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Management of invasive invertebrates: lessons from the management of an invasive alien ant

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Declare the past, diagnose the present, foretell the future; practice these acts . . . make a habit of two things—to help, or at least to do no harm.

Hippocrates *Epidemics,* Book I, Section XI

11.1 Introduction

In the literature on management of invasive species, heuristic models that outline and integrate management processes across the entire spectrum of invasion, from pre-border risk assessment and surveillance to operational control and monitoring of established populations, are now commonplace (e.g. Wittenberg and Cock 2001; Wotton and Hewitt 2004; Hulme 2006; Lodge *et al.* 2006). Generic frameworks for rapid response to a biological invader typically follow a sequence from detection, to assessment, then action, and monitoring (Fig. 11.1). These models are triggered by detection and diagnosis of an invasive species, followed closely by informing stakeholders and initial assessment of the situation. This includes delimitation of the range and density of the invader, establishment of operational authority, defining and evaluating operational options, seeking initial funding, and commencing interim management. Following the initial assessment a decision is taken on the method of operational control; concerted action is taken to suppress the invader so as to mitigate its impacts. This is typically linked to a monitoring programme to assess the efficacy of control, and, if needed, planning for follow-up action. Unfortunately, few published studies put the flesh on the bones of these idealized generic frameworks to reveal the complex realities of coordinating and implementing on-the-ground control for specific invasive species (but see Anderson 2005, Coutts and Forrest 2007) to test the ideal against the real.

Some of the most intractable and serious of biological invaders are invertebrates (e.g. woolly adelgid and gypsy moth, Lovett *et al.* 2006; social wasps, Beggs 2001; earthworms, Holdsworth *et al.* 2007; land snails, Cowie 2005; and ants, Holway *et al.* 2002). Although invertebrates comprise most described biodiversity in both

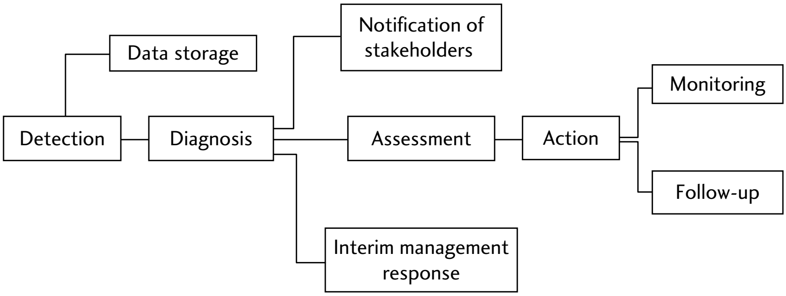

Fig. 11.1 A generic response framework for control of an invasive species. Detection and diagnosis sets off initial assessment of the status of the invasive species, including delimitation, evaluating operational options, funding arrangements, and interim management. Once operational control methods are decided upon, action is taken to suppress the invader and linked to a monitoring programme.

terrestrial and aquatic environments, and an even greater fraction of estimated biodiversity (Hawksworth and Kalin-Arroyo 1995), it is curious that they make up only 26% of the listed 100 of the world's worst invaders (17 terrestrial, nine aquatic; Lowe *et al.* 2000) and just 20% (10% for aquatic and terrestrial invertebrates, respectively) of the 485 species listed on the Global Invasive Species Database (GISD; ww.issg.org/database). This suggests that invertebrates, in both terrestrial and aquatic habitats, are either under-represented among invasive species or that their variety and importance are under-emphasized by invasion biologists, managers, and policymakers. We think that the latter is much more likely. The increasing recognition of ants as key biological invaders of natural environments reinforces this point.

Hundreds of ant species have been moved by humans across biogeographic barriers (McGlynn 1999; Wilson 2005) so it is not surprising that ants figure prominently among lists of invasive invertebrates. For example, five species (*Anoplolepis gracilipes*, *Linepithema humile*, *Pheidole megacephala*, *Solenopsis invicta*, and *Wasmannia auropuncata*) are listed as among 100 of the world's worst invaders (Lowe *et al.* 2000) and ants comprise 3% of all invasive species listed on the GISD. This prominence is probably recognition that key features of ants, including sociality, may lead to a greater capacity to dominate as invaders (Passera 1994; Moller 1996). This subset of invasive ants share overlapping attributes that increase the probability of transport, survival, establishment, and spread (Holway *et al.* 2002; Tsutsui and Suarez 2003; Suarez *et al.* 2005), and high impact (Davidson 1998). Many of these invasive ants form expansive supercolonies with high, sustained densities of worker ants that extend from hectares to many square kilometres (Tsutsui and Suarez 2003). This key attribute leads to major impacts on natural ecosystems (Holway *et al.* 2002). This may be especially so on islands, where native species richness and functional redundancy are low, and propagule pressure can be high (Denslow 2003, Daehler 2006). Indeed, native ant species are uncommon on most oceanic islands (Wilson and Taylor 1967) and even some large archipelagos, like New Zealand (Valentine and Walker 1991).

The perceived vulnerability of island ecosystems to invasion and impact by invasive alien species has led some natural resource managers to consider the protection and restoration of insular environments as impossible (Reaser *et al.* 2007). This pessimism is probably related to both the attributes of islands and island species (e.g. limited ranges), and the particular operational difficulties of managing islands including isolation, the ongoing lack of sufficient resources, lack of operational capacity, and high rates of staff turnover, all of which lead to loss of morale and institutional memory. However, numerous successes in invasive species management on islands belie these obstacles, making for renewed optimism (Simberloff 2002; Veitch and Clout 2002).

We have four straightforward aims in this chapter. First, since documented case histories of control programmes for invasive invertebrates are few, especially in natural areas and on islands, we describe the evolution of the control campaign against the yellow crazy ant *Anoplolepis gracilipes* in rainforest on Christmas Island (Indian Ocean). Second, we crystallize the key ingredients that led to the climax of the operational programme in an aerial baiting operation. Third, because every control programme operates under unique circumstances, we illustrate the complexities of the actual response against generic integrated response frameworks. Fourth, and perhaps most importantly, we evaluate the campaign to produce a list of issues and lessons that apply not only to ongoing efforts to suppress this invasive ant on Christmas Island, but that might also resonate with, and inform efforts to, manage other intractable invasive invertebrates.

11.2 History

11.2.1 The yellow crazy ant as a pantropical invader

The yellow crazy ant (*Anoplolepis gracilipes*, hereafter YCA; Fig. 11.2a), is one of the world's 100 worst invaders (Lowe *et al.* 2000). Its area of origin is obscure, but is typically cited as Africa where all other congeneric species are found (Wilson and Taylor 1967). This generalist consumer has invaded many oceanic islands across the tropics, and continents including Australia and North America (Lowe *et al.* 2000). Propagule pressure (estimated by interception rates at Australian and New Zealand ports) and vector diversity are both high, and source regions are diverse (Commonwealth of Australia 2006; Ward *et al.* 2006).

As in other important invasive ant species, kinship and intraspecific aggression in the yellow crazy ant are negatively correlated, suggesting that relatedness facilitates supercolony formation (Drescher *et al.* 2007). Extensive, polygynous supercolonies can form where worker ants are sustained at high densities. Given its numerical abundance, rapid recruitment to food resources, and aggressive

Fig. 11.2 Key players and elements in the management programme. (a) YCA tending the mooncake scale *Tachardina aurantiaca*. (b) The Bell 47 Soloy helicopter with underslung bait hopper. (c) Presto®01 pelletized bait containing fipronil as the active ingredient at 0.01%. This bait was dispersed from the hopper above the rainforest canopy at 4kg per ha. (d) Dedicated field crew loading Presto®01 into the hopper for aerial broadcasting.

behaviour, the YCA appears to break the resource discovery-–resource dominance trade-off (Davidson 1998) to disrupt ant and invertebrate communities on both islands and continents (e.g. Haines and Haines 1978; Hill *et al.* 2003; Sarty *et al.* 2007; Bos *et al.* 2008). Impacts may extend to vertebrates, including nesting seabirds (Feare 1999) and land birds (Davis *et al.* 2008).

11.3 YCA invasion of Christmas Island

Christmas Island (10°30′S 105°40′E) is an elevated, oceanic limestone island, 360km south of Java in the north-eastern Indian Ocean. The 134 km2 island rises sharply to a central plateau (maximum elevation 361m) in a series of cliffs and terraces running parallel to the coast. Average rainfall is ca. 2000 mm, most of which falls between November–May. The island is covered by structurally simple, broadleaved rainforest. Of the 51 tree species present, ca. 25 are common canopy trees. The island is an Australian external territory of outstanding national and international conservation significance. BirdLife International has listed the island as an Endemic Bird Area and there are two Ramsar Wetland Sites of International Importance. Over 75% of the rainforest that originally cloaked the island still remains, making Christmas Island one of the best-preserved insular tropical ecosystems anywhere in the world. Rainforest dynamics are dominated by the activities of abundant land crabs, including the red crab (*Gecarcoidea natalis*). This native omnivore regulates seedling recruitment and litter breakdown across the island rainforest (e.g. Green *et al.* 1997, 1999, 2008).

The YCA has been present on Christmas Island since at least the 1930s, but supercolony formation is a relatively recent phenomenon, and has occurred mostly since the mid-1990s. The two supercolonies that triggered the emergency response were detected incidentally in 1997, during long-term research on the effect of the native redland crab on seedling recruitment (Green *et al.* 1997, 2008). By 2002, YCA supercolonies had formed across 3000 ha of rainforest—about 30% of all island forest. Most of these supercolonies had formed in the Christmas Island National Park, which comprises 63% of the island.

On the forest floor, *Anoplolepis* has extirpated millions of red crabs from large tracts of rainforest (O'Dowd *et al.* 2003), which has resulted in the formation of distinctive forest states across the landscape, with altered resource levels and habitat structure (O'Dowd *et al.* 2003). In the forest canopy, the ant forms new associations with herbivorous, honeydew-secreting Hemiptera (Fig. 11.2a; O'Dowd *et al.* 1999; Abbott and Green 2007) that result in reciprocal increases in their population sizes. The combined direct and indirect effects of the YCA and several species of scale insects have been rapid and multidirectional, affecting forest structure and composition, species of special conservation value (O'Dowd *et al.* 1999, 2003), ecosystem processes (Davis *et al.* 2008), and secondary invasions (O'Dowd and Green 2009). This demanded a coherent, coordinated response among scientists, managers, and policymakers.

11.3.1 The interim response

Although the identity of the ant species was unknown when expansive supercolonies were detected in 1997, it was immediately obvious that this ant affected the red land crab, seedling recruitment, scale insect populations, and litter decomposition (Fig. 11.3). Even in the absence of identification, the urgency of a management response was clear. Parks Australia North Christmas Island (PANCI), the responsible management authority, was notified immediately. This sense of urgency was heightened by the subsequent authoritative identification of voucher specimens, followed by a literature search (O'Dowd *et al.* 1999) that revealed some aspects of its biology and impacts, especially in the Seychelles (e.g. Haines and

1995	Research, begun in 1986, continues on red crab
1996	Research on red crab extends across island
1997	YCA supercolonies detected; mass crab deaths; Parks Australia notified; impact assessment begins
1998	YCA impact assessment continues; scoping supercolony distribution begins
1999	YCA impact report; media coverage; formation of steering committee
2000	PA-Monash University Linkage Grant; bait testing begins; IWS is designed and approved
2001	1st IWS conducted over 3 months; CIGIS integrated into programme; evaluation of ground baiting
2002	**Build-up, conduct, and evaluation of the aerial campaign**
2003	2nd IWS conducted, surveillance and follow-up control; linage grant ends
2004	Surveillance and follow-up control
2005	3rd IWS conducted; resurgent supercolonies; YCA listed as key threatening process under EPBC Act
2006	Parks Australia submits 10-year plan and funding request
2007	Long-term funding guaranteed by Australian government

19 December 2001	Steering Committee (SC) recommends options paper for the control programme.
8 February 2002	SC endorses aerial baiting using a helicopter.
15 February	SC endorses rapid deployment of helicopter.
15–24 March	Pilots visit island; indicate that aerial baiting is feasible.
26 April	SC reviews draft Environmental Assessment for aerial baiting.
7 May	Director of National Parks approves purchase of 13t of Presto ant bait.
14 May	Island-wide supercolony boundary delimitation begins.
20 May	SC endorses Environmental Assessment for aerial baiting
30 May	Tender for aerial baiting operation awarded to McDermott Aviation.
28 June	Contract for non-target assessment of aerial baiting on canopy arthropods and vertebrates
27 June	Trial plots set up for aerial baiting operation.
12 July	Referral for aerial baiting submitted to Approvals and Legislation Division
1 August	Teleconference with Approvals and Legislation Division on referral.
5 August	Effort begins to minimize impacts of aerial baiting on robber crabs
12–27 August	YCA activity assessed at 44 waypoints in supercolonies before aerial baiting
14 August	Approvals and Legislation Division determines that aerial baiting is not a Controlled Action and that the operation could proceed
2 September	Pilot/engineer arrives on the island
3 September	Ship transporting the bait and helicopter arrives
5 September	Helicopter re-assembled for flight testing, trial of coordinate systems, and potential impacts of aircraft on seabirds; Presto®01 arrives too moist for broadcasting. Drying of 13t of bait begins.
6 September	Assessment of non-target impacts of aerial baiting on canopy vertebrates and arthropods begins.
8 September	Trial begins to assess efficacy of aerial bait delivery for YCA control.
13 September	SC endorses island-wide aerial baiting of all supercolonies.
14–21 September	All targeted supercolonies treated by helicopter.
26 September	Non-target impact assessment of aerial baiting on Robber crabs.
10–21 October	YCA activity assessed at 44 waypoints after aerial baiting.
28 October–23 December	Areas excluded from the aerial baiting campaign, including research plots, are baited on foot.

Fig. 11.3 (Con't.)

Haines 1978). The events of 1997 crystallized observations of an ant 'infestation' made much earlier, in 1989. At this time the ant was identified as *A. gracilipes*, but the discovery of what in hindsight was a small YCA supercolony occurred prior to most of the subsequent research on red land crabs, and the supercolony and its potential significance were almost forgotten until the discoveries in 1997.

The task of engaging key stakeholders began. Local PANCI managers were immediately convinced of the threat. However, persuading the administrative officers in Darwin (Parks Australia North) and Canberra (Environment Australia) was more challenging, because unlike the local staff, they had no first-hand experience of YCA supercolonies and their impacts, especially on red crabs. Furthermore, the notion that a single invasive ant species could extirpate tens of millions of the dominant red crab was met in at least one instance with open scepticism. Others felt that the ant invasion could be transient—an irruption soon followed by collapse and recovery (cf. Simberloff and Gibbons 2004). Rapid, quantified assessment of impacts at several sites on the island (O'Dowd *et al.* 1999) helped tip the scales. Public interest generated through the media also helped to maintain focus on the problem.

Initial scoping of the distribution of the supercolonies was ad hoc, involving infrequent but epic treks through remote tracts of the rugged island. This illustrated that supercolonies were widespread, but reinforced the need for a systematic island-wide survey (IWS) of the invasion (O'Dowd *et al.* 1999). The IWS was based on a grid of 1024 waypoints spread across the island (including rainforest, built environment, and areas cleared for phosphate mining) on a grid of 364 m intervals. This interval coincided with an existing network of overgrown 'drill-lines' bulldozed across much of the island plateau in the 1960s for phosphate exploration. Drill-lines were crucial because they provided ready access for field crews conducting the survey. Survey also depended on the existing Christmas Island GIS system. Each waypoint was offset into undisturbed forest and field crews used hand-held GPS units to locate them. At each waypoint, a 50 m transect was set out on which YCA activity was recorded using card counts (Abbott 2005); red crab burrow density was used as an indicator of impact at each waypoint. Supercolonies were defined operationally (rather than biologically) as those areas where there were sufficient ants to cause death of the red crab. Data were displayed in ARCView to show the spatial distribution of ant supercolonies in relation to crab burrow densities.

The initial IWS took 3 months to complete and revealed three key findings. First, YCA were widespread and occurred at 47.6% (359/754) of waypoints in undisturbed rainforest (Fig. 11.4a). Second, supercolonies were found at 24.0%

Fig. 11.3 Timeline from 1995–2007 showing key events leading to the aerial control campaign of the yellow crazy ant in 2002 and its aftermath. Key dates and events in the rapid build-up, conduct, and evaluation of the aerial campaign are telescoped to the right.

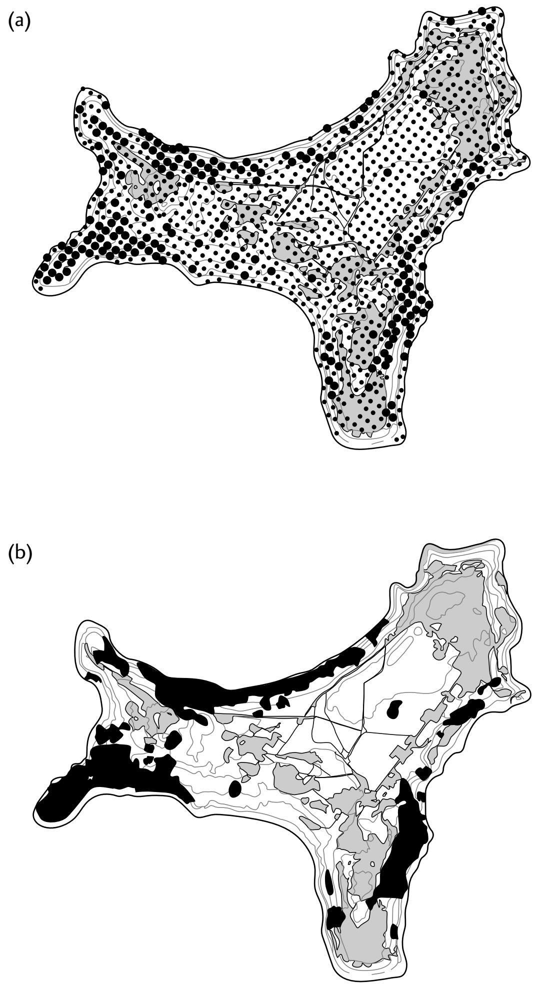

Fig. 11.4 The island-wide survey for supercolonies of the yellow crazy ant *Anoplolepis gracilipes* prior to the aerial campaign of 2002. (a) Supercolony occurrence at 1024 waypoints spaced at 364 m intervals across the island in 2001. Large dots indicate waypoints with supercolonies of the YCA. The grid was rotated 27° from north to align with the existing network of drill lines. Actual survey transects at each waypoint were offset 25 m away from the drill line. (b) Final distribution of supercolonies following detailed boundary delimitation by ground crews in 2002. Some supercolonies areas discovered during the IWS were baited by ground crews before the aerial operation, and do not appear in (b). In both maps, grey areas indicate clearings without forest cover, mostly abandoned phosphate mining areas. Contours are indicated at 50 m intervals.

(181/754) of waypoints, equating to ~25 km^2 of island forest. Third, burrow densities at waypoints indicated that YCA had killed c.15 million red crabs (c.25% of the total island population).

Simultaneously with development of the IWS, two other key elements for the response were initiated. First, PANCI commenced efforts to source and evaluate an effective ant bait. Initial trials with commercially available bait formulations were unsuccessful. Eventually, Presto®01, a fishmeal bait with an active constituent of fipronil, was identified as effective (Fig. 11.2c). At the time this bait was unregistered in Australia, but use was permitted on Christmas Island under an emergency permit issued by the National Registration Authority. Ground crews treated a total of 371ha of YCA supercolonies between 2000–2001, achieving a knockdown of >95% of ant workers within days.

Second, a small steering committee comprising volunteer scientists, managers, and policymakers was formed, independent from the management authority. The key functions of the committee were to provide advice and support for the operational programme, strategic direction, and, on occasion, advice to the Director of National Parks. Committee members met regularly by teleconference, and routinely produced discussion papers to present, evaluate, and recommend options for the programme, establish timelines for actions, and review and monitor progress.

11.3.2 The aerial control campaign

The genesis of the aerial control campaign lay in the compelling findings of the IWS (Orchard *et al.* 2002); two-thirds of supercolonies were in areas too rugged for field crews to operate safely and effectively, and in any case, ground control was impractical given the sheer pace and scope of the invasion relative to the number of personnel available. In late 2001, the steering committee canvassed the idea of an aerial approach to YCA control, based largely on the aerial campaigns in New Zealand to control invasive rats (e.g. Towns and Broome 2003) and the newly initiated campaign to eradicate the red imported fire ant in Brisbane (Vanderwoude *et al.* 2003).

Given the novelty of an aerial approach, the Steering Committee recommended in February 2002 that a trial be conducted to determine if YCA supercolonies could be effectively controlled from the air. Two timelines were considered: (1) where both the trial and island-wide control programme were conducted during a single 3-week period in September 2002, whereas (2) involved a staged approach with a trial in 2002 followed by control in 2003. The first plan was considered feasible within the 3-week window because the ant bait is fast acting so the efficacy of aerial broadcasting of bait would be evident within days. Three factors weighed in the recommendation:

1) The urgency of controlling all supercolonies as soon as possible.
2) The high cost involved in transporting a helicopter to the island twice.
3) The high purchase and transport costs of stockpiling tonnes of ant bait if the first plan was adopted but the trial failed.

The first plan was endorsed, thus imposing an extremely tight timeline—in effect to plan, test, and execute the operation within just 7 months (Fig. 11.3). There were seven components to the overall planning and implementation of the aerial baiting campaign.

11.3.2.1 Legislative approval

Approval to aerially broadcast toxic ant bait in the Christmas Island National Park was sought under the Environment Protection and Biodiversity Conservation Act (1999). First, a Referral was submitted that outlined the extent of the invasion, its documented and suspected impacts, and that aerial application of toxic bait was the only effective method of control. A full environmental impact assessment of the potential benefit and risks was submitted (Green *et al.* 2002) and reviewed by Environment Australia. The key conclusion was that the probable consequences of not acting were far worse than the potential non-target impacts. The aerial baiting operation was endorsed by Environment Australia (see http://www.environment.gov.au/cgi-bin/epbc/epbc_ap.pl?name=referral_detail&proposal_id=722), but the pace was such that official approval was given while the helicopter and bait were en route to Christmas Island.

11.3.2.2 The helicopter

It was necessary to source a civilian contractor with an appropriate aircraft, suitable delivery technology, and experience to fulfil the operational requirements of the baiting programme. In March 2002, pilots from two helicopter companies were bought to Christmas Island to reconnoitre potential loading sites and local flying conditions, especially the hazards posed by seabirds. The successful tenderer had previous experience of aerial baiting as part of the eradication programme for the red imported fire ant in Brisbane. They used a Bell 47 Soloy helicopter, which was partially dismantled for shipment to the island, and reassembled at the Christmas Island airport (Fig. 11.2b).

The accurate treatment of YCA supercolonies presented special challenges for the pilot, because boundaries were irregular, many supercolonies were relatively small, and most lay within continuous forest and were not identifiable from above the rainforest canopy. The pilot developed a new system of precision navigation to deal with these challenges, involving the use of two independent GPS units—a highly accurate (sub-metre) Trimble differential GPS unit to stay on track as each run was flown and a hand-held Garmin GPS unit to delineate supercolony boundaries at the start and end of each run. Great skill was required as the pilot was flying the aircraft at around 100 km/hour, while simultaneously keeping track of the aircraft's instrument panel, the two GPS units, and seabirds.

Quality control was an important consideration when choosing the successful tender. An on-board differential GPS recorded the exact routes flown while the bait stream was switched on. Once downloaded to the CIGIS, and buffered to a width of 12 m (the width over which bait was dispersed on each run), these records allowed a detailed assessment of how well target areas had been treated, in terms of both accuracy around the perimeter, and coverage across the treatment area.

11.3.2.3 Dispersion of Presto®01 ant bait

Ant bait was dispersed from a bucket suspended beneath the helicopter (Fig. 11.2b). This bucket was an inverted cone into which about 90 kg of bait was loaded (Fig. 11.2d). A key factor in bait dispersal was its moisture content—the pelletized bait had to be dry enough to flow without blockage through a 25 mm diameter hole at the bottom of the bucket, onto a petrol-driven, rotating spreader. Despite prior testing on the mainland to establish the ideal moisture content, the Presto®01 shipped to the island was too moist and would not flow. So, all 13,000 kg of Presto®01 had to be dried by spreading it thinly with garden rakes on sheets of black plastic in full sun. This was an incredibly labour-intensive exercise, required 250 person hours to complete, and risked photodegradation of fipronil. Drying barely kept pace with the demands of flight operations.

11.3.2.4 Mapping supercolonies

The accurate mapping of YCA supercolonies was crucial to the success of the control programme. The map was based largely on the results from the 2001 IWS, followed by boundary delimitation during the four months leading up to aerial operations in September 2002 (Fig. 11.4b). All boundaries were mapped in the field with hand-held GPS units, and maps were generated using the CIGIS. Field crews used several cues to determine the boundaries of supercolonies, including subjective assessments of crazy ant abundance, both on the ground and as 'trunk traffic' on trees, and the presence or absence of dead crabs. In areas where supercolony boundaries did not correspond with a physical feature of the landscape (e.g. a cliff, forest edge), three field workers walked abreast 10–20 m apart along the length of the boundary, with the two outer people keeping the middle person accurately positioned on the boundary—the outer person continually confirmed the absence of ants, while the inner person continually confirmed their presence. The middle person held the GPS unit and coordinates were taken every 20–50 m. Some boundaries were easily identifiable by observers on the ground, but often there was a wide 'transition zone' between heavily ant-infested forest and intact forest (Abbott 2006). These boundaries proved too finely resolved to be practicable for aerial operations. Accordingly, boundaries were rounded on the CIGIS, but this process never pared off sections of supercolonies. This increased the total treatment area increased by 167 ha from 2378 ha to 2545 ha.

Sections of several supercolonies were excluded from the aerial control programme. These included all freshwater streams and soak areas, including the two Ramsar Wetlands of International Importance. Fipronil is reported to have strong negative effects on freshwater fauna, so exclusion zones of 100 m were imposed around these areas. Five supercolony research plots were excluded from the aerial baiting programme but later treated by ground baiting. The total area excluded from the baiting programme was 76.2 ha.

11.3.2.5 Trial of aerial baiting

The aims of the trial of aerial broadcast were threefold:

1) To assess the efficacy of Presto®01 delivery by helicopter for controlling supercolonies against a target of 99% knockdown.
2) To identify the lowest effective rate of Presto®01 for supercolony control.
3) To assess the degree of bait penetration through the canopy to ground level.

The efficacy of aerial bait delivery for supercolony control was assessed using a before-after-control-impact design. The CIGIS was used to delineate 6 plots (each 9–53 ha) in supercolonies, two for each application rate plus two untreated control plots. In each plot YCA activity was monitored on cards (Abbott 2005) placed at 44 stations along four parallel transects (each 150 m long and 40 m apart), three times before and eight times after aerial baiting.

Some aerial broadcast bait is likely to be intercepted by the forest canopy, reducing the amount reaching the forest floor. Even though the YCA forages extensively in the forest canopy (O'Dowd *et al.* 2003, Abbott and Green 2007) and would be likely to collect suspended bait, decreased bait reaching the forest floor could compromise control. Penetration of bait dispersed through the canopy was estimated with 30 one m^2 catch bags along the transects in each plot. Large plastic bags were stapled to a circular wire hoop held up by wooden stakes. Catch bags were placed in the plots 2–3 hours before aerial baiting and emptied 3–4 hours after treatment. The catch bags were emptied again 3–4 days later in case more pellets fell from the canopy, and the catch dried and weighed.

Bait application rates averaged 5.9 kg/ha and 4.4 kg/ha on the high and low application plots, respectively, very close to the target rates of 6–4 kg/ha. Eighty percent of catch bags intercepted >90% of bait within 3–4 hours of application. The mean rate of bait penetration was 59.2% across all plots. Although a considerable fraction of bait was intercepted by the canopy, YCA activity declined dramatically following aerial baiting. Aerially-dispersed Presto®01 had a significant negative impact on crazy ant activity within days of treatment, at both rates of application. Ant activity on the control plots was high during the week preceding treatment and remained so during the week after treatment. Conversely, on the baited plots, ant activity in the week after aerial treatment declined by an average of 91% of pre-treatment levels, and was essentially nil after 12 days, regardless of application rate and sufficient to achieve >99% knockdown. Five days after the trial, the Steering Committee endorsed the full treatment of all remaining supercolonies on Christmas Island, at a nominal rate of 4 kg/ha.

11.3.2.6 Measuring the success of the island-wide operation

Success of aerial operations was assessed in terms of both the coverage and accuracy of the baiting operations, and the impact on YCA activity. GPS downloads from the helicopter indicated almost blanket coverage of all target supercolonies, more than 2500 ha in just 8 days. The few mistakes included 3 ha that were baited in

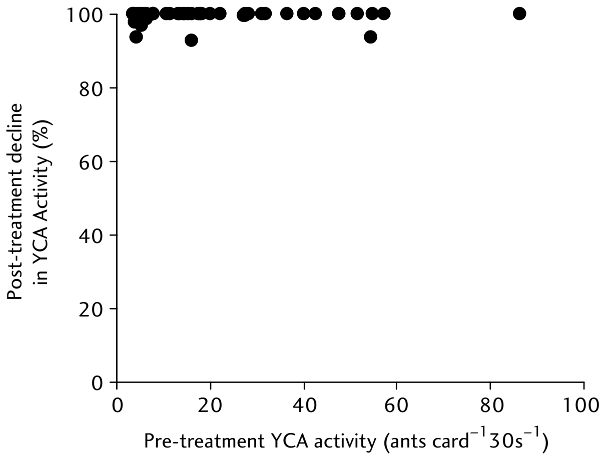

Fig. 11.5 The knock-down effect of Presto®01 ant bait on the activity of the yellow crazy ant at 44 waypoints, 1 month before, 1 month after aerial broadcast of Presto 01. X axis is the number of ants running across a 100 cm^2 card in 30 s, averaged across 11 cards placed on the soil surface along a transect at each waypoint. Note that over the entire range of ant activity, knockdown was consistent, i.e. density independent.

error, mostly as the result of occasional overshoots on baiting runs. A total of 9 ha were missed, including a 6 ha in the north-west of the island which could not be baited because of the high density of flying seabirds.

Pre- and post-baiting surveys of ant activity were conducted at 44 waypoints in supercolonies from the IWS to measure efficacy of control. At each waypoint, card counts of YCA were used as per the IWS and the aerial baiting trial. Ant activity at each site was assessed once 1 month before and 1 month after waypoints were treated. YCA activity declined precipitously following aerial treatment (Fig. 11.5). Ant activity fell from 21.6 ± 18.7 ants/30s (SD) prior to treatment, to 0.13 ± 0.50 ants/30s after treatment, an average decline of 99.4%. The decline was >97% at 40 of 44 waypoints, and 100% at 77% of waypoints. This met the target of 99% knockdown set by the steering committee prior to the aerial baiting operation.

11.3.2.7 Non-target impacts

Aerial broadcasting of tonnes of toxic bait in the National Park had the potential to cause serious impacts to non-target species of special conservation significance. These included endemic reptiles, several endemic land birds, an endemic seabird, and an unknown number of endemic invertebrates.

Although fipronil is toxic to crabs, the risk posed to the red crab population by the aerial baiting campaign was considered minimal because resident red crabs were already annihilated within supercolonies. Furthermore, live crabs near the boundaries of supercolonies were unlikely to encounter bait because they rarely emerge from their burrows in the dry season, when aerial baiting operations were conducted. Robber or Coconut Crabs (*Birgus latro*) were of more concern because they forage more widely and are more active under dry conditions. Moreover, the robber crabs on Christmas Island are genetically distinctive from robber crabs elsewhere (Lavery *et al.* 1996), and, until the YCA invasion were the largest and least impacted population anywhere in the world (Schiller 1988). Although the YCA extirpates robber crab populations in supercolonies, baiting operations posed a significant threat because *Birgus* have a well-developed olfactory system, move large distances for food, are attracted to the fishmeal matrix in Presto®01, and are extremely susceptible to fipronil.

Considerable effort was invested in minimizing non-target impacts on this charismatic species. Two kinds of attractive food lures were used to entice robber crabs from baited areas during helicopter operations. First, 44 senescent trees of the endemic palm *Arenga listeri* were felled several weeks prior to aerial operations, several hundred meters apart and up to 300m away from baited supercolony boundaries: the pith of this monocarpic palm attracts robber crabs in large numbers from hundreds of metres. Second, where possible, targeted supercolonies were also ringed with depots of poultry food pellets mixed with shrimp paste. This lure had been used during initial ground-based control. Using the CIGIS, over 250 sites were selected around supercolony perimeters. One or two days before areas were aerially treated with ant bait, 15 kg of the lure was dropped from the helicopter at intervals of 150–250 m around the perimeter and at distances between 50–200 m outside supercolony boundaries.

The effect of these lures on mitigating robber crab mortality was assessed after the aerial baiting operation. Mortality was estimated at 5.3% for sites close to edges of baited supercolonies, but because all supercolonies were ringed with food lures, there were no supercolonies without lures to act as controls. However, estimates made during initial ground baiting indicated mortality rates of 15% in the absence of food lures (D. Slip, pers. comm.). In spite of this considerable effort, a comprehensive assessment of food lures to reduce *Birgus* mortality in association with baiting has since shown them to be ineffective (Thomas 2005).

An analysis of non-target impacts on litter invertebrates during ground control operations using the identical bait formulation (but at a higher rate of application) found no evidence for off-target impacts (Marr *et al.* 2003). Despite several reports of dead and dying introduced cockroaches in a hollow tree stump, and mortality of the introduced ant *Campanotus melichloros* in the immediate aftermath of the aerial operation, it is highly unlikely that the aerial operation caused broad and substantive non-target impacts on litter invertebrates. The sheer abundance of the foraging YCA in supercolonies meant that these ants largely monopolized the bait (Marr *et al.* 2003). Contractors engaged to assess impacts on canopy invertebrates, forest reptiles, and land birds found no evidence of non-target impacts (Stork *et al.* 2003).

The aerial baiting campaign was a success in terms of:

- Design and implementation of the island-wide survey as the basis for the aerial campaign.
- Approval under the EPBC Act (1999) of aerial baiting operations. All conditions specified in the approval were met.
- The recruitment of a reputable aviation company and skilled pilot/engineer to conduct aerial baiting.
- Proof of concept for the feasibility and efficacy of island-wide aerial baiting.
- Island-wide suppression of YCA supercolonies that met the pre-operational target of 99% knockdown.
- Assessment of non-target impacts.

11.3.3 Evaluation and lessons learned from the aerial campaign

At least 13 hard-won insights broadly relevant to rapid response to invasion by alien invertebrates emerge from the experience with YCA on Christmas Island. Except for the first three, these are in no particular order:

1) **The human dimension**. Successful responses to invasive species depend in large part on the passion and determination to succeed of the people involved. Top-down directives rarely engender zeal in scientists, managers, and field crews at the coalface of the invasion. We agree with Anderson (2005) that success is engendered from the bottom up. On Christmas Island, the coincidence of people with a 'love of place' sustained the effort, especially through moments of uncertainty and despair. Equally, the frailties of personality can be the Achilles heel of these efforts, and more than once threatened this programme. The consequences of these human failings assume greater proportion and immediacy in the crisis management of biological invasions.
2) **Solid science supported by good natural history**. Without a documented understanding of the impacts of the yellow crazy in rainforest on Christmas Island, it would have been nigh on impossible to convince management authorities and funding agencies of the seriousness of the problem. Embedding the scientific culture (e.g. design, analysis, reporting, synthesis, interpretation, and review) in invasive species management is essential and we believe it was crucial on Christmas Island. A sound understanding of the island's natural history was fundamental to crystallizing the implications of the invasion.
3) **Capacity for responsive funding**. Almost by definition, the crisis management of biological invasions is unpredictable and therefore not built into the operational budgets of management agencies. However, their capacity to respond to these demands in a timely fashion is crucial. The decision in February 2002 to implement the aerial campaign just 7 months later placed considerable financial demands on Environment Australia. In fact, one-third of the funding was sourced competitively through a Natural Heritage Trust

(NHT) grant, and it was pure coincidence that the timelines of this scheme suited the tight timelines of the aerial baiting operation.

4) **GPS and GIS technology.** Hand-held GPS units and GIS software (Christmas Island Geographic Information System) were both critical. Without GPS, sites could not have been located with accuracy and speed to conduct the IWS, to delimit supercolonies, and to transfer coordinates to the pilot for aerial operations. Without the CIGIS, data management, presentation, and interpretation would have been impossible.
5) **Public awareness**. Increased public awareness of impacts on the island through local, national, and international media helped focus the attention of the management authority on the emerging crisis. Furthermore, public awareness of the ongoing control effort increased both nationally and internationally the profile of the YCA in particular, and invasive ants and invasion on islands more generally. For example, the inclusion of the YCA in the list of 100 of the world's worst invaders (Lowe *et al.* 2000) was a direct result of its known and quantified impacts on Christmas Island.
6) **Clear demarcation of responsibility**. The aerial operational succeeded because there was a single authority responsible for management and funding. Invasion of the YCA into built environments, agricultural lands, and natural areas on mainland Australia has generated jurisdictional disputes on just who is the responsible agency for management (Commonwealth of Australia 2006). These disputes can cause significant delays in response and fuel a public perception of confusion and inaction.
7) **Bridging the science-management interface.** A cooperative programme of research and management of the YCA on Christmas Island through the Australian Research Council's Linkage programme brought scientific expertise to the operational programme. Essentially, university scientists were 'embedded' with natural resource managers to achieve the objectives of the programme. Once the magnitude of the challenge became apparent, traditional suspicions and demarcation of roles between scientist and manager blurred: scientists, who focused initially on impact analysis crossed over to support the planning and implementation of the operational programme, while managers rallied behind the scientific approach to achieve their goals. However, bridging the science–management interface can cause conflicts of interest within individuals. As scientists, we wanted to research and understand the nature of the YCA invasion and its cascading impacts. At the same time, we recognized the absolute need to destroy that which we wished to study.
8) **Competing resource demands**. Research and management of the YCA invasion was all consuming. This almost certainly had unintended consequences for other important management activities on the island. First, the YCA campaign diverted resources from other important programmes for invasive species (e.g. weeds, feral cats, and the introduced wolfsnake).

Second, other pressing issues of direct relevance to the management of the Christmas Island National Park (e.g. planning for a refugee detention centre, a satellite launching facility, and phosphate mining activities) all placed an extraordinary burden on managers in the lead up and conduct of the aerial operation.

9) **An independent steering committee**. A steering committee comprising scientists, managers, and policymakers guided, advised, reported, and evaluated the programme with independence from the management authority in a timely fashion, without any formal jurisdiction or direct funding. All were unpaid volunteers working primarily through frequent teleconferences across three time zones.
10) **Successful response sometimes requires a healthy dose of luck.** Serendipity played a significant role in the success of the programme. For example, the early detection of supercolonies was largely due to chance, while doing basic research on the last funded trip examining the role of the red land crab in island rainforest dynamics. This basic natural history and research, which began 15 years earlier, primed an appreciation for impacts following the removal of the native red land crab, a keystone species. We agree with Louis Pasteur: chance really does favour the prepared mind. Second, military-grade GPS became more widely available only in May 2000, increasing its precision fivefold and making it possible to navigate accurately beneath the rainforest canopy with hand-held units just in time for the first IWS. Previous attempts just a few months earlier had been a depressing and dismal failure. Third, an aviation company with the capacity to do job was available and a single pilot/engineer was willing to take on what was for them a relatively small job.
11) **Successful response requires quick thinking**. Things go wrong, and on Christmas Island, two incidents threatened to derail the aerial baiting operation almost before it began. First, the complexities of transferring coordinates from the CIGIS to the pilot's dual GPS system did not become apparent until after the aircraft was actually on the island. Even worse, all supercolonies had been mapped in the IWS on a metre (UTM) grid, but the pilot required coordinates in the form of degrees, minutes, seconds, and decimal seconds. Second, the bait arrived on the island too moist to flow through the hopper. In both situations, good old-fashioned nous was key to solving these problems and salvaging the project.
12) **Who you know is as important as what you know.** Networking with other groups proved pivotal. First, the notion of aerial baiting on a remote oceanic island stood on the shoulders of previous successes on New Zealand islands. Second, the fact that one steering committee member was involved directly in the complex effort to eradicate the red imported fire ant in Brisbane gave the control operation on Christmas Island access to their technology for aerial bait delivery and key contacts, including the aviation company.

13) **Isolation and tight timelines are not show-stoppers for invasive species management.** We think that the rapid conduct (Fig. 11.3) and success of the aerial operation (Fig. 11.5) dispels the notion that isolation stymies invasive species management (cf. Simberloff 2002). A can-do attitude, along with facsimiles, emails, and telephone conference calls were sufficient to overcome the tyranny of distance; restrictions imposed by the vagaries of shipping schedules were countered by good advanced planning.

11.4 Conclusions

Heuristic models that describe idealized responses to biological invasions are useful, but only to a point. These models (Fig. 11.1) describe adequately the sequence of events as they unfolded on Christmas Island, from initial detection and diagnosis of the invader, through to notification of stakeholders, interim management, more comprehensive assessment of threats, and to action and follow-up monitoring. The model even describes accurately that interim management responses and broader threat assessment occurred more or less simultaneously on Christmas Island. Perhaps it was inevitable that the Christmas Island response, and responses elsewhere (e.g. Anderson 2005; Coutts and Forrest 2007), even in the absence of specific or generic contingency plans, should all have followed this general pattern simply because it is logical to proceed in this way. What these models fail to do, however, is to educate practitioners—managers and scientists alike—of the cold, hard reality of confronting rapid, expansive, and high-impact invaders. We argue that models like these are only truly, and usefully, heuristic if they are accompanied by detailed case studies that flesh out the abstractions. 'Action' in our generic model (Fig. 11.1) belies the complexities of mobilizing a team and securing the funds to tackle the problem, overcoming myriad technical and organizational details, and even managing a large team whose very humanity makes the whole enterprise vulnerable.

We have identified ingredients to the success of the aerial baiting operation for YCA supercolonies on Christmas Island. Arguably, some of these, such as the drive and dedication of the people involved, good science, and the capacity for responsive funding should be seen as generic prerequisites. Others, such as sourcing the right aircraft and pilot, are obviously more idiosyncratic to this specific operation. Furthermore, we are quite willing to acknowledge lady luck in some aspects of the planning and implementation of the programme. While it would be unrealistic to expect that all emergency responses to invasive species will be successful, we should not fall to fatalism and the failure to act. Aim high (Simberloff 2002).

Events since the aerial campaign of 2002 offer further insights on invasive species management. First, the warm afterglow of success can be counterproductive because the very act of mitigating an urgent situation can foster a perception that the problem has been 'fixed'. This puts at risk the resources required for continued surveillance and maintenance management. By 2005, the YCA was resurgent in some areas treated during the aerial campaign, and new supercolonies had formed elsewhere (Fig. 11.3). Island managers have had to battle over many years to secure sufficient resources to sustain the gains of 2002, despite the fact that the ongoing nature of the problem, and the downturn in support, were both foreseeable (O'Dowd and Green 2002).

Second, the Christmas Island experience has had much broader, knock-on effects. It has directly influenced management of the YCA in the Northern Territory and Queensland in mainland Australia, and efforts to eradicate or control this ant on Pacific islands. Furthermore, this response on Christmas Island led to the successful listing of the YCA as a key threatening process under Australia's Environment Protection and Biodiversity Act (1999). Along with the listing of the red imported fire ant as a key threatening process, this led to a national threat abatement plan for invasive ants in Australia and its territories, which contains 72 actions, including regional cooperation to build capacity for prevention and rapid response to invasive ant species (Commonwealth of Australia 2006).

The aerial baiting campaign was but one battle in what will be a protracted war, but the prognosis for the suppression and containment of YCA supercolonies on Christmas Island is good. Environment Australia now has in place a 10-year plan (Fig. 11.3), with stable, ongoing funding for at least the first 4 years. Much of these resources will be devoted to maintenance management—biennial island-wide surveys, and ground based control—but funds have also been allocated for another aerial campaign, if needed, as well as the development of alternative baits, and research and development on novel approaches to control (O'Dowd and Green 2003).

If there is one overarching lesson from the aerial baiting campaign on Christmas Island and its aftermath, it is this: while funding and technology are fundamental in the battle against invasive species, it is passion, tenacity, and a steely will to succeed that will eventually tip the scales.

11.5 Acknowledgements

Natural resource and park managers at PANCI—D. Slip, S. Comport, M. Orchard, and M. Jeffery—provided crucial support to all aspects of this project. J. Barry (PAN) was instrumental in obtaining funding and in guiding the project through the EPBC referrals process. A. Andersen and the Crazy Ant Steering Committee provided strategic oversight and direction throughout the development and conduct of this programme. G. Foo, K. Retallick, and T. Zormann conducted both the IWS and initial ground baiting. A. bin Yon and E. bin Johari refuelled and reloaded the helicopter, and research students K. Abbott, N. Davis, and R. Marr helped provide the research underpinnings for the project. Chief pilot F. van Beek showed consummate skill and professionalism in the aerial campaign and J. McDermott committed his company to this effort. L. binte Bahari, J. bin Jantan, R. bin Sani, and A. bin Wahid provided field assistance. P. Morrow, J. Einam, and D. Meek facilitated production and delivery of the ant bait. K. Sandford-Readhead and the Brisbane City Council assisted in the conversion of GPS coordinates to compatible shapefiles. The Natural Heritage Trust and the Australian Research Council financially supported the control and research programmes, respectively. We thank the Director of National Parks, P. Cochrane, and former Environment ministers R. Hill and D. Kemp for their support of this programme.