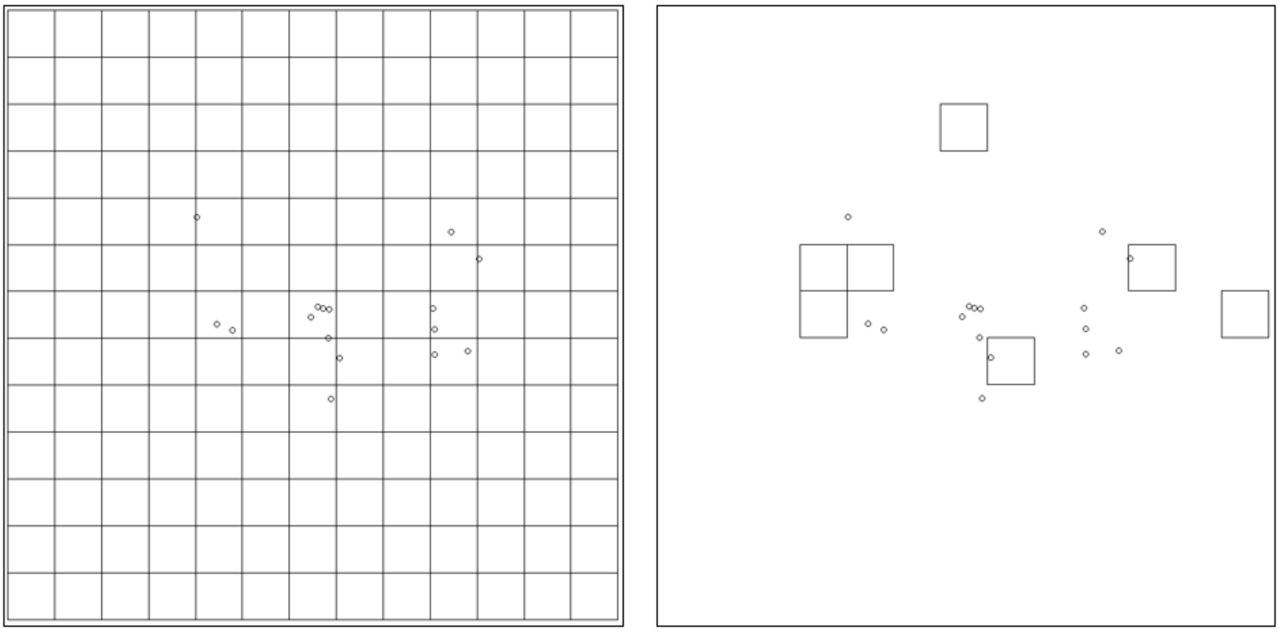

Figure 6. a) Example simulation of spread in year two, overlaid by 15-ha surveillance cells, and b) an example random search allocation of seven surveillance cells, encountering two colonies.

3.1.4. Simulation Results: Detection Rates

Table 2 shows the resulting detection rates, as estimated from simulations, for each of 25 levels of surveillance effort, at each year following the completion of eradication treatment. For convenient application of the Wintle et al. (2005; see Section 3.1.1) algorithm, instantaneous detection rates from our simulations have been transformed into cumulative detection probabilities, according to the following algorithm:

$$CP(\text{detection})_{t,j} = 1-(1- CP(\text{detection})_{t-1,j}) \times (1- P(\text{detection})_{t,j})$$

where CP(detection) is the cumulative detection probability, and P(detection) is the instantaneous detection probability, for every surveillance effort level j and every year post-treatment t.

Table 2. Simulated cumulative detection probabilities for each year following eradication treatment (x axis), and for each level of surveillance effort (y axis; hectares of visual inspection), for a spreading infestation within a 2500-ha clearance zone.

Annual Surveillance / CZ (ha)	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
30	0.0089067	0.0294882	0.0777720	0.1805660	0.3747548	0.6454800
60	0.0177067	0.0576939	0.1481428	0.3259145	0.6053574	0.8711827
105	0.0318933	0.1017976	0.2506369	0.5058855	0.8067254	0.9717836
135	0.0435733	0.1346484	0.3175890	0.6024908	0.8811279	0.9897520
180	0.0587733	0.1777199	0.4024815	0.7101769	0.9414073	0.9976063
210	0.0663467	0.1998872	0.4458283	0.7592274	0.9616016	0.9989995
255	0.0788800	0.2358697	0.5108137	0.8220922	0.9804434	0.9997334
285	0.0922667	0.2680985	0.5589973	0.8586376	0.9878682	0.9998908
330	0.1005867	0.2950299	0.6059882	0.8938954	0.9936328	0.9999686
360	0.1168533	0.3286507	0.6466170	0.9156685	0.9959521	0.9999860
405	0.1273600	0.3580522	0.6885490	0.9380186	0.9979035	0.9999957
435	0.1369600	0.3809710	0.7166923	0.9501711	0.9986702	0.9999981
480	0.1497067	0.4102635	0.7504186	0.9630777	0.9992780	0.9999993
510	0.1560000	0.4260552	0.7690426	0.9692013	0.9995030	0.9999997
555	0.1772800	0.4667247	0.8055871	0.9787469	0.9997563	0.9999999
585	0.1835733	0.4822845	0.8208335	0.9824705	0.9998325	0.9999999
615	0.1900800	0.4977903	0.8354802	0.9856804	0.9998887	1.0000000
660	0.2052800	0.5264577	0.8580625	0.9896147	0.9999394	1.0000000
690	0.2150400	0.5452630	0.8718475	0.9917718	0.9999609	1.0000000
735	0.2315200	0.5733450	0.8902472	0.9940814	0.9999785	1.0000000
765	0.2428267	0.5924007	0.9019327	0.9953532	0.9999862	1.0000000
810	0.2613867	0.6211303	0.9173433	0.9967431	0.9999928	1.0000000
840	0.2648000	0.6293793	0.9226653	0.9972341	0.9999947	1.0000000
885	0.2768533	0.6495638	0.9331441	0.9979899	0.9999971	1.0000000
915	0.2842667	0.6627168	0.9397364	0.9984123	0.9999981	1.0000000

Eradication treatment and biosecurity requirements

To achieve the target of >90% of CZs being free from fire ants after eradication treatment, the following must be met:

a) The entire CZ and all neighbouring CZs must receive eradication treatment with at least three rounds of IGR bait each year for **at least** two consecutive years, possibly up to four consecutive years (for overlap/buffer areas). The timeframes may change if more effective alternative baits become available.
b) There are no gaps in treatment.
c) The first round of baiting each year ideally occurs early in the treatment season. Any places not receiving early treatment must be treated as soon as possible in the subsequent scheduling round, along with all neighbouring sites within 1.5km of the gap.
d) Rigorous biosecurity measures must be in-place and enforced, mitigating the risk human-assisted movement poses to local (CZ-level) absence of fire ants.

The 90% target is achievable, as most remnant infestations are the result of gaps in treatment, or failure to treat according to plan (three rounds / year for two consecutive years).

4. Clearance Surveillance: Updating Certainty in Freedom

In Section 3, we reviewed Bayes' rule, Bayesian updating, and demonstrated how spread and surveillance simulations can be used to generate likelihoods which can be used to update certainty in freedom, considering our hypotheses that any remnant infestations will grow in size and become easier to detect. In this section we will show how we use our likelihoods, combined with prior expectations of eradication, to update certainty in clearance, and ultimately total eradication.

4.1. Prior Certainty in Clearance (i.e. local eradication)

If a no-gaps strategy, with three completed treatment rounds is applied for two consecutive years, we estimate there would be a 90% rate of local freedom from fire ants in treated CZs. The evidence for this estimate is based on surveillance results from Area 1 and Western Boundary.

Over the course of three years, beginning in summer of 2017, Area 1 received broad-scale IGR treatment. While the Program did a remarkable job executing a huge campaign aimed at eradication, there were very few large, contiguous places—the size of a clearance zone, for example—that received three rounds of IGR treatment, with a properly placed "early" round, each year for two consecutive years, with *no gaps*. In fact, outright gaps, missed treatments, and other treatment weaknesses, were so numerous that predicting the locations of eradication failures was nearly impossible. Despite that, two plus years' surveillance returns from Area 1 and Western Boundary have shown that the vast majority of remnant infestations have stemmed from the survival—and subsequent spread—of minimal number of remnant colonies at the centre of each residual location. In other words, even though no places in Area 1 ever received sufficient *eradication* treatment, actual local eradication in most places was possibly imminent with perhaps one more years' treatment. Of the many residual infestations detected, there have been several isolated cases (notably the Summerholm and Washpool infestations) where numerous, widespread gaps and missed treatments cannot be implicated as the cause for failure. Furthermore, while Summerholm and Washpool are confusing and troubling because of an apparent lack of explanation, they seem to be exceptional and rare.

Based on evidence that a no-gaps, complete treatment strategy would effect a 90% CZ-level success rate, and because we have shown that a 90% success is a critical target for containment of remnant infestations, we have chosen 0.90 (90%) as our *prior* expectation in CZ-level clearance (i.e. local eradication). By using negative surveillance returns (Bayes's Rule) the program can update certainty in the eradication of fire ants (Anderson *et al.* 2017).

We can now simply insert each entry from Table 2 into Baye's Rule sensu Section 3.1.1, with a starting Prior(absence) = 0.9, and achieve the resulting Table 3, which show the probability of clearance (local freedom) at the CZ-level.

Table 3. CZ-level probability of clearance (local freedom) based on surveillance simulations and an initial prior certainty = 0.9 (90%).

Annual Surveillance / CZ (ha)	1 Years	2 Years	3 Years	4 Years	5 Years	6 Years
30	0.9008023	0.9026618	0.9070543	0.9165498	0.9350411	0.9621017
60	0.9015964	0.9052226	0.9135333	0.9303205	0.9579928	0.9858889
105	0.9028796	0.9092560	0.9231372	0.9479557	0.9789765	0.9968746
135	0.9039388	0.9122838	0.9295206	0.9577006	0.9869642	0.9988626
180	0.9053209	0.9162842	0.9377424	0.9688021	0.9935318	0.9997341
210	0.9060111	0.9183568	0.9419969	0.9739445	0.9957516	0.9998888
255	0.9071556	0.9217411	0.9484480	0.9806157	0.9978318	0.9999704
285	0.9083813	0.9247936	0.9532886	0.9845360	0.9986538	0.9999879
330	0.9091448	0.9273599	0.9580571	0.9883480	0.9992930	0.9999965
360	0.9106411	0.9305837	0.9622187	0.9907168	0.9995504	0.9999984
405	0.9116103	0.9334214	0.9665518	0.9931603	0.9997671	0.9999995
435	0.9124976	0.9356454	0.9694820	0.9944939	0.9998523	0.9999998
480	0.9136784	0.9385034	0.9730170	0.9959143	0.9999198	0.9999999
510	0.9142625	0.9400514	0.9749801	0.9965896	0.9999448	1.0000000
555	0.9162432	0.9440617	0.9788553	0.9976441	0.9999729	1.0000000
585	0.9168306	0.9456051	0.9804812	0.9980561	0.9999814	1.0000000
615	0.9174387	0.9471481	0.9820482	0.9984115	0.9999876	1.0000000
660	0.9188624	0.9500142	0.9844740	0.9988474	0.9999933	1.0000000
690	0.9197789	0.9519038	0.9859607	0.9990866	0.9999957	1.0000000
735	0.9213306	0.9547395	0.9879522	0.9993428	0.9999976	1.0000000
765	0.9223983	0.9566734	0.9892211	0.9994840	0.9999985	1.0000000
810	0.9241562	0.9596039	0.9908995	0.9996383	0.9999992	1.0000000
840	0.9244802	0.9604486	0.9914805	0.9996928	0.9999994	1.0000000
885	0.9256263	0.9625219	0.9926263	0.9997767	0.9999997	1.0000000
915	0.9263325	0.9638778	0.9933486	0.9998236	0.9999998	1.0000000

4.1.1. Revising the Prior

While a prior expectation of 90% is desired and achievable, it is not guaranteed. If surveillance returns in the two years immediately following eradication activities indicate that failure is substantially higher than 10%, then the prior expectation can be modified accordingly, and program analyses can be adjusted accordingly. **However, a conservative surveillance effort (see section 5) is robust to a CZ-level failure rate of up to 40% (prior probability of local freedom = 60%), while still resulting in an overall probability of freedom, across all CZs, that is > 50%.**

5. Overall Proof of Freedom

The surveillance required per CZ to progress to PoF across the entirety of SEQ depends on:

1. the number of CZs
2. the initial (prior) probability of each individual zone being free from fire ants prior to surveillance.

The main goal of clearance surveillance is to clarify which CZs do not have fire ants, and then to update our confidence in absence of fire ants of those CZs.

In order to estimate the overall proof of freedom across all CZs, we simply exponentiate the *per CZ* certainty in clearance (local freedom) by the total number of CZs. There are 350 CZs that will need to be progressed through the PoF Framework. Therefore, we can raise each entry in Table 3 to the power of 350 to calculate overall certainty in freedom. Those results are shown in **Table 4**. According to this table, following eradication treatment, annual surveillance *without a detection* must exceed 435ha (17%; 29 team days), for five consecutive years of ground-based surveillance per CZ to achieve >95% of overall freedom.

Table 4. Simulated overall chance (%) of total eradication across 350 CZ's for yearly surveillance effort (ha; y axis) and consecutive years without a detection (years; x axis), per CZs. Highlighted region represents > 50% overall chance

Annual Surveillance / CZ (ha)	1 Years	2 Years	3 Years	4 Years	5 Years	6 Years
30	0.00	0.00	0.00	0.00	0.00	0.00
60	0.00	0.00	0.00	0.00	0.00	0.69
105	0.00	0.00	0.00	0.00	0.06	33.43
135	0.00	0.00	0.00	0.00	1.01	67.15
180	0.00	0.00	0.00	0.00	10.32	91.11
210	0.00	0.00	0.00	0.01	22.54	96.18
255	0.00	0.00	0.00	0.11	46.78	98.97
285	0.00	0.00	0.00	0.43	62.41	99.58
330	0.00	0.00	0.00	1.65	78.07	99.88
360	0.00	0.00	0.00	3.82	85.44	99.95
405	0.00	0.00	0.00	9.05	92.17	99.98
435	0.00	0.00	0.00	14.48	94.96	99.99
480	0.00	0.00	0.01	23.86	97.23	100.00
510	0.00	0.00	0.01	30.25	98.09	100.00
555	0.00	0.00	0.06	43.80	99.06	100.00
585	0.00	0.00	0.10	50.61	99.35	100.00
615	0.00	0.00	0.18	57.33	99.57	100.00
660	0.00	0.00	0.42	66.79	99.77	100.00
690	0.00	0.00	0.71	72.63	99.85	100.00
735	0.00	0.00	1.44	79.45	99.92	100.00
765	0.00	0.00	2.25	83.47	99.95	100.00
810	0.00	0.00	4.08	88.11	99.97	100.00
840	0.00	0.00	5.01	89.80	99.98	100.00
885	0.00	0.00	7.50	92.48	99.99	100.00
915	0.00	0.00	9.67	94.01	99.99	100.00

However, if a CZ contains a remnant infestation, the program needs to detect that infestation within two years following eradication treatment. Instantaneous detection rates (see mention in Section 3.1.4) from spread and surveillance simulations show that the minimum required annual surveillance to confer a ≥ 50% chance of detecting an infestation within two years is 405 ha (27 team days, or 16% of a CZs total area) of ground-based surveillance (Table 6; Section 6) per CZ. Therefore, the recommendation to survey 17% each CZ is also good for early detection.

For simplicity and to be conservative, the program will maintain the 17% surveillance for five years following eradication treatment, which would confer a 95% chance of overall eradication. That is, for clearance surveillance, every CZ undergoes a minimum five consecutive years of intensive, ground-based surveillance, without a detection, at a rate of at least 17% coverage annually.

Furthermore, a 17% surveillance rate for five years without a detection is robust to a CZ-level failure rate of up to 40% (prior probability of local freedom = 60%), while still resulting in an overall probability of freedom, across all CZs, that is > 50%

6. Clearance Surveillance: Early Detection

Figure 4 illustrates a simulated spreading infestation within a neighbourhood of twenty-five cells, each 100 hectares (1 km x 1km) in area.

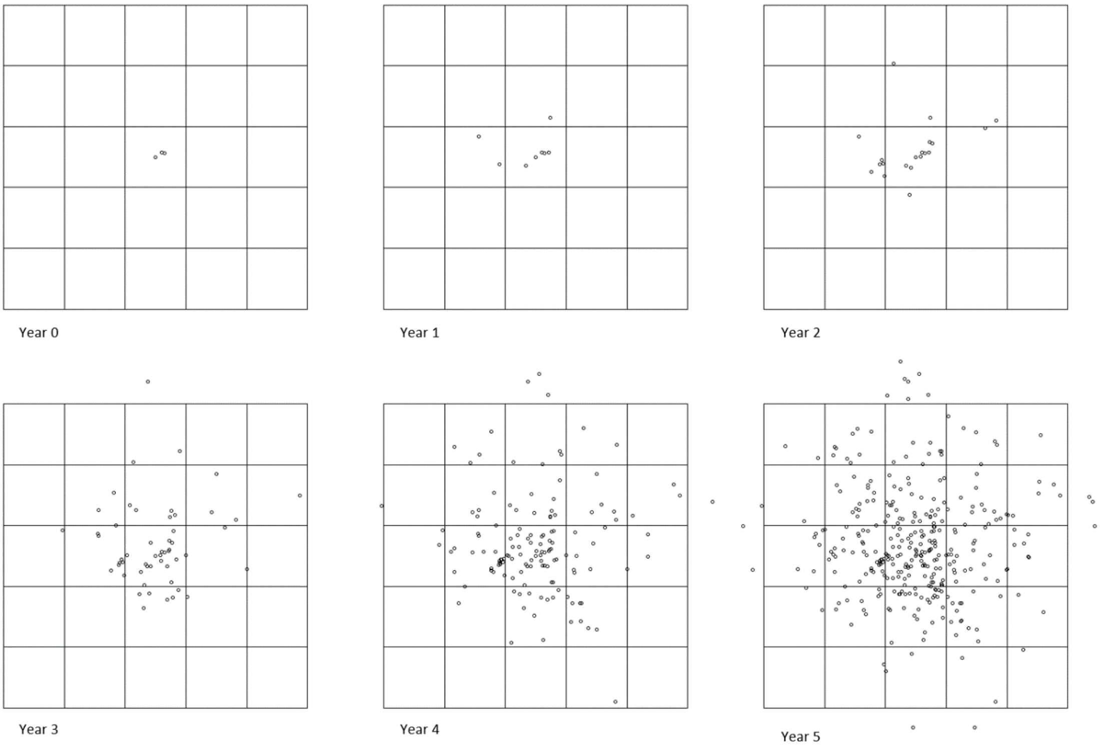

Figure 4. Simulated annual spread of fire ants. Large boxes are 5km x 5km, each small box is 1km x 1km

Table 5. Maximum distance across simulated infestations (N = 100) emerging from a single remnant nest, for each year of spread

Year Post-Treatment	Maximum Span (m)					Mean Conservative Treatment Area (ha)
	Min	5%	Mean	95%	Max	
0	0	0	0	0	0	0
1	0	12.46	871	1825	2098	238
2	55	570	1802	3190	4620	1020
3	0	1446	2894	4420	5552	2631
4	2081	2770	4015	5564	6034	5064
5	1931	3455	5424	7298	8135	9242

Figure 4 and **Table 5** display that by year three of spread, on average, an infestation will be about 3 km across. Upon detection, without knowing the exact spatial relationship between the detected colony and its family members (it could be on the right edge, or the left edge, or in the centre, etc.), a conservative 3km treatment must be extended in every direction to capture the entire infestation.

In year two, the required responsive treatment would be roughly the area of an entire CZ, which is convenient because it allows us to maintain an expected failure rate of 10% without assuming secondary failures due to spreading infestations. Therefore, we recommend initial clearance surveillance have a target time-to-detection of **2 years.**

Based on spread and surveillance simulations, **Table 6** shows the average probability of detecting one or more colonies of a spreading infestation, given the level of annual search effort.

Table 6. The average instantaneous probability of detecting one or more colonies of an outwardly growing infestation located within a 2500-ha CZ, based on 100 simulated infestations, and simulated randomly placed (without replacement) 15-ha searches.

Annual Surveillance / CZ (ha)	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
30	0.0089067	0.0207665	0.0497508	0.1114627	0.2369792	0.4329904
60	0.0177067	0.0407080	0.0959868	0.2086872	0.4145512	0.6735848
105	0.0318933	0.0722072	0.1657080	0.3406208	0.6088465	0.8540087
135	0.0435733	0.0952243	0.2114061	0.4174929	0.7009577	0.9137893
180	0.0587733	0.1263740	0.2733394	0.5149554	0.7978329	0.9591462
210	0.0663467	0.1430301	0.3073830	0.5655271	0.8405202	0.9739443
255	0.0788800	0.1704335	0.3598130	0.6363190	0.8900744	0.9863665
285	0.0922667	0.1937043	0.3974562	0.6794523	0.9141792	0.9910011
330	0.1005867	0.2161890	0.4410943	0.7307071	0.9399911	0.9950753
360	0.1168533	0.2398212	0.4736228	0.7613595	0.9520006	0.9965420
405	0.1273600	0.2643613	0.5148345	0.8009914	0.9661760	0.9979545
435	0.1369600	0.2827343	0.5423354	0.8241174	0.9733131	0.9985608
480	0.1497067	0.3064317	0.5767918	0.8520630	0.9804462	0.9990787
510	0.1560000	0.31997056	0.5975966	0.8666475	0.9838639	0.9993230
555	0.1772800	0.3518143	0.6354362	0.8906804	0.9885340	0.9995562
585	0.1835733	0.3658763	0.6539287	0.9021608	0.9904420	0.9996574
615	0.1900800	0.3799268	0.6724081	0.9129610	0.9922288	0.9997412
660	0.2052800	0.4041394	0.7002643	0.9268317	0.9941644	0.9998218
690	0.2150400	0.4206876	0.7181834	0.9357939	0.9952514	0.9998762
735	0.2315200	0.4448066	0.7427598	0.9460735	0.9963616	0.9999128
765	0.2428267	0.4616829	0.7594027	0.9526158	0.9970220	0.9999304
810	0.2613867	0.4870527	0.7818334	0.9605969	0.9977915	0.9999611
840	0.2648000	0.4958913	0.7913372	0.9642346	0.9980755	0.9999622
885	0.2768533	0.5154010	0.8092209	0.9699345	0.9985347	0.9999773
915	0.2842667	0.5287585	0.8213263	0.9736541	0.9987986	0.9999815

According to **Table 6**, **the required effort to confer a ≥ 50% chance of detecting a remnant infestation within the target two years is 405 ha per 2500 ha CZ, or the equivalent of 16% of the area under consideration.**

It is important to consider that, while we placed the origin of our simulated infestations in the centre of each surveillance cell array, notionally representing a CZ, there is no guarantee that real infestations will in fact begin in the centre of real CZ, or any analogue thereof. That is why in the CZ System, the neighbourhood status structure described in Section 2 is critical for dealing with detecting infestations that straddle CZs.

7. Final Proof of Freedom

Following the clearance of CZs, a possibility human assisted movement remains from non-cleared CZs could cause reinfestation of previously cleared CZs. The location and timing of human assisted movement is difficult to predict. Therefore, our models of spread and detection following eradication treatment **are not robust** to human assisted movements reinfesting CZs.

Therefore, the final Phase 3: Final PoF involves a minimal amount of “maintenance” surveillance in all cleared CZs, until all CZs have undergone successful clearance. At that time, the program may elect to continue maintenance surveillance for an undetermined time period.

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