Biol Invasions (2019) 21:1789–1805
https://doi.org/10.1007/s10530-019-01937-7

ORIGINAL PAPER

The eradication of ungulates (sheep and goats) from Dirk Hartog Island, Shark Bay World Heritage Area, Australia

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Received: 7 October 2018 / Accepted: 29 January 2019 / Published online: 5 February 2019

Abstract The eradication of ungulates from offshore islands has now become achievable for island managers, with the size and complexity of an island no longer a major impediment to the desired outcome. Here, we report on a whole-of-island eradication campaign of ungulates (sheep *Ovis aries* and goats *Capra hircus*) from the semi-arid Dirk Hartog Island (63,300 ha) off the western Australian coast. The motive behind this campaign was to contribute towards the ecological restoration of this former grazing lease. From 2005, a concerted effort to remove ungulates began with regular destocking, and from 2010 a methodical aerial and ground shooting campaign was undertaken. Long-term commitments of funding and departmental support, staff with diverse skills, and an advisory network of professional people, have been critical components to this large-scale exercise. From 2005 to 2017 a total of 16,318 ungulates (5185 sheep and 11,133 goats) were removed from Dirk Hartog Island: 6839 by mustering, 2422 by ground shooting, 7040 by aerial shooting, and finally 17 by follow-up aerial monitoring and ground shooting. The island was declared free of ungulates in November 2017. To determine the success of the whole-of-island eradication campaign, multiple methods were adopted to locate remaining animals: use of 'Judas' goats, monitoring by motion-sensor cameras at water sources and across the island, and recording of tracks and fresh scats to locate any remaining animals. We estimated the likelihood that sheep and goats have been successfully eradicated from the island is 99.9% and 96.9%, respectively. The total cost (AUS$) of the aerial component of the eradication was $1,055,184, an average of $150/goat or $16/ha. The monitoring phase of the campaign (aerial detection and ground shoot) cost the least in terms of actual expenses (approximately $187,000) but the most is terms of cost per remaining goat (approximately $14,400). Ecosystem recovery following the eradication is already apparent with increased vegetation cover and reduced erosion. We conclude with some shared lessons that may assist similar large-scale eradication campaigns of islands. To date, Dirk Hartog Island is the largest island in the world where whole-of-island goat (and sheep) eradication has been achieved.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10530-019-01937-7) contains supplementary material, which is available to authorized users.

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Keywords *Capra hircus* · Eradication · Invasive species · Island conservation · Judas · Sheep

Introduction

The eradication of many large alien vertebrates on offshore islands is now a feasible management objective for island managers (Parkes et al. 2010; Cruz et al. 2009). The most invasive ungulates to occur on islands are goats (*Capra hircus*) (Campbell and Donlan 2005). Anthropogenic introductions of goats to islands worldwide have led to major changes to vegetation diversity and structure resulting from overgrazing, often leading to ecosystem degradation (Coblentz 1978; Schofield 1989; Courchamp et al. 2003; Garcillán et al. 2008; Chynoweth et al. 2013; Gizicki et al. 2018). Sheep and goats also spread weeds by transporting seeds in their coats. In addition, much of the vegetation is eaten, exposing large areas of soil to erosion (Walker 1991; Desender et al. 1999; Ortiz-Alcaraz et al. 2016). Removal or eradication of ungulates is therefore an important component of ecosystem restoration on many islands (Parkes et al. 2002; Campbell and Donlan 2005).

By 2002, goats had been eradicated from 120 islands worldwide (Campbell and Donlan 2005) with a further 38 whole-of-island eradications across 18 countries reported since then (DIISE 2015). Within the Australian context, goats and sheep have been eradicated from 51 islands to date (J. Parkes, *unpubl. database*).

With larger islands (> 10,000 ha), managers have sought to combine the most efficient suite of eradication techniques coupled with monitoring programs, especially when animals are present at low densities (Campbell and Donlan 2005; Ortiz-Alcaraz et al. 2016). The combined use of global positioning systems, geographic information systems, aerial hunting by helicopter, specialised detection dogs, and/or the use of Judas goats, have dramatically increased efficiency and significantly reduced the duration of eradication campaigns. Island size and habitat complexity are arguably no longer a limiting factor for island restoration (Cruz et al. 2009). Whole-of-island eradication of goats has now been achieved on islands as large as 58,465 ha (Santiagio Island, Ecuador; Cruz et al. 2009), and on part-island areas as large as 458,812 ha (Isabela Island; Carrion et al. 2011) and 440,000 ha (Kangaroo Island, Australia; Masters et al. 2018) with 79,000, 62, 868 and 1200 goats removed, respectively. Notwithstanding these successes, obtaining the necessary funding, logistics and community support to undertake a large-scale eradication campaign remain challenging. Island remoteness, dense vegetation cover, difficult terrain to walk or drive on, and temperature extremes all present circumstances that may collectively slow progress in ungulate eradication (Campbell and Donlan 2005; Genovesi 2007).

Here we report on the eradication of sheep and goats from Dirk Hartog Island, a large semi-arid island off the western coast of Australia, following 150 years of ungulate occupation. We describe the management actions undertaken, the timeframe over which the eradication campaign occurred, the statistical analyses used to determine the probability of success, and describe the early environmental benefits. This is, to date, the largest successful whole-of-island ungulate eradication program in the world. We also report on the financial and logistic investments required to achieve this outcome to inform the planning of future large-scale island eradication programs.

Study site and historical context

Dirk Hartog Island (25°48′S, 113°1′E; 48–188 m above sea level) is situated within the Shark Bay World Heritage area (DEC 2008, Fig. 1). It is the tenth largest island (63,300 ha) off the Australian coast and the largest island off the western Australian coastline. It is the base for a small tourism industry focused on offshore and onshore recreational fishing.

Shark Bay has a semi-arid to arid climate. Rainfall is sporadic and unreliable (mean annual rainfall is 224 mm; Bureau of Meteorology); both long periods of drought or consecutive seasons of above average rainfall may occur and there are occasional cyclonic events. Vegetation consists of low open shrubland generally dominated by spinifex (*Triodia* sp.) and wattle (*Acacia* sp.) (Strategen 2012). The island has an elongated, north–south orientation, approximately 80 km long and 10 km wide. The west coast contains high dunes and cliffs, contrasting with the east coast of sandy, low-lying, shallow beaches. The soils consist of sandy coastal dunes that are particularly susceptible to

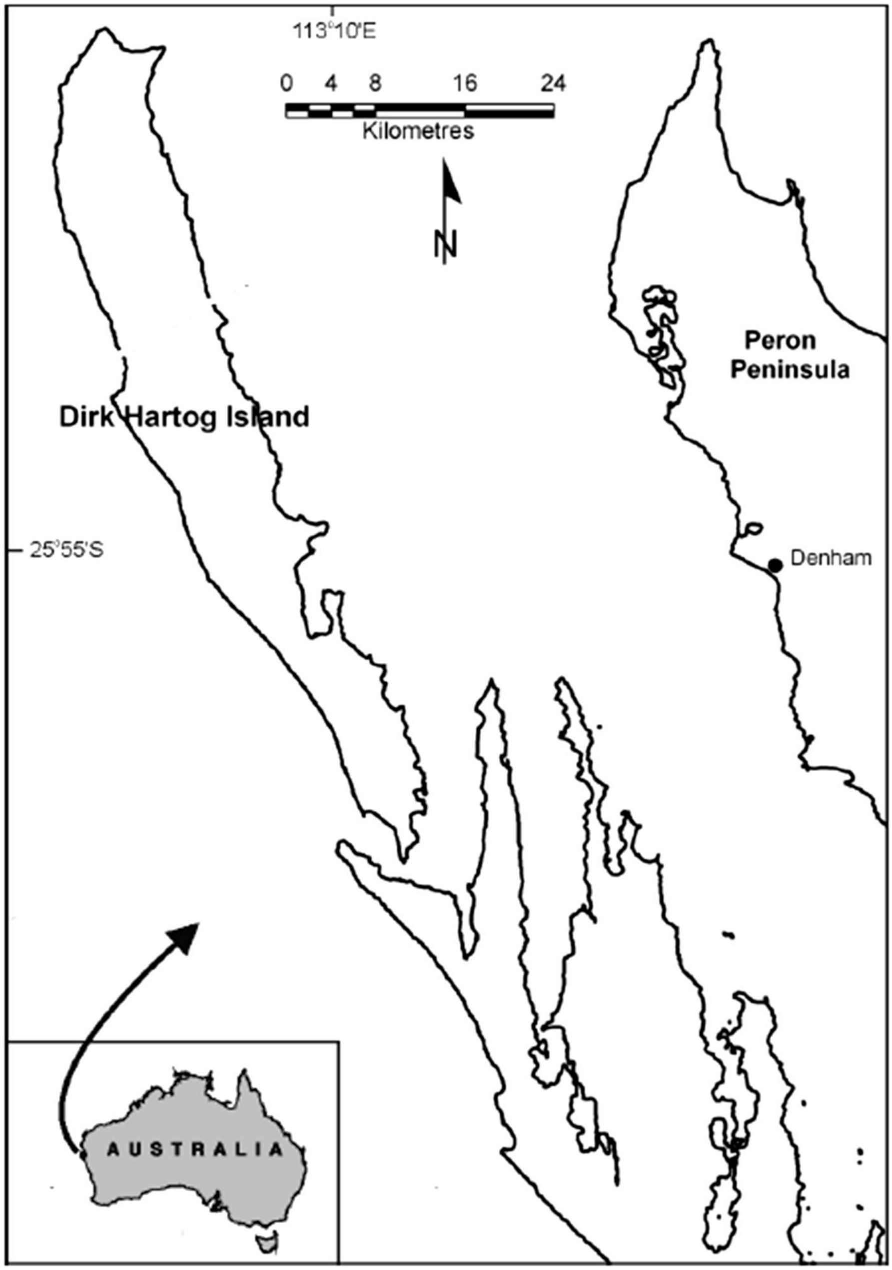

Fig. 1 Location map of Dirk Hartog Island relative to the Shark Bay peninsulas of mainland Australia

erosion and can take considerable time to rehabilitate in the dry climate.

Dirk Hartog Island once supported at least 13 native terrestrial mammal species (Baynes 1990; McKenzie et al. 2000). However, a combination of impacts on native vegetation from sheep and goat grazing between the 1860s and 2009, along with predation from feral cats (eradicated in 2018, Algar unpubl. data), has reduced the number of native terrestrial mammal species extant on the island to three (Strategen 2012).

The island was first settled for sheep grazing purposes in the 1860s with the lease being surrendered in 2009. Goats were introduced to Dirk Hartog Island in 1906, when the lighthouse keepers at Cape Inscription brought the animals over as a ready source of milk and meat (DEC 2011). After the automation of the lighthouse in 1917, the lighthouse keeping staff left Dirk Hartog Island and it is believed that the small goat herd kept at the lighthouse were released. Goats then established across the island. Sheep reportedly numbered about 26,000 in the 1920s, and were kept during the 1930s at a density of one sheep per 6 ha (Ride and Tyndale-Bicoe 1962). Stocking rates, determined from farm grazing records, varied considerably during this period. During the early 1960s the island was estimated to support 20,000 sheep and goats (DEC 2011).

The feral goat is listed under legislation as a declared pest in Western Australia (Biosecurity and Agriculture Management Act 2007), requiring land managers to control their numbers and seek permits for their transport. Removal of goats and sheep from Dirk Hartog Island commenced when the former lessee began destocking in 2005 in anticipation of the island becoming a national park. With the establishment of the national park in 2009 several small freehold properties remained on Dirk Hartog Island and the owners supported the eradication of sheep and goats from the island, including from their properties. Regular aerial shooting operations began in February 2010 funded under Australian Commonwealth and State initiatives. This enabled the implementation of a whole-of-island eradication program as part of an ambitious ecological restoration project (DEC 2011). The ecological restoration program involved ungulate and feral cat eradication, weed management, vegetation restoration, fire management, reintroduction of the mammal fauna, and the implementation of biosecurity protocols to prevent the introduction of high-risk non-indigenous species.

Methods

The removal of ungulates as part of the Dirk Hartog Island eradication program followed a specified sequence of events: ground shooting goats and destocking of sheep (2005–2007), ground shooting of goats and sheep (2008–2009), aerial hunting and shooting of goats and remaining sheep (2010–2015), and finally a monitoring phase involving aerial searches and ground shooting of remaining goats (2016–2017) (Fig. 2).

Destocking and ground shooting

During the early phase of the campaign (2005–2007), effort commenced to shoot goats on the ground but to also destock the island of sheep.

Ground shooting phase

From 2008 to 2009 ground shooting effort increased using five or six ground-based experienced hunters to target remaining goats and sheep across the island. Sorties involved vehicle-based or foot patrols, with effort concentrated around watering points. Vehicle tracks on the island are limited, but spoor was followed to locate individuals or herds. Firearms used were 0.308 and 0.243 calibre rifles. Hunters were licenced, experienced hunters trained in firearms handling and use, were re-trained every 3 years, and maintained first aid skills.

Aerial searching and shooting phase

Aerial searching and shooting of remaining sheep and goats commenced from 2010. Shooting was timed to take advantage of sheep and goat breeding and behaviour patterns: during the cooler winter months (June/July) when conditions were suitable for animals to be foraging across the day; during the breeding months (September/October); and at dawn and dusk during the hottest and driest time of the year (January/February).

Aerial shooting operations were carried out with a Robinson 44 helicopter and licenced marksman, and utilised self-loading rifles of 0.308 calibre using 130 grain hollow point and 150 grain soft-point projectiles. All flights comprised one shooter and one pilot, with flying times primarily during dawn and dusk, when goats and sheep were more active. Animals were shot three times in the chest ('triple-tap' shoots) to ensure death was immediate. Aerial shooting was conducted bi-annually from 2010 to 2013 and tri-annually from 2014 to 2015, with each program consisting of three 2-h sorties daily over 5 days.

To maximise visual surveillance and repeat coverage of the island during the aerial programs, a series of parallel east–west flight paths were flown during each sortie totalling around 3000 km. These flight paths were flown below 30 m above ground level and less than 800 m apart, which allowed the pilot and

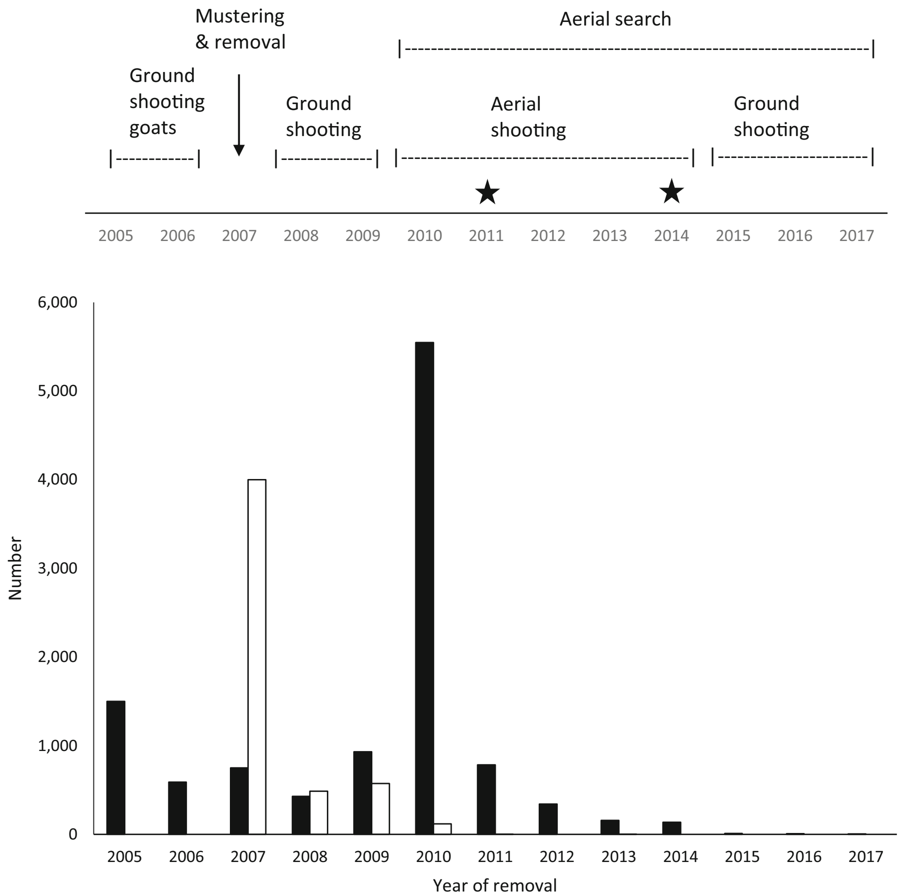

Fig. 2 Summary of 13 years of goat and sheep removal from Dirk Hartog Island (2005–2017), with the number of goats (dark bars) and sheep (open bars) either removed via destocking (2007) or shot at different time periods. Judas goats were used in 2011 and 2014 (starred)

observer to locate goat movements or fresh tracks within the transect lines.

Aerial monitoring phase

Operations changed to aerial monitoring from November 2015 to November 2017. During this phase, monitoring involved aerial surveys to first locate collared (Judas) goats and (if present) accompanying uncollared goats, and then survey the remainder of the island for lone uncollared goats. The intent was to sight goats after which the helicopter would land and deploy hunters to shoot animals from the ground. This reduced the logistical, planning and approval processes required for aerial shooting, and allowed the national park to remain open to the public during the shoot. The low vegetation and open sandy areas of Dirk Hartog Island allowed the pilot to land safely without the marksman losing sight of the target animal(s). Aerial shooting consisted of three 2-h sorties daily over 5 days.

Judas goats

Judas goats—in combination with a ground motion-sensor camera network—were used to attract remaining goats that were difficult to locate by observation alone. Goats are social animals and the use of collared decoy animals to attract them is an effective method of locating and removing difficult-to-find individuals or at low population densities (Taylor and Katahira 1988). The use of Judas goats followed standard operating procedures developed by the Australian Invasive Animals CRC (Sharp 2011). Unlike some other studies that imported non-resident Judas goats (Campbell et al. 2004; Masters et al. 2018), we captured goats in situ thereby using goats that were familiar with the local habitat and terrain, and we did not sterilise these goats.

Between 2011 and 2012, 20 healthy adult female goats were captured and fitted with radio-telemetry collars to assist with the location of remaining herds. We used only female Judas goats because they are reported to be more successful than males in locating and joining conspecifics (Taylor and Katahira 1988) and any offspring remain with them. In 2014, 15 new female Judas goats were captured, collared, and released following the expiry of batteries from the previously collared goats. Searching for the location of the Judas goats and, in parallel, following fresh sheep and goat tracks to their source during both aerial- and ground-based operations assisted with the location of small herds or individuals. All un-collared goats or sheep located were shot.

In 2014, a cat-proof fence was established across Dirk Hartog Island to assist a concurrent feral cat eradication program. This fence divided the island into two management units and assisted the goat and sheep eradication campaign by preventing the north–south movement of goats and effectively separating 'Judas' goats into two groups (four south of the fence, 11 north of the fence).

Records were kept of the number of sheep and goats shot in each shooting program to estimate the numbers of goats and sheep removed, and to support statistical analysis.

Motion-sensing cameras

Three watering points were established on the island to attract any remaining goats and sheep. During the hot dry summer periods there is little or no surface water available on Dirk Hartog Island. Sheep on the island were reliant on bore-fed troughs. While goats are less reliant on surface water, they also used livestock water troughs. Sensor cameras were used to detect any use of these troughs by ungulates.

As part of the feral cat eradication program, 174 motion-sensing cameras were installed on an approximate 2 × 2 km network across Dirk Hartog Island. A total of approximately 350 km of tracks was also monitored for feral cat activity using cameras, with some beaches also monitored on an ad hoc basis. This extensive network of tracks and cameras, with incidental observations by staff working on concurrent programs on the island, provided an additional surveillance tool to locate remaining ungulates.

Estimating the likelihood of successful eradication

Managers seeking to eradicate a species from an area often face the dilemma of deciding when to cease monitoring (Morrison et al. 2007). Failing to detect a species does not provide absolute certainty that the species is absent, as one or more individuals may be present but remain undetected (MacKenzie 2005). This imperfect detectability can be measured by the detection probability (p), which varies with both the species and other factors such as search effort or weather conditions. In this study, 'detectability' is used in a broader than usual sense as the probability that a goat is both detected and removed from the closed population.

The decision to declare the removal of ungulates from Dirk Hartog Island was supported by information on the likelihood that one or more (uncollared) ungulates remained, based on the estimated detectability of each species. This additional information could then be judged by managers when deciding whether and when to terminate the eradication program (Morrison et al. 2007; Ramsey et al. 2011). The detectability of both sheep and goats was estimated from the numbers shot in each previous shooting program to assess the likelihood of one or more target animals remaining on the island. Using a Bayesian occupancy statistical analysis, the detectability of sheep and goats was estimated—with and without incorporation of search effort (flight time)—and the likelihood that both had been eradicated was determined.

In a removal experiment, if the initial population size (N_0) is unknown it can be estimated from the number of removals during each successive survey and an appropriate statistical model (Farnsworth et al. 2002). The number of animals detected and removed (R) during the survey conducted at time t is:

$$R_t = p_t N_{t-1}$$

where p_t is the probability of removal (detectability) and N_{t-1} is the number of animals remaining after the previous survey. The number of animals remaining after animals are removed during survey t is:

$$N_t = N_0 - \Sigma R_{i \le t}$$

It follows that:

$$R_t = p_t (N_0 - \Sigma R_{i \le t-1})$$

This is the model used for data analysis. That is, the detection rate during each survey (p_t) is a proportion of the animals remaining (the initial number less the number of animals removed to date). This detection rate can be assumed to be constant for each survey or can be modelled as a function of covariates such as survey effort (St. Clair et al. 2013).

The assumptions required for this model were that there are no additions (immigration, births) or losses (emigration, deaths) from the initial population, other than animals deliberately removed. Any deaths from natural causes are irrelevant to determining detectability as animals that die naturally can be considered as undetected and excluded from the initial population estimate. For the goat and sheep populations on Dirk Hartog Island both immigration and emigration are nil, although there may be some population increase due to breeding between surveys.

Using this model, the initial population size and detectability of sheep and goats on Dirk Hartog Island were estimated using generalized linear models, with identity link and a generalized Poisson error distribution. Judas goats present during the study were excluded from the analysis and the results applied only to uncollared goats. The models were fitted using the procedure *glimmix* in the software package SAS (SAS Institute Inc. 2011).

Estimating catch effort

The catch per unit effort (CPUE) value (Seber 1982) was calculated over the 2010–2017 period to better understand the relationship between the time spent conducting aerial surveys (effort) and the numbers of ungulates (goat and sheep combined) removed ('catch'). This index is useful to compare trends over the 8-year period when aerial shooting was undertaken, and the subsequent effort required to remove ungulates as their densities declined. CPUE is assumed to be a linear index of ungulate abundance but may be biased at high animal densities (densities are such that shooters spend all the available time shooting animals) and at very low densities when animals become difficult to find (Forsyth et al. 2003).

Financial effort

We maintained records of all major costs (human resources, consumables, aircraft hire, travel) required to undertake the eradication campaign. We only used cost data where the source allowed discrimination of major cost centres. Human resources included salaries of key staff and associated costs (e.g. consultant breathalyser calibration test contracts as part of a fitness-to-work-program). Consumables included all equipment and related consumables required to undertake the campaign (e.g. firearms, field equipment, ammunition, vehicle use on island). Travel includes costs associated with the transport of equipment (road freight, barge transfers) and personnel (flights, overnight accommodation) to/from Dirk Hartog Island.

Cost per effort ($ per hectare surveyed, $ per animal killed) was calculated as a measure of the financial cost of the program particularly when animal densities were low. Costs are reported in Australian dollars unless specified for comparisons to international studies.

Results

From the early ground-based destocking of goats and sheep in 2005, to the removal of the last Judas goat in 2017, the Dirk Hartog Island goat and sheep eradication campaign lasted 13 years. Collectively, 11,133 goats and 5185 sheep were either removed from the island or shot in situ.

Land-based management phase

Ground shooting of goats commenced in 2005. A single mustering event in 2007 removed 750 goats and 4000 sheep to the mainland (Fig. 2). Ground shooting continued as the primary eradication method until 2010, when aerial shooting commenced. Ground shooting removed 1061 sheep and 3420 goats from Dirk Hartog Island over 5 years. Most sheep (n = 5061) and about one-quarter of goats on the island (n = 4200) were removed in 6 months between November 2007 to December 2009.

Aerial-based management phase

Aerial shooting removed the remaining 122 sheep from the island over four separate flights with the last two sheep removed in February 2013. No sheep were found on the island in 13 successive aerial and ground surveys to November 2017. Sheep were declared eradicated in June 2015, 2 years and 4 months after sheep had last been sighted across any of the hunting programs.

From 2005 to 2017, 11,133 goats were removed from Dirk Hartog Island (Fig. 2). Aerial shooting from 2010 was an effective means of reducing and ultimately eradicating goats, particularly when coupled with the use of Judas goats to assist with the location of remaining individuals. During the period February 2010 to November 2017, 20 aerial operations removed 6933 goats (including 13 Judas goats) from the island.

Previous records of the tracks and way-point positions of all Judas goats enabled shooters to return to the approximate locations where Judas animals were encountered ensuring this approach an effective means for searching, and shooting, un-collared goats. Judas goats remained within the vicinity of the area they were captured making it easy to find them—and associated uncollared goats—between flights. Judas goats continued to actively associate with uncollared conspecifics after each hunting event. During the period September 2013 to November 2015, 112 conspecifics were culled in association with Judas goats. Mean group size was 3.1 with a range of 1–10 uncollared goats associating with each Judas goat (Fig. 3). The last four uncollared goats were juveniles, detected with a Judas female by motion sensor cameras in November 2015. Further surveys and subsequent analysis (see below) suggested that these four uncollared goats were the last on Dirk Hartog Island. Investigations of fresh tracks in the sand during subsequent aerial programs found that these were consistently made by Judas goats.

Monitoring of the remaining Judas goats continued for a further 2 years (six programs) after which no uncollared goats were found. The last Judas goat was removed (shot) from the western cliffs of Dirk Hartog Island in November 2017, representing 2 years since uncollared goats had been sighted across any of the hunting programs.

Across 20 aerial field surveys, a total of 534 flight hours (equivalent to 22.2 flight days) were flown (Table 1). The average (± SD) flight time was 5.2 (0.5) hours per day. Most of the island was traversed by flight paths (Fig. 4). The effectiveness of aerial shoots was observed early in the program: 90.1% of the ungulate population (primarily goats) was shot after just 23.1% (123.5 h) of the total flight time. However, most effort (76.8%, or 410.4 h) was spent searching and culling 9.4% of goats that remained on the island.

Costs

The financial cost of the aerial shooting and surveillance program over 8 years equated to just over one million dollars, or approximately $150 per animal removed (Tables 1, 2). These values reflect a minimum spend across salaries, travel, vehicle, consumables, aircraft hire, and additional labour. Costs per ungulate were highest during the monitoring phase of the campaign ($14,395 per animal) when animal

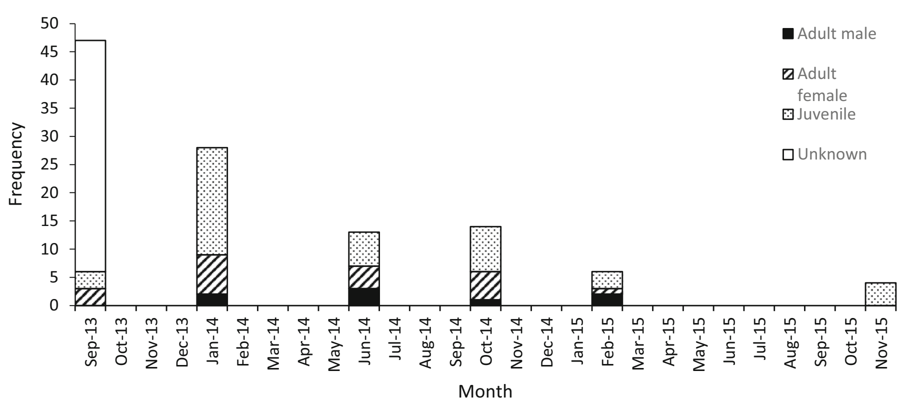

Fig. 3 Distribution and age cohort of uncollared goats that were found associated with Judas goats during the September 2013–November 2015 period on Dirk Hartog Island. Records of age cohort commenced in the latter part of the 2013 sortie

Table 1 Parameters used to quantify the catch per unit effort (CPUE) and costs of shooting goats and sheep on Dirk Hartog Island (Australia) during aerial operations (February 2010-November 2017)

Parameter	2010	2011	2012	2013	2014	2015	2016	2017	All years
No ungulates shot	5609	785	343	159	138	10	8[c]	5[c]	7057
Effort (total flight h)	67.90	55.55	52.50	64.50	70.97	79.07	72.60	70.73	534
Total cost[a] ($)	96,377	119,798	111,202	154,328	169,200	143,741	131,418	129,120	1,055,184
CPUE (kills/h)	82.61	14.13	6.53	2.47	1.94	0.13	1.14	0.75	13.22
Cost[a] ($)/goat	17.18	152.61	324.20	970.61	1,226.09	14,374.14	1583.35	2436.22	149.52
Total Cost[a]/ha[b]									16.67

Costs in $AUS

[a]Costs reflect minimum costs of campaign

[b]Area of 63,300 ha used to represent land area of Dirk Hartog Island

[c]Judas goats only

densities were low and only Judas goats remained on the island. During 2015, with 10 uncollared goats remaining on the island, costs reached nearly $15,000 per animal shot, and almost $2500 per goat in 2017 to remove the last Judas goats (Table 1). Costs of the aerial component of the eradication campaign were $16–17 per hectare (Table 2). An additional $187,139 (or 18% of the total aerial budget, Table 2) was spent on the subsequent monitoring phase of the campaign (six field trips) to confirm eradication following the removal of the final four juvenile goats in November 2015.

Catch per unit effort (2010–2017)

The CPUE for ungulates shot from the air was highest when abundance was high in 2010 and declined with time as animal numbers declined (Table 1, Fig. 5). The time to shoot one goat increased considerably: from seconds during the early aerial shoot phase (February 2010 to June 2014) when numbers were high, to one goat every one-quarter hour in October 2014. As goat densities declined further, the effort increased to one goat every 5 h in June 2015, and one goat every 4.3 h by the completion of the aerial campaign in November 2017. Number of goats shot per day were highest when the total flight time per trip was 33–34 h (Fig. 6).

Detection models-goats

Flight time alone may not be a reliable measure of survey effort. The amount of time required to shoot the goats (and remaining sheep) varied between trips (field surveys), and this influenced the remaining time actually spent searching for other goats.

The model-estimated initial size of the goat population on Dirk Hartog Island was 6918 individuals, close to the known number of goats shot of 6920 (Table 3). A single survey was estimated to remove (on average) 44.1% (standard error 3.8%) of the remaining goats. Notable in the data is a higher number of goats shot during the second flight trip (3029) compared to the first flight trip (2461), which is at odds with the model assumed for these data. Although exclusion of the initial survey from the analysis improved model fit and resulted in a substantially higher detection rate (50.9%), we took a conservative approach and retained all of the survey data in the final detection model.

Given that there were six successive surveys since the last uncollared goat was detected on Dirk Hartog Island in November 2015, the probability that no goats remain on the island can be estimated by assuming that one or more goats remain, but have avoided detection on six successive occasions. The probability of failing to detect any goats, if present, during a single survey is $1–0.441 = 0.559$ and the probability of this occurring on six successive occasions is $0.559^6 = 0.969$ with 95% confidence intervals (0.964–0.975, Fig. 7). The estimated likelihood that goats have been successfully

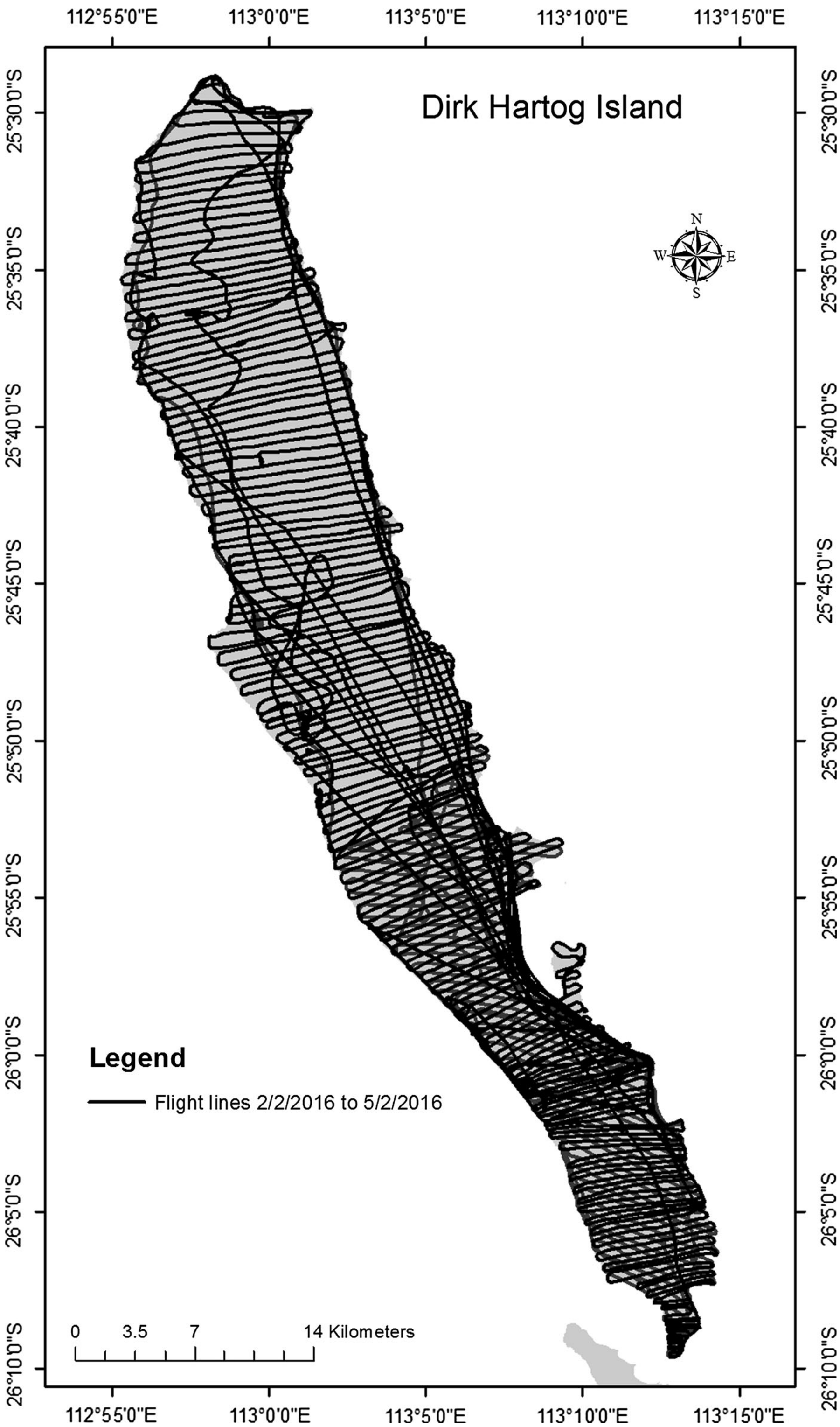

Fig. 4 Total flight paths over Dirk Hartog Island across a 5-day aerial helicopter program in February 2016

Table 2 Financial investment ($AUS) during the aerial search and shoot phase, and the aerial monitoring and ground shoot phase, of the goat and sheep aerial eradication campaign on Dirk Hartog Island (2010–2017)

Expenditure category	Search/shoot phase (2009/2010–2015/2016)	Monitoring phase (2016/2017–2017/2018)	Total
Human resources	165,115.35	33,335	198,450
Travel	73,448	21,964	95,412
Equipment	186,638	27,365	214,003
Aircraft hire	442,844	104,474	547,318
Total (% of total)	$868,045 (82.3%)	$187,139 (17.7%)	1,055,184
Cost/ungulate	$123	$14,395	$150

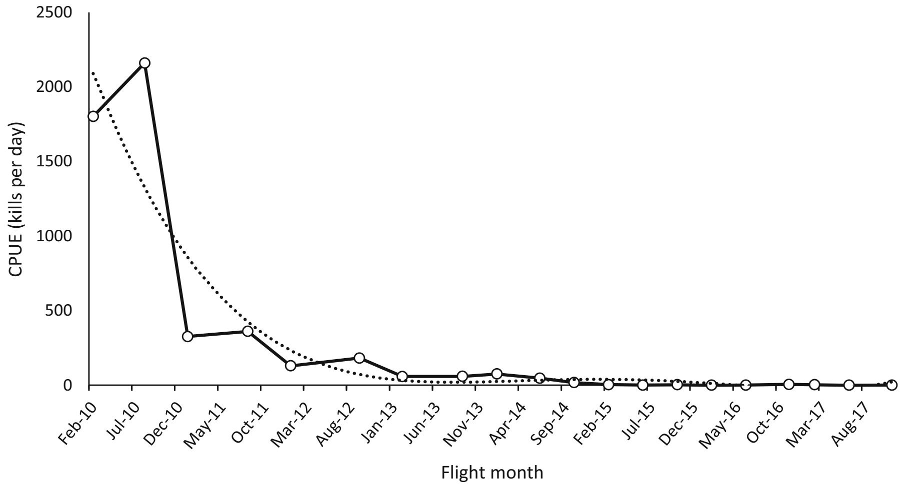

Fig. 5 Trend in catch per unit effort during the Dirk Hartog Island ungulate aerial campaign (February 2010 to November 2017). Trend line reflects a polynomial distribution of the data records

Fig. 6 Relationship between the number of goats shot per day (per trip) and total flight time (hours per trip) during the Dirk Hartog Island ungulate aerial campaign (February 2010 to November 2017)

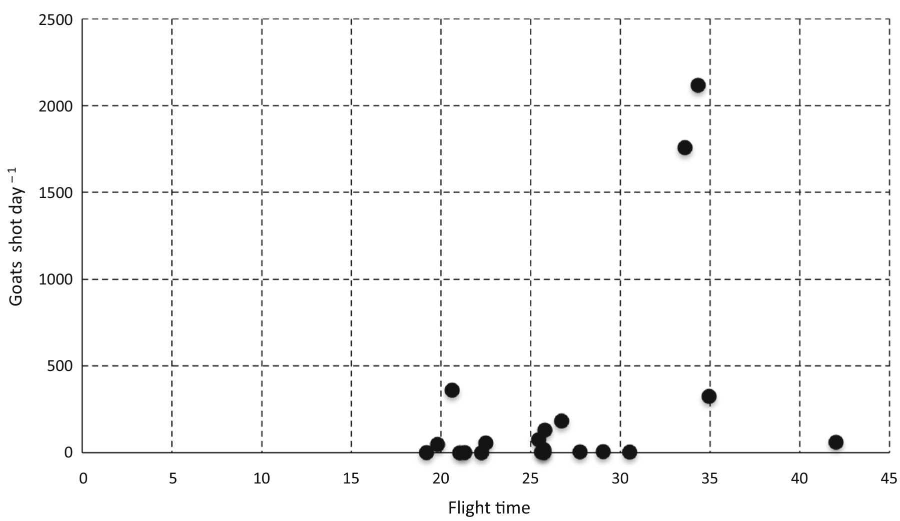

Table 3 Parameter estimates of the generalized linear model of goat population size and detectability on Dirk Hartog Island, and the estimated initial (pre-February 2010) abundance (N_0) based on data from 20 aerial surveys up to November 2017

Parameter	Estimate	SE
Intercept ($p \times N_0$)	3050.64	260.92
Detectability (p)	0.4410	0.03774
Estimated initial abundance (N_0) = intercept/detectability	6917.6	837.0

Standard errors for the model have been adjusted for overdispersion (scaled Pearson χ^2 = 50.4). The estimated standard errors of the initial population estimates use the formula for the variance of a ratio

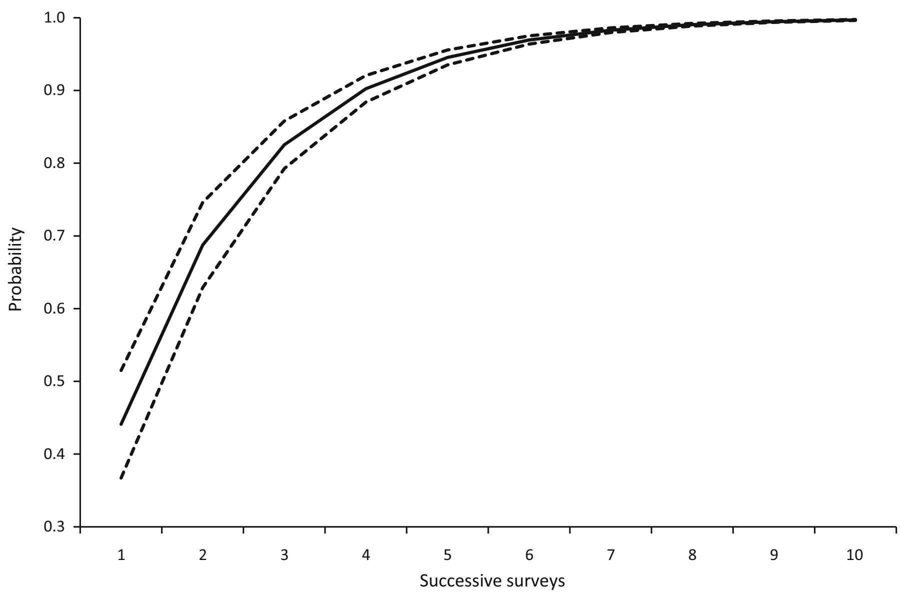

Fig. 7 Probability (with 95% confidence limits) that no goats are present on Dirk Hartog Island (i.e. eradication has been achieved) given that between 1 and 10 successive surveys fail to detect any goats. For six successive surveys, the probability of eradication is 0.969, with 95% confidence interval 0.964–0.975

eradicated from the island is therefore 96.9%. The complementary likelihood that one or more goats persist on the island but remain undetected is 3.1%.

Detection models-sheep

Using the results from seven aerial surveys, the size of the sheep population on Dirk Hartog Island in early 2010 was estimated to be 123 individuals (Table 4). Including all seven surveys when sheep were known to be present, a single survey was estimated to remove (on average) 64.2% of the remaining sheep. As for goats, excluding the first survey in 2010 resulted in a substantially higher detectability (94%) but all survey data were retained in the analysis.

Table 4 Parameter estimates of the generalized linear model of sheep population size on Dirk Hartog Island and their estimated initial (pre-February 2010) abundance (N_0) based on the seven aerial surveys up until no further sheep were located

Parameter	Estimate	SE
Intercept ($p \times N_0$)	78.9	7.21
Detectability (p)	0.642	0.059
Estimated initial abundance (N_0) = intercept/detectability	122.9	16.0

Standard errors for the model have been adjusted for overdispersion (scaled Pearson χ^2 = 3.72). The estimated standard errors of the initial population estimates use the formula for the variance of a ratio

Given there have been nine successive surveys since the last sheep was detected on the island in February 2013, the probability that no sheep remain on the island is $(1–0.642)^9 = 0.9999$ with 95% confidence intervals [0.9998–0.9999]. The estimated likelihood that sheep have been successfully eradicated from the island is therefore 99.99%. The complementary likelihood that one or more sheep persist on the island but remain undetected is 0.01%.

Discussion

It has taken 13 years (2005–2017) to remove a combined total of 16,318 ungulates from Dirk Hartog Island and to confirm their eradication, making this campaign the largest whole-of-island removal of goats and sheep conducted to date. This project had an approximate total cost of about $1,055,000 ($US 759,000).

Aerial hunting using a helicopter and a trained marksman proved to be a reliable means for the eradication of ungulates (particularly goats) from Dirk Hartog Island. The effectiveness of this technique has been backed up by the results: it took approximately 138 h of flying time to dispatch a large part (some 86%) of the remaining goat and sheep population. Most animals were dispatched in a few days of work. The use of helicopters allowed hunters to survey difficult-to-access areas, such as the west coast cliffs, and to locate individual or small herds of animals that otherwise would have been challenging to find by foot. The ability to observe goat prints clearly from a helicopter contrasted against the white sand of the island, particularly after rain, also provided an effective method of tracking sheep and goats. While the major cost component of the program, the effectiveness of aerial hunting to locate and shoot goats has been found to be a significant catalyst to the successful recent eradications of goats from other large islands (Campbell and Donlan 2005; Ortiz-Alcaraz et al. 2016).

The use of Judas goats was crucial for attracting any remaining animals. Selecting locally-sourced female goats, and not sterilising them attracted isolated individual goats as reported in other studies (Taylor and Katahira 1988). Collared animals remained resident within the area they were initially captured, suggesting they maintained a consistent home range which made it easier to locate them. This philopatry is in contrast to goat behaviour reported elsewhere. For example, Judas goats increased their home range on Aldabra Atoll to seek conspecifics, in response to reduced goat densities (Bunbury et al. 2018). Feral goats in Western Australia have previously been reported to remain at waterholes especially when conditions were driest (King 1992). Similarly, we suspect the arid nature of Dirk Hartog Island precluded Judas goats from roaming far from known water sources or shelter. Maintaining freshwater sources in arid environments to attract or retain animals in an area seems prudent in similar environments elsewhere.

CPUE was likely a biased estimate during 2010 when hunter training was conducted during the first flying sortie; goat densities were highest in February 2010 compared to subsequent trips, however, shooter returns were lower during the first sortie compared to the second sortie in August 2010. The outcome of the second sortie indicates either an increase in detectability of goats by hunters or a natural population increase due to births. We consider it likely that locating goats increased after the initial sortie because of an increased effectiveness in locating and shooting goats following pilot and shooter experiences from the first sortie. Shooters may have improved their knowledge and skills of where to observe goats and changed their shooting strategies accordingly. If true, establishing animal-specific shooter training programs in advance of scheduled (and expensive) field aerial campaigns is a worthwhile consideration.

One important strategy maintained during this campaign was the consistently high ‘hunting effort’ at considerable cost (as high as $14,395 per animal during 2015) committed during the monitoring phase of the work and despite the fewer numbers of goats observed. Flight times of between 70 and 79 h over the 2015–2017 period were maintained even when numbers of goats were low. While these costs seem high on face value, they are justified within the context of eradication uncertainty (Morrison et al. 2007): premature management decisions to cease further monitoring effort are known to have resulted in the subsequent detection of goats (Campbell and Donlan 2005; Campbell et al. 2004). High hunting pressure on Dirk Hartog Island minimised the risk of locating lone and/or cryptic individuals, and therefore a likely future increase in numbers associated with recruitment. In Egmont National Park (New Zealand) hunter effort decreased after a commensurate decline in goat numbers, however, goats subsequently increased in abundance leading to a need for increased hunter effort (Forsyth et al. 2003).

Although it is not possible to calculate the costs of 13 years of ungulate eradication efforts on Dirk Hartog Island before 2010, the subsequent financial investment over the 8-year aerial hunting campaign was approximately $1.05 million ($US 759,151, US$ 110/goat or US$ 12/ha). Compared to similar investments reported for large island goat eradications elsewhere, the investment for Dirk Hartog Island was substantially less: $US 6.1 million ($US 77/goat or $US 105/ha) for Santiago Island, Galapagos (Cruz et al. 2009), $US 4.1 million ($US 65/goat or $US 9/ha) for Isabela Island, Galapagos (Carrion et al. 2011), and $US 185,105 ($US 815/goat or $US 31/ha) for Aldabra Atoll, Seychelles (Bunbury et al. 2018). We posit that the arid nature of Dirk Hartog Island, with predominantly low and sparse vegetation and limited free water, caused goats to congregate near known water sources. This congregation of animals, together with high hunting pressure (three trips per annum) to minimise goat recruitment rates between surveys, were contributing factors to aid the eradication program compared to more challenging topographies experienced on other islands.

Management lessons

Dirk Hartog Island is now believed to be free of both goats and sheep. This effort demonstrates that whole-of-island eradication across large island scales can be an achievable outcome. Our data provide useful information to island managers for assessing cost efficiencies for conservation (Bode et al. 2013), for strategically evaluating biodiversity offsets (Donlan et al. 2014; Pascoe et al. 2011), or to assess resource allocation between surveillance, quarantine and eradication (Moore et al. 2010).

The success of the campaign on Dirk Hartog Island was built upon several key factors, both strategic and logistical in nature. Strategically, the financial security of the campaign was secured through an Australian Commonwealth initiative and resource-sector net conservation benefit fund over a 10-year period. This long-term investment allowed planning for a reliable source of funds to implement the campaign until eradication could be confirmed with some confidence. Using a sequence of removal events that taught survivors the least (mustering, ground shooting, intensive aerial shooting, and finally aerial searching combined with ground shooting) was important to reduce 'wary behaviours' of individuals who may avoid being sighted. Logistically, the use of helicopters to locate ungulates optimised shooting rates, and in so doing ensured a cost-efficiency which would otherwise have been higher with ground-hunting alone. The use of resident un-sterilised female Judas goats to attract the remaining goats proved crucial to improve the chance of locating uncollared animals and, in particular, the presence of male goats (when Judas females had young). Finally, monitoring Judas goats over a further 2 years following the removal of the last (juvenile) uncollared goat involved a combination of integrated approaches (skilled hunters, limited free-water sources, camera traps at water stations, additional camera stations across the island) including the involvement of population modellers to develop probability (detection) models to estimate the likelihood of persistence and confidence that eradication was likely. An operational plan to remove all sheep and goats on Dirk Hartog Island by November 2015 and June 2018, respectively, maintained this ambitious schedule with eradication achieved by June 2015 and November 2017, reducing the initial eradication estimates by 4 and 7 months, respectively (DEC 2013).

While our models suggest the likelihood of goats remaining on the island is as low as 3%, we cannot discount refuges exist on Dirk Hartog Island where one or more goats—with learned behaviours to render them difficult to locate as a result of selection and/or learning from unsuccessful shoots—may persist. A further four surveys would have provided close to 100% confidence for eradicating goats, however this would have come at a significant cost. Camera traps that were established to detect feral cats continued to be monitored on the island after goat and sheep were declared eradicated so this approach continued to increase certainty of whole-island ungulate eradication. The higher costs associated with the final campaigns to ensure the few remaining Judas goats did not attract additional uncollared (and yet unseen) animals remains justified. The alternative scenario (declaring eradication too early to reduce expenditure) would have reduced community confidence in the agency undertaking the campaign and bring into question further expenses (and possible animal welfare issues) to redeploy people and equipment to continue to remove goats from the island.

While 13 years may appear a long time to achieve successful eradication for Dirk Hartog Island, this time is notably less than previous eradication campaigns: 25 years for Aldabra Atoll, Seychelles (Bunbury et al. 2018), 30 years for Pinta Island, Galapagos (Campbell et al. 2004), and 28 years for Raoul Island, New Zealand (Parkes 1990).

The remoteness of Dirk Hartog Island—and the combination of logistical challenges that were overcome to proceed with a campaign of this size—requires some context. All land equipment and supplies needed to be transported over considerable distances and via barge from the mainland, with the nearest city of Perth some 900 km south of the island. Helicopter time, and shooters, required specific flight conditions to operate for safety reasons: temperatures not exceeding 40 C, winds not exceeding 25 knots (at the pilot's discretion), and flight times not exceeding 6 h daily (three 2-h sorties maximum). While using a helicopter directly following heavy rainfall events was an effective strategy to track animals, as the sand was then cleared of old tracks, there were difficulties in contracting helicopters and shooters at short notice. Fresh water on the island was restricted to known wells, however this restriction became useful for attracting (and locating) animals during the hot dry periods of the year.

The benefits of the removal of ungulates from Dirk Hartog Island are already noticeable. Vegetation monitoring using remote sensing and photo point observations between 1988 and 2017 has shown a significant increase in vegetation cover, and a reduction in the size and rate of erosion of sand dunes following sheep and goat removal (van Dongen and Huntley 2017). Of 33 vegetation sites monitored since 2008 (following removal of most sheep) 17 (52%) showed increases in vegetation cover. In addition, the area of exposed sand dune on the southern third of the island dropped from 2402 ha in 2009 to 1777 ha in 2017, a reduction of 625 ha. These results are consistent with those from other islands where ungulates have been removed and the vegetation has responded rapidly (Campbell and Donlan 2005; Gizicki et al. 2018). Removing goats, in particular, has demonstrated a rapid recovery to the vegetation of islands (Hamann 1979; Campbell and Donlan 2005) although additional island restoration needs to be maintained for long-term recovery (Gizicki et al. 2018).

There are other strategic benefits to the eradication outcome: the Dirk Hartog Island National Park Ecological Restoration Project (DEC 2011) aims to reintroduce 10 threatened native mammal and one bird species that were known to have once existed on the island, and introduce a further two species—considered likely to have been present in the past—to improve their conservation status. To date (September 2018) no further ungulates have been found on Dirk Hartog Island despite continued work on the island.

Acknowledgements On behalf of the Department of Biodiversity, Conservation and Attractions, the authors thank Geoff Wardle, former lessee of Dirk Hartog Island, for commencing sheep and goat removal in expectation of Dirk Hartog Island becoming a national park and in allowing the Department early access to his grazing lease to commence ground shooting. We also thank Jock Clough and the Wardle family for allowing their private land on Dirk Hartog Island to be included in the whole-of-island eradication program, and Tory and Kieran Wardle for their hospitality during the aerial shooting operations. We thank Butch Maher for his piloting expertise, and skills in aerial shooting and animal tracking from a helicopter. Aerial shooting was initially made possible through funding from the Australian Government's Caring for Our Country Program. Ongoing funding was available from the Gorgon Barrow Island Net Conservation Benefits Fund which enabled these eradications to be achieved. The Net Conservation Benefits Advisory Board, Shark Bay District staff and the Dirk Hartog Island Management Committee are thanked for their continued support of this Project. Two anonymous referees provided helpful comments to improve this manuscript, and we thank John Parkes for access to his unpublished database on global island goats and sheep eradications. Finally, we thank Ricky van Dongen for production of the flight path map and access to remote sensing unpublished data related to vegetation recovery.

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