EVALUATION OF THE COST-EFFECTIVENESS OF STERILE INSECT RELEASE STRATEGIES AGAINST PAINTED APPLE MOTH, *TEIA ANARTOIDES*

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ABSTRACT

Although the painted apple moth (PAM) eradication programme in West Auckland appears to have been successful, the large volume of trade from Australia, PAM's native range, makes re-invasion likely. Recent work has focused on modelling the spatial and temporal effects of optimal release strategies in the sterile insect technique (SIT) programme to enable assessment of the time required and likelihood of eradication success. However, the cost-effectiveness of each strategy is not known. Based on the rearing and operational costs from the past PAM SIT release programme, the unit cost of a single irradiated male moth for a release programme has been quantified. A simple economic model for cost analyses and comparison of a few selected SIT release strategies at ≥95% confidence level of eradication success is presented. This model could be used to select an appropriate cost-effective strategy, thus aiding in prompt decision-making of PAM re-incursion responses.

Keywords: painted apple moth, *Teia anartoides*, sterile insect technique release programme, release strategy, cost analysis.

INTRODUCTION

The incursion of the native Australian painted apple moth (PAM) (Lepidoptera: Lymantriidae: *Teia anartoides* Walker) into Glendene, West Auckland, in May 1999, prompted an area-wide eradication programme by the New Zealand Ministry of Agriculture and Forestry (MAF) Biosecurity Authority. PAM is a polyphagous pest of horticulture and plantation forestry as well as New Zealand's native vegetation (Suckling et al. 2002). The economic and ecological impact of the PAM incursion was estimated at NZ$50-350 million over 20 years if no action was taken to eradicate the insect (Self 2003).

The eradication programme against PAM (1999-2006) was a large eradication attempt using a combination of tactics, including the first use of the sterile insect technique (SIT) in New Zealand (Suckling et al. 2005; Wee et al. 2005). The SIT component was added to the eradication programme in February 2003 once the pest population was brought down to <1% of population level in 2001-2002, as indicated by trap catches (Suckling et al. 2005, 2007). The initial SIT programme ran from February 2003 until May 2004, involving 13 weekly releases each of several thousand insects (Suckling et al. 2005), and forms the basis for this analysis. The second phase of the PAM SIT programme commenced in May 2005, but is not considered here.

The PAM SIT programme featured three major components, rearing, research, and operational aspects. The major role of SIT rearing was to mass rear PAM on an artificial diet for release. SIT research focused on the irradiation biology to determine an optimum dose to confer inherited sterility (production of viable sterile males that leave no offspring), with the best male fitness-sterility trade-off. SIT operations involved setting up and servicing female moth-baited monitoring traps and mass releasing irradiated male moths to map the dispersal and spread of the insects.

Although the current eradication programme appears to have been successful (Kean & Suckling 2005), the large volume of trade from Australia, PAM's native range, makes re-invasion likely. In fact, the recent catches of seven PAM males (May, August, October, November and December 2005 and April and May 2006) in the eastern part of Auckland appear to be due to separate incursions, and mtDNA analysis of isotopic ratios present in these moths suggested that none were from Auckland and they had originated in a region more arid and/or at lower latitude than Auckland (R. Frew, Isotrace NZ Ltd, pers. comm.).

Knowledge from the previous PAM SIT programme can enable better preparation for future needs. For example, new population models can demonstrate how releases of sterile males may be optimised in time and space (Kean et al. 2005, 2007). In relation to this, a simple economic model to estimate the relative costs involved in SIT programmes was seen as a helpful tool to weigh the cost-effectiveness of different release strategies. Presented here is a simple model for cost estimation of different SIT release strategies using new population models (Kean et al. 2005, 2007) with their predicted likelihood of success and time required to achieve eradication.

METHODS

The economic model presented here utilises results obtained from a population model developed explicitly for PAM that predicted the impact of releasing irradiated males on wild populations (Kean et al. 2005, 2007). The population model was based on PAM's key biological parameters, and allowed for mating between irradiated, wild and irradiated-lineage moths with spatial components that incorporated PAM dispersal as derived by Suckling et al (2005). Using time-step analyses, the quantitative analyses predicted the likelihood of eradication success and time required to achieve eradication for different release strategies and scenarios.

The economic costs involved in a future PAM SIT programme would be largely from insect rearing and operational costs, since the development of an artificial diet and rearing system (A. Barrington, unpubl. data), and determination of the radiation dose (i.e. 100 Gy) for optimal fitness-sterility trade-off for irradiated male moths (Suckling et al. 2004a,b; Wee et al. 2005) have already been established. Therefore, SIT research costs have been excluded from this analysis although experience suggests that some ongoing research alongside an operational programme would be prudent. Operational cost assessment can be subdivided into three aspects: (a) fixed and variable costs involved in moth production and irradiation, (b) release costs and (c) monitoring costs. However, it should be noted that this cost analysis was based on the actual costs incurred during the 2003-2004 SIT programme (excluding GST), and no attempt was made to include inflation or other factors leading to increased costs, such as staff wages.

Production and irradiation costs

Table 1 lists the fixed and variable costs incurred in moth production. The fixed costs include building rental for laboratory, insect rearing and quarantine facilities. The variable costs for moth production were based on rearing, insect quality assurance and project management. Rearing costs primarily include the diet, materials and personnel needed to rear, sex and mark males for release, while quality assurance costs cover examination of the irradiated male fitness before release. General operating costs, costs of premises, overhead costs and subcontracting costs directly involved in this project were included in the unit cost.

Costs for moth irradiation (irradiation treatment and transport between Auckland and Lincoln, and Lincoln and the National Radiation Laboratory, Christchurch) were expressed as cost per release rather than cost per unit moth as this cost involved one-off radiation treatment per release batch, regardless of the number of moths being irradiated each time.

TABLE 1: Estimated costs involved in the rearing, operation and release activities of a sterile insect technique (SIT) programme based on past experience in the painted apple moth eradication programme in New Zealand (2003-2004).

Activities	Component breakdown	Unit cost (NZ$)
Rearing		
(a) Production	Fixed costs: Rental of buildings (laboratory, insect rearing and quarantine facilities)	$142.00/day
	Variable costs:	
	Rearing	$1.090/male
	Quality assurance	$0.033/male
	Project management	$0.026/male
(b) Irradiation	Irradiation	$784.00/release
Operational		
(a) Release (depends on release strategy)	(a) hotspot release	$172.64/release
	(b) regular release scenarios:	
	d_{reg}[1] = 500 m	$1644.72/release
	d_{reg} = 1000 m	$423.76/release
(b) Monitoring	Examination for dye	$2.00/recaptured male
Overall unit costs		
	Rental	$142.00/day
	Moth production	$1.149/male
	Release:	
	(a) Hotspot	$956.64/release
	(b) Regular release scenarios:	
	d_{reg} = 500 m	$2428.72/release
	d_{reg} = 1000 m	$1207.76/release
	Monitoring	$2.00/male

[1] d_{reg} = distance between the release points in a regular release strategy.

Release costs

This is a variable cost encompassing the transport (travel time) and labour expenses (release time and personnel wages) involved with irradiated moth release, based on past PAM SIT experience. The cost depends on the release strategy being used, which largely depends in turn on knowledge of the distribution of the wild moth population.

In this analysis, two different spatial release strategies in a 50 × 50 grid with 100 × 100 m cells were considered: (a) hotspot and (b) regular releases (Fig. 1) (see detailed discussion by Kean et al. 2005, 2007). Under a regular release strategy, irradiated males were released on a square grid with dimension d_{reg} between adjacent release points. Under a hot-spot release strategy, male moth releases were made randomly within a radius d_{spot} of wild populations. A range of scenarios was investigated, each differing in the release pattern and in d_{reg} (d_{reg}=500 m and 1000 m) and d_{spot} (d_{spot}=0, 250 m, 500 m and 1000 m). Simulations were initialised with ten randomly-distributed wild populations, each of 100 wild adults split according to the sex ratio, χ. Release sites were fixed for the duration of each simulation.

Under the two different strategies, three release intervals, daily, 4-daily and weekly, were investigated. Simulations were run until either global eradication (at generation t_e), or until it became clear that eradication was unsuccessful (at 100 generations) for >95% probability of eradication. Each scenario was simulated 100 to 250 times to capture the variability in outcomes arising from the inbuilt demographic stochasticity. Each scenario

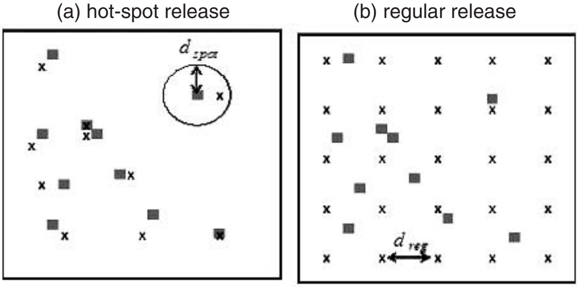

FIGURE 1: Conceptual illustration of the (a) hot-spot and (b) regular release strategies for the sterile insect technique programme for painted apple moth. Grey squares correspond to randomly-distributed wild populations, while crosses indicate release sites (50×50 grids, 100×100 m cells). d_{spot}=radius distance from the actual location of a wild moth population in hot-spot releases; d_{reg}=distance between the regularly-spaced release points in regular releases.

was summarised in terms of the proportion of simulations leading to eradication (p_e) and the time to eradication (t_e) for each successful simulation with their respective number of males released per day for each successful eradication.

It was assumed that 10 release points were required (10 populations) for each hotspot analysis for varying values of d_{spot}. d_{spot} values give an indication of the accuracy of knowledge of the breeding population, with the lower the value the better the knowledge. Therefore, using a Microsoft® Excel spreadsheet, the minimum travel distance between release points based on 10,000 simulations was calculated by algorithm. By assuming the travel path is a closed circuit for both strategies (Fig. 2), a mean of 15.8 km was obtained between 10 release points for hotspot strategy (lower and upper limit of 11.6 to 20.6 km). An example calculation of a simulation of hotspot travel distance is given in Figure 2a. For the regular scenario, the number of release points depends on d_{reg}, and results showed that regular release with d_{reg}=500 m and 1000 m, the travel distances were 55.9 and 29.7 km, respectively. An example of the travel path for d_{reg}=1000 m is illustrated in Figure 2b.

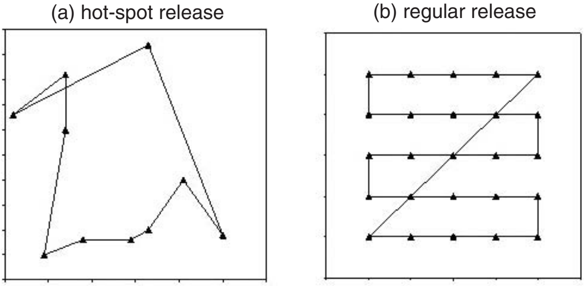

FIGURE 2: Illustration of the travel route in (a) hot-spot and (b) regular release strategies for the sterile insect technique programme for painted apple moth. Solid triangles correspond to release points. Trend lines indicate the paths taken, which for hot-spot releases was calculated by algorithm. An assumption was made that the path is a closed circuit.

The obtained travel distance, together with information on operating costs for moth release and personnel wages were used to scale the overall costs for different release strategies and options; and the cost involved per release is given in Table 1.

Monitoring costs

Additional costs are involved to examine the male moths recaptured in the sticky trap bases for the presence of internal or external dye (the presence/or absence of dye indicating released and wild male moths, respectively) or dye colour (used to indicate the release location for mapping sterile moth dispersal). The initial PAM SIT programme (February 2003 to May 2004) produced a total of 3266 males recaptured of 242,757 released in suitable weather conditions (defined as release times from which at least one moth was recaptured), which represented a recapture rate of 0.0135 (Kean & Suckling 2005; Suckling et al. 2005). This recapture rate was used to estimate the monitoring costs for the different release strategies in this paper.

The time to eradication, t_e, for selected release strategies, assuming >95% probability of eradication, was used to calculate the number of release days and the total number of male moths required for the whole eradication programme according to the following formulae:

(a) Number of release days required for eradication = time to eradication (days) / release interval (days)

(b) Total males required for eradication = number of release days required for eradication × number of release sites × number of males released per site.

Based on the overall unit cost and the different release strategies versus rate of eradication success, the overall costs involved for each eradication strategy can be determined by summing the total rental costs [A=Time to eradication × rental cost ($/day)], total production cost [B=Total males required for eradication × production cost ($/male)], total release cost [C=Number of release days required for eradication × release cost ($/release)] and total monitoring cost [D=Total males required for eradication × recapture rate × monitoring cost ($/recaptured male)].

Each release strategy and option leads to different cost values for A, B, C and D, and the resulting total cost (A+B+C+D) can then be used to select the most cost-effective strategy to achieve eradication in relation to the time to eradication, probability of eradication success and the daily moth rearing capacity.

RESULTS AND DISCUSSION

The overall costs, the probabilities of eradication and time to eradication estimated from the population model for PAM (Kean et al. 2005, 2007) for daily, 4-daily and weekly hot-spot and regular release strategies are given in Table 2.

The average longevity of PAM male moths in the field is typically ≤4 days (Suckling et al. 2005). For the hotspot strategy, daily releases would ensure that irradiated males are present at all times and would more effectively reach the wild population. However, this would be very labour intensive and will incur a high release cost (Table 2). For weekly releases, a large number of irradiated moths would have to be released otherwise during the latter half of the week (between releases) there would be no irradiated males available to compete with the wild males. However, this would give high total production and monitoring costs compared with other release intervals and would not be recommended (Table 2). In this respect, 4-daily releases offer the advantage of continuous availability of irradiated males to mate with wild females but with much lower release and production costs compared with daily and weekly releases (Table 2). The time needed for a 95% likely eradication for different release intervals under the hot-spot strategy was similar, and ranged from 1060-1170 days, leading to a similar total rental cost (Table 2).Overall, as d_{spot} increases (decreasing knowledge of location of breeding populations), the 4-daily release is the best option, achieving successful eradication in a similar time frame while incurring minimum costs (Table 2).

For the regular release strategy, as the number of release sites increases, the total release cost increases dramatically compared with the hotspot strategy (Table 2).

TABLE 2: Estimated rearing and operational costs using the simple economic model for different release distances and intervals in hotspot and regular strategies to eradicate painted apple moth re-incursion with 95% confidence.

Release distance (m)[1]	Release interval	Mean males released/day	Release site	Time to eradication (days)[2]	Number of releases required	Number of males required	Total rental cost ($)	Total production cost ($)	Total release cost ($)	Total monitoring cost ($)	Total cost ($)
Hotspot Strategy											
0	1	1201	10	1114	1114	1338678	158256	1538140	1066155	36144	2798696
0	4	5912	10	1161	290	1715946	164856	1971622	277655	46331	2460463
0	7	50768	10	1131	162	8205473	160657	9428088	154618	221548	9964911
250	1	1499	10	1100	1100	1649106	156215	1894823	1052408	44526	3147972
250	4	6681	10	1170	292	1954503	166161	2245724	279853	52772	2744511
250	7	54128	10	1149	164	8888767	163234	10213194	157099	239997	10773522
500	1	4094	10	1060	1060	4338505	150496	4984942	1013879	117140	6266456
500	4	10047	10	1122	281	2818807	159362	3238809	268402	76108	3742681
500	7	77177	10	1146	164	12633581	162714	14515985	156598	341107	15176403
Regular Strategy											
500	1	3596	100	1235	1235	4441825	175390	5103657	2999805	119929	8398780
500	4	13954	100	1211	303	4223500	171916	4852801	735099	114035	5873851
500	7	97104	100	1201	172	16656132	170500	19137895	416597	449716	20174708
1000	1	5223	25	1171	1171	6113459	166215	7024364	1413720	165063	8769363
1000	4	12570	25	1185	296	3722171	168199	4276774	357648	100499	4903120
1000	7	95410	25	1192	170	16244528	169238	18664963	205633	438602	19478436

[1] Release distance for the hotspot strategy – d_{spot} = radius (m) from the actual location of a wild population and for the regular strategy – d_{reg} = distance between the regularly-space release points.

[2] Results based on simulations on a new population model of painted apple moth at 95% confidence level (Kean et al. 2005, 2007) on a randomly distributed initial wild population of 1000 moths over a conceptualised 50×50 grid (100×100 m cells).

The 4-daily release incurred the lowest operating costs. The operating costs for a daily- and 4-daily release are very similar, with the exception of the release cost, which is four times higher for daily release than the 4-daily release (Table 2).

Moth production was the highest cost component, followed by release, rental and monitoring in decreasing order. Labour charges in PAM rearing contributed a significant cost to moth production (Table 1). These include egg inoculation, diet preparation, larval sexing (only male pupae are need for the release programme), pupae counting and sorting before emergence and other culture and release-related activities. Pupal sorting is a time-consuming activity, as careful handling at pupal stage is important for physical well-being of the moths emerging subsequently. Identification of more efficient methods for the above tasks has the potential to greatly reduce the cost of moth production.

Since the time to eradication was similar for all scenarios in both strategies, rental cost for buildings and laboratory space was similar (Table 2). However, the analysis assumed that the quarantine and laboratory space needed to rear and prepare the 50,768 irradiated males/day required for weekly releases is the same as required for the 1201 or 5912 males/day for daily or 4-daily releases. This is unlikely to be true in practice, and this would further increase the relative cost of weekly releases. Total release cost was heavily dependent on the release strategy, as more releases within a week contribute to a higher release cost, as shown in Table 2.

The total cost of eradication generated in this model would be higher than in the 2003-2004 SIT programme, as this simulation assumes SIT was used alone to combat scenarios with a population of 1000 wild moths distributed across 10 sites. In Auckland, the PAM eradication programme in 2003-2004 was based on a number of different strategies, with SIT introduced once the wild moth population was suppressed to a very low level. In addition, there were only three or four sites identified for PAM sterile male release for the 2003-2004 programme.

Figures 3 and 4 illustrate the estimated rearing and operating costs to achieve 95-99% eradication success for different scenarios of hotspot and regular release strategies. For a hotspot strategy, daily releases are able to eradicate PAM within the shortest time frame but at a higher cost than 4-daily releases (Fig. 3). Weekly releases cost the most with a slightly shorter time to eradication than 4-daily release (Fig. 3). With a slight compromise on the eradication time, 4-daily releases again offer the advantage of the lowest cost of other release options. However, as the d_{spot} increases, the overall cost increases whereby even daily releases were not as good as 4-daily releases at 97% probability of eradication success (Fig. 3c).

Similar results were obtained for the regular strategy whereby 4-daily release incurred the lowest cost but with a similar time frame to other scenarios (Fig. 4). As d_{reg} increased from 500 to 1000 m, the costs were not substantially different and a shorter time to eradication was observed (Fig. 4). Interestingly, for 4-daily releases, rearing and operational costs were lower at d_{reg}=1000 m than d_{reg}=500 m (Fig. 4b). However, the effect of higher d_{reg} could not be modelled as at $d_{reg} \geq 1500$ m, the level of eradication confidence level was below 95% (Kean et al. 2005).

A key factor in deciding whether to undertake a regular versus hotspot release strategy is likely to be whether the locations of wild populations can be accurately estimated, and the confidence that these finds represent the entirety of the breeding population. When the locations of breeding populations are poorly known, then a strategy that enables sterile moths to reach all potential breeding sites is essential, and a regular grid may be the most efficient way of achieving this. In practice a mixed strategy of hotspot plus smaller releases on a regular grid (intermediate or higher d_{reg}) might be considered if it was sufficiently likely that unknown wild populations might be present. One method of quantifying the chance of undetected wild populations being present has been suggested by Kean & Suckling (2005), based on interpretation of zero trap catches in light of temperature-dependent development rates and flight thresholds.

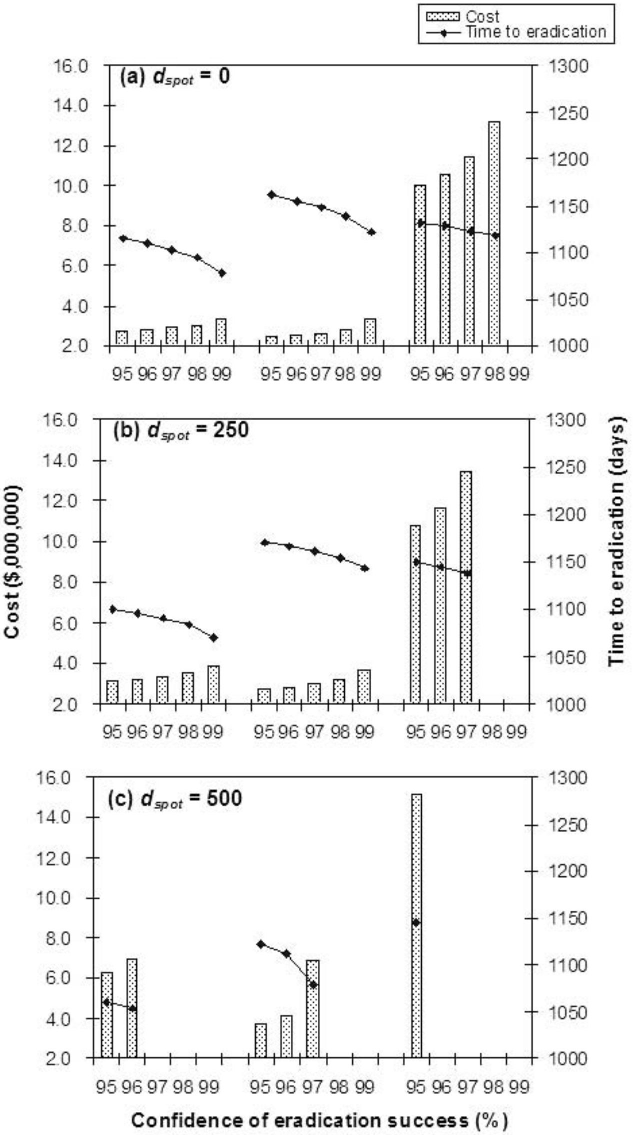

FIGURE 3: Estimated total rearing and operational costs ($NZ) and time to eradication (days) using the simple economic model for hot-spot strategies using different release distances (d_{spot}) and intervals (daily, 4-daily and weekly) at various levels of confidence of eradication success for painted apple moth re-incursions. (a) d_{spot}=0 m, (b) d_{spot}=250 m and (c) d_{spot}=500 m.

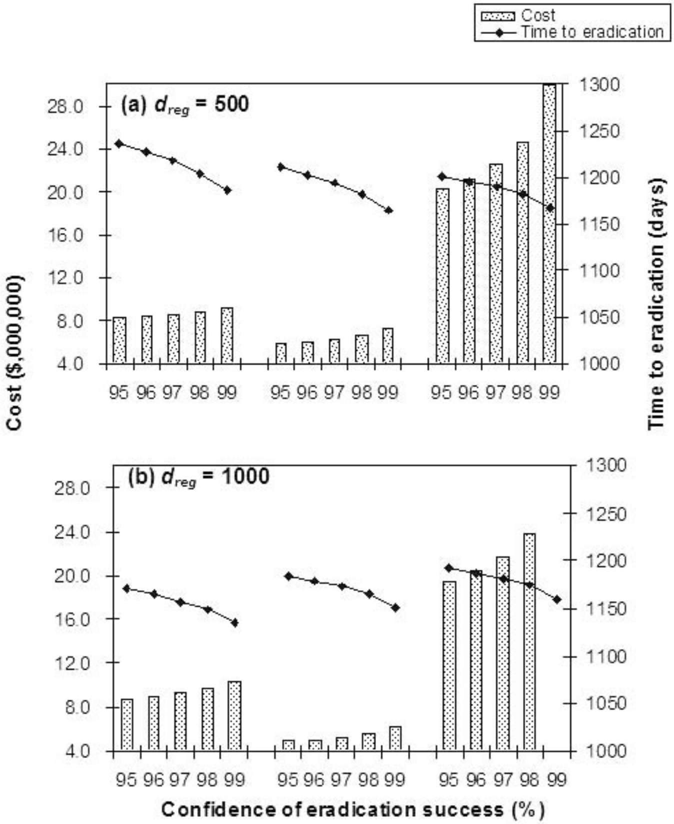

FIGURE 4: **Estimated total rearing and operational costs ($NZ) and time to eradication (days) using the simple economic model for regular release strategies using different release distances (d_{reg}) and intervals (daily, 4-daily and weekly) at various levels of confidence of eradication success for painted apple moth re-incursions. (a) d_{reg}=500 m and (b) d_{reg}=1000 m.**

CONCLUSIONS

Successful eradication using the sterile insect technique requires a critical overflooding ratio of the released sterile moths to the feral population in time and space. Modelling of different release strategies has provided an understanding of the spatial components of an optimum release strategy in relation to the aggregated distribution and dispersal of the insect in the field (Kean et al. 2005, 2007). The analysis presented here has shown how this may be used to estimate the costs for each release strategy, thus aiding decision making, especially when an immediate incursion response is needed.

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