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A reassessment of population size and trends of Hutton's shearwater following the 2016 Kaikōura earthquake and outlook for the species' management

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R.J. Cuthbert

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The large-scale earthquake centred near Kaikōura on 13 November 2016 caused widespread damage and raised major concerns about the long-term impact of this event on the population of Hutton's shearwater *Puffinus huttoni*: a globally Endangered burrowing petrel whose key remaining breeding sites are in the Seaward Kaikōura Mountains, along with a small newly established colony on the Kaikōura Peninsula. Previous studies indicate that Hutton's shearwater used to be more widespread, but the action of feral pigs *Sus scrofa* has restricted the species to two mountain colonies – Kowhai Valley and Shearwater Stream. Within these sites the species is preyed upon by stoats *Mustela erminea*, however the impact of this on the population is low and the shearwater population is ultimately limited by its restriction to two colonies and availability of habitat within these sites. Fieldwork was undertaken in the larger Kowhai Valley colony in December 2016, along with visits by helicopter and on foot to Shearwater Stream and other areas, in order to evaluate the impact of the 2016 earthquake on the population, to assess ongoing threats and limits to the population, and to evaluate options for establishing further breeding sites to secure the future of the species.

High quality aerial imagery and spatial software were used to map the pre and post-earthquake areas of breeding habitat, and were then combined with previous and new data on burrow densities and measures of burrow occupancy by breeding pairs. These figures indicate that there were around 312 600 pairs (95% C.I. 287 200–339 400) of Hutton's shearwater in 2007, prior to the earthquake. This figure is nearly three times larger than earlier estimates, most likely a consequence of map scaling errors in previous population calculations. This revised population size is supported by mark re-sighting estimates of Hutton's shearwater at sea, and this independent assessment of numbers will be repeated in September 2018 as part of this wider study. Following the 2016 earthquake the shearwaters' population is estimated to be around 191 550 breeding pairs (179 500–203 550), an overall reduction of 40%. This decrease is a consequence of the destruction of colony areas from rock falls and landslips (about 12% of the area) and a reduction in burrow densities in remaining areas of habitat (about 30% of burrows). The earthquake took place when shearwaters were sitting on eggs, and consequently is likely to have caused the immediate mortality of about 40 000 birds in landslip areas with potentially up to a further 80 000 birds trapped and killed in burrows in remaining areas.

Despite the impact of the earthquake other aspects of the breeding colonies appear unchanged: there were large numbers of shearwaters incubating eggs in the colony, with many birds courting and digging burrows at night, and breeding success was 71% in the 2017/18 season and in the upper range of previously recorded values. Crucially the boundaries of the two breeding colonies remained undamaged by the earthquake and the sites remain inaccessible to pigs. Over the coming decades the population of Hutton's shearwaters is predicted to slowly increase again within the remaining breeding areas; however the species will remain restricted to two vulnerable mountain sites and one small lowland locality, with 94% of the species' population occurring in less than 50 ha of suitable habitat within the Kowhai Valley. In the long-term this situation places the species at high risk from future earthquake or other major events, and establishing further large breeding colonies must be given serious consideration to secure the future of the species. Potential options for new areas include expansion of the existing Peninsula colony, along with new sites near to Mount Fyffe and Mount Alexander. Recommended actions to ensure the species' recovery include repeating estimates of shearwater numbers and demographic parameters to monitor population trends, ongoing control of pigs and browsing mammals in the colony areas, and undertaking a comprehensive assessment of the potential for establishing new and large-scale breeding colonies in the Kaikōura region.

1. INTRODUCTION

Hutton's shearwater *Puffinus huttoni* is a medium-sized (approximately 360 g) seabird within the family Procellariidae that is endemic to New Zealand and whose population, with the exception of a newly established and small breeding colony on the Kaikōura Peninsula, is restricted to two alpine sites within the Seaward Kaikōura Mountains. These two sites – Kowhai Valley and Shearwater Stream – are the remnant areas of the species' former breeding range, which up until the late nineteenth century used to extend to at least ten sites along both the Seaward and Inland Kaikōura Ranges (Harrow 1965, 1976; Sherley 1992). Sub-fossil records of shearwaters suggest an even broader distribution into the hill country of north Canterbury (Worthy & Holdaway 1995). The species is classified as globally "Endangered" by the International Union for the Conservation of Nature (BirdLife International 2016) and as "Nationally Vulnerable" within New Zealand (Robertson et al. 2016) due to its small restricted range and dependence upon ongoing conservation management. Previous calculations have estimated the population size to be around 106 000 breeding pairs (Sherley 1992; Cuthbert & Davis 2002a) with more than 90% of the population within the Kowhai Valley colony. Based on this figure of 106 000 pairs and information from other Procellariidae, the likely total population including immature and non-breeding birds was estimated to be around 300 000–350 000 individuals (Brooke 2004).

The species' contraction to just two sites within the Seaward Kaikōura Mountains is primarily a consequence of predation and habitat destruction by feral pigs *Sus scrofa* at other sites within the Inland and Seaward Kaikōura Ranges (Cuthbert 2002). Within the two remaining mountain colonies the shearwater population is subject to ongoing losses from introduced stoats *Mustela erminea* that are present within the colonies throughout the year. However, extensive research in the Kowhai Valley during the late 1990s established that shearwater losses are inversely density-dependent, with the 20–30 resident stoats in the valley (Cuthbert & Sommer 2002) only able to take a very small proportion of the approximately 100 000 pairs of Hutton's shearwater present at this site and with stoats on average killing 0.25% of breeding adults and 12% of chicks in each season (Cuthbert & Davis 2002b). The limited impact of these losses on the population of Hutton's shearwater is further confirmed by measured rates of annual adult survival and breeding success which averaged 93.1% and 46.5% respectively, a range of values (based on ten years of data) that are very similar to other *Puffinus* shearwater species breeding in environments free from introduced predators (Cuthbert & Davis 2002a). Population modelling with these parameters and other demographic data suggests that the impact of stoat depredation is a reduction in the potential yearly growth rate of around 0.86%, however the overall average growth rate of the model at 0.44% a year was still positive (Cuthbert & Davis 2002b). Population monitoring of the species, based on repeated measures of burrow densities within the two mountain colonies, confirm the results of these modelling and demographic studies, with evidence for a slowly increasing population from 1987 to 2007 (Cuthbert & Sommer 2009; Sommer et al. 2009).

The action of pigs and other predators has prevented the re-establishment of breeding areas within the species' former range and Hutton's shearwaters remain restricted to two alpine breeding sites. Within these two sites breeding burrows occur at over twice the density recorded for other similar sized *Puffinus* species (Cuthbert & Davis 2002c); birds occur in nearly all areas where the soil depth and rock content and slope angle allow burrowing (Cuthbert & Davis 2002c); and there is evidence for a high degree of competition for burrows at the start of each breeding season (Cuthbert 1999). This evidence suggests that the population of Hutton's shearwater is limited by the availability of breeding habitat (Cuthbert 2001; Cuthbert & Sommer 2009) rather than other factors, such as at-sea food availability, climatic conditions, disease or predation. The conclusions that introduced stoats are not driving population declines, that predation and habitat destruction by feral pigs were responsible for the contraction in breeding range, and that the current population of shearwaters is limited by habitat availability, have had important consequences for the conservation management of this species. This includes ongoing culling and management of pig numbers around the boundaries of the two remaining mountain breeding sites and the establishment over the last decade of a small breeding colony of Hutton's shearwaters on the Kaikōura Peninsula. The latter held about 25 breeding pairs in the 2017–18 breeding season and is slowly increasing in size. These actions follow recognition that any loss or degradation of the species' mountain breeding sites is likely to be the single most critical threat to the ongoing survival of the species and that the species will always remain threatened if restricted to two potentially vulnerable breeding sites (Cuthbert 2002).

These concerns, over the vulnerability of the species within only two mountain areas, were sharply realised following the Kaikōura earthquake of November 2016 and helicopter flights to both colonies in the days immediately after the earthquake revealed major rock falls and habitat destruction in the Kowhai Valley colony, as well as damage to Shearwater Stream. The extent that the earthquake has impacted the population and the implications of this are unknown, but in the worst case scenario the two remaining colonies may now be accessible to feral pigs: such a result would result in significant loss and destruction of birds and breeding habitat and a very adverse outlook for the survival of the species. The earthquake and presence of just two sites for the species has also further raised concern about the long-term viability of the species at just two alpine sites and highlighted the need for the establishment of further secure sites within the species' former range.

This document reports on research undertaken in late 2017 to quantify the immediate impact of the earthquake on the population and evaluate the long term implications for the conservation management of the species. This includes re-assessing the pre and post-earthquake population size of the species to quantify the extent of losses from the earthquake. Site visits to the two remaining mountain colonies were undertaken to evaluate the area for potential new areas of breeding habitat and to determine if birds were already attempting to dig burrows and re-colonise sites that were damaged during the earthquake. Visits to these two colonies were also used to determine whether the colonies are now accessible, or more accessible, to feral pigs, and evaluate whether fencing or renewed control measures are required to protect the sites. As well as visiting these two colonies fieldwork also involved visiting other former breeding sites within the Kaikōura Ranges and other sites within this region in order to assess their suitability as new sites in order to secure the long-term viability of the species.

The above assessments were made in order to meet the overall objective of the commissioned project which was "to survey Hutton's shearwater populations in colonies around Kaikōura". Specific objectives of the project include 1) to survey Hutton's shearwater populations in colonies around Kaikōura and 2) to assess ongoing threats and limits to recovery from recent earthquake impacts on the colonies of Hutton's shearwater around Kaikōura.

2. METHODS

2.1 Location and timing of fieldwork

Both Kowhai Valley and Shearwater Stream occur in remote areas of the Seaward Kaikōura Mountains (Figure 1) and were accessed via helicopter during the 2017 fieldwork. A team of four spent five days (from 1 to 5 December 2017) at the Kowhai Valley, with two of the team (including the author) remaining for a further two days to continue fieldwork. Due to safety concerns from loose rocks and unstable terrain, visits into Shearwater Stream were unable to be made on foot, and instead the assessment of this site consisted of observations from the air along with photography. Three observers, including the landowner (Nicky McArthur), Mike Morrissey from the Kaikōura Department of Conservation (DOC) (who is very experienced at working at this site) and the author, spent 30 minutes in the air over the site in good weather conditions on 30 November in order to assess damage to the site. Following visits to both these sites the author spent a further seven days in the area visiting former and potential shearwater colony areas on foot as well as taking a further helicopter flight on 15 December to search for the presence of burrowed ground and potential sites in the Seaward Kaikōura Range.

2.2 Breeding ecology and general monitoring methods

Like other burrowing petrels, Hutton's shearwaters spend the majority of their time at sea and only return to the breeding colonies at night where pairs of birds nest in burrows within the breeding colonies. Following a winter migration to Australian waters Hutton's shearwaters return to New Zealand in late August and start to make nightly nocturnal visits to the often snow-covered mountain breeding colonies during September. Once the winter snow has cleared birds continue to visit the breeding colonies in order to clean out and extend existing breeding burrows and to start to dig new burrows. Breeding burrows are around 1.2 m in length but can extend from 0.4 to 3.0 m (Cuthbert & Davis 2002c) and typically the same breeding pair reoccupies the same burrow from one year to the next. Pairs produce a single egg in early November and following egg laying the male and female birds alternate incubation shifts of around one week while the other member of the pair is feeding at sea and replenishing its energy reserves before commencing another incubation shift. Hatching occurs after 50 days and the breeding pair then take short turns to brood and feed the chick during its first week, after which time the chick remains alone in the burrow with both parents foraging at sea and returning every 5–7 days to feed (Cuthbert 1999). Chicks reach fledging age after around 3 months and depart from the breeding colonies by the end of March (Cuthbert & Davis 2002c). Following chick fledging breeding adults undertake their winter migration before returning to the breeding grounds in the following season. Newly fledged birds spend their first 3–4 years at sea before returning to the breeding grounds and spending 1–2 years to find a mate, dig or occupy a burrow and commence breeding.

Assessing the population size and trends for Hutton's shearwaters and other burrowing petrels is complicated by their behaviour and breeding ecology as described above, as direct observations and counts of birds are not possible due to their nocturnal behaviour and burrow nesting habits. As a consequence population estimates of burrowing petrels typically depend on an assessment of the total area of burrowed ground, measurements of the density of burrows within this area, and determining the proportion of burrows that are occupied by an incubating pair (as opposed to empty burrows or burrows containing non-breeding birds) at the start of the breeding season. These methods have been utilized in previous population estimates of Hutton's shearwater, with mapping of colony areas and quadrats for burrow densities undertaken during the late 1980s to providing an initial population estimate of 134 400 pairs (Sherley 1992). This figure was later refined using the same area and density estimates along with a measured estimate of average burrow occupancy of 70.5% recorded over ten breeding seasons during the period 1989–1990 to 1998–1999 (Cuthbert & Davis 2002a). Because burrow occupancy is highly variable from one year to the next, with the proportion of incubating birds likely to vary with at-sea feeding conditions, recommended monitoring of population trends of Hutton's shearwaters has been based on monitoring changes in burrow densities within the colony (Cuthbert 2001). Such an approach depends on the fact that burrows within the soft and friable soils of the Kowhai Valley and Shearwater Stream are rapidly filled in if breeding birds are not present, and within the Kowhai Valley an average of 5.7% of burrows are lost from one season to the next (Cuthbert & Sommer 2009). As a consequence, estimates of burrow density should be a sensitive measure of change in the total population of breeding birds, and this approach has been used to monitor trends over a two decade period from the late 1980s to 2007, during which time there has been no major change in colony area (Cuthbert & Sommer 2009; Sommer et al. 2009).

Figure 1: Map of the Kaikōura region showing the Seaward Kaikōura Range (running northeast) and the Kaikōura Peninsula and indicating the location of extant colonies (red colour) and approximate location of known extinct sites (blue). Colony numbers refer to 1 = Kowhai Valley; 2 = Shearwater Stream; 3 = Peninsula Colony; 4 = Big and Little Haa, Mt Fyffe; 5 = Te Rakaomaru Spur, Mt Fyffe; 6 = Cribb Creek; 7 = Orange Grove Creek; 8 = Snowflake Stream; 9 = Stace Creek; 10 = Jordan Stream. The extinct site of Branch Stream (42°13'S, 173°42'W) in the Inland Kaikōura Range is not indicated on the map.

Previous estimates of the total area of Hutton's shearwater breeding habitat relied upon plotting the boundaries on foot on aerial photographs of approximately 1:5000 scale (Shearwater Stream) and 1:6441 scale (Kowhai Valley) and then tracing and calculating these areas with a digital planimeter (Sherley 1992). Since this time higher resolution aerial imagery and sophisticated spatial software has become readily available, including imagery from before and after the 2016 earthquake. Consequently, this report provides a new assessment of the total breeding area of Hutton's shearwater prior to and after the 2016 earthquake calculated with ArcGIS software. The resulting areas are then used with pre and post-earthquake measurements of burrow densities in the colonies in order to provide new population estimates, an assessment of population trends over time, and to quantify the impact of the 2016 earthquake on the breeding population.

2.3 Pre and post-earthquake measurements of breeding areas

Breeding areas within the Kowhai Valley and Shearwater Stream colonies were measured using high quality aerial imagery (rural resolution imagery with 0.3 m Ground Sampling Distance (GSD)) covering the wider Kaikoura area and captured during December 2016 and February 2017 in order to provide accurate post-earthquake images of both colonies (these images were taken by Aerial Surveys Limited, Albany, New Zealand). Pre-earthquake imagery of these sites was obtained through ArcGIS online resources (ArcGIS 2018) utilizing 0.3 m GSD Rural Aerial Photos held by Land Information New Zealand (LINZ 2016). Ortho-photography for the Canterbury region, including the Hurunui and Kaikōura council areas, was obtained by Aerial Surveys Limited in the 2014–2015 summer flying season, about two years before the 2016 earthquake. Area estimates for before these periods of time were derived from the author's own observations in the breeding colonies (in the late 1990s) and subsequent visits and from aerial photographs from 1966, shortly after the discovery of the species' breeding grounds (Harrow 1965), held by the Kaikōura DOC office.

The Kowhai Valley colony and Shearwater Stream colony both consist of numerous sub-colonies, with shearwater burrows occurring within discrete patches of vegetated ground among areas of bare rock and scree. Burrowed areas are present within almost all vegetated areas of the Kowhai Valley and Shearwater Stream where the slope angle, soil depth and rock content of the soil allows burrowing to occur (Cuthbert & Davis 2002c). Burrows are mainly found in slopes dominated by *Chionochloa* snow tussock, as well as among areas of *Hoheria lyallii* and other montane scrub vegetation. Areas of burrowed ground within snow tussock slopes can be swiftly recognized, both in the field and from aerial imagery, by its darker green and lusher vegetation, and these characteristics were utilized to map the extent of each sub-colony from the imagery. The boundaries of sub-colonies within areas of *Hoheria* and scrub are harder to demarcate, however knowledge of both sites and fieldwork during 2017 were used to confirm the extent of these areas including, where necessary, taking handheld GPS coordinates of the boundaries of sub-colonies. Pre and post-earthquake imagery were mapped in ArcGIS 10.2 using a New Zealand Transverse Mercator 2000 (NZTM2000) projection (LINZ 2017) and mapping polygons around each sub-colony. These polygons were mapped in December 2017; immediately after field visits to both sites. The planimetric area of these polygons was calculated within ArcGIS 10.2 utilizing a projected NZTM2000 coordinate system, with subcolony areas measured to the nearest square metre.

Both the Kowhai Valley and Shearwater Stream colonies are in mountainous country, with burrowed ground typically occurring in areas with a slope angle of 33.5–37.3° (95% confidence interval (C.I.) from 50 randomly located points within the Kowhai Valley; Cuthbert & Davis 2002c). As a consequence the horizontal planimetric area will underestimate the actual surface area where shearwater burrows can occur. In order to calculate the true surface area the slope angle of each sub-colony was estimated by taking the average of three measurements of the horizontal distance between contour lines for each area (distances and contour lines measured in ArcGIS). Horizontal distances in ArcGIS were measured perpendicular to the contour lines (i.e. the shortest possible measurement) and across the maximum vertical distance for each site depending on the sub-colony size and shape (the median vertical distance was 40m, range 20 – 140m, n = 62 sub-colonies). Comparison of the slope angle estimated in this manner in the Kowhai Valley indicated a very similar range of values (mean slope

37.5°, 95% C.I. 35.8–39.2°, n = 49) to measurements made during fieldwork at the same colony when slope angle was measured directly with a handheld inclinometer (mean 35.4°, 95% C.I. 33.5–37.3°, n = 50; Cuthbert & Davis 2002c); providing confidence in the validity of the estimates from ArcGIS.

Simple trigonometry was used to calculate the slope angle (relative to the horizontal) and the sub-colony surface area was calculated as:

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Surface Area = Planimetric Area / cosine(Slope Angle)
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In order to evaluate the precision of this approach 30 of the 62 sub-colonies from Shearwater Stream and the Kowhai Valley were randomly selected, and the above procedures were repeated (mapping and measuring the planar area, estimating the slope angle, and calculating the surface area). I then calculated the percentage error of each pair of estimates from the 30 duplicate measurements and the overall mean error and 95% confidence intervals. Repeat mapping of sub-colony areas indicated a mean error of 0.2% in the precision of the calculated area estimates (95% confidence intervals -5.4 to +5.7%, n = 30) in comparison with earlier mapping of these same sub-colonies.

2.4 Pre and post-earthquake measurements of burrow density

Information on previous assessments of burrow densities in the Kowhai Valley and Shearwater Stream colonies are summarised in Table 1, as well as figures from the current study. These include estimates based on fixed quadrats of 10 × 10m in size in both colonies, as well as random quadrats of 4 × 4m distributed within selected sub-colonies of the Kowhai Valley and circular quadrats of 20 m^2 area in Shearwater Stream. The use of fixed monitoring quadrats (Sherley 1992) ceased in later studies, as winter snowfall and the unstable soils meant that marker posts and quadrats became lost over time. The use of a larger number of smaller-sized random quadrats was also undertaken to ensure that sampling was representative of each sub-colony and to provide more accurate estimates of mean burrow densities and confidence intervals.

Table 1: Information on surveys for burrow density estimates at Kowhai Valley and Shearwater Stream breeding colonies indicating the year of survey, number of quadrats, quadrat area and method used, total area covered by quadrats. Sub-colonies numbers follow Figures 3 and 6.

Survey year	Number of quadrats	Method used	Total area of quadrats (ha)	Sub-colonies sampled
	Kowhai Valley			
1987[a]	17	Fixed, 100 m^2	0.170	1, 4, 5, 6, 7, 8, 9, 21, 14, 15, 16, 18, 24, 29
1991	15	Fixed, 100 m^2	0.150	1, 4, 5, 6, 7, 8, 9, 15, 16, 18, 29
1998	296	Random, 16 m^2	0.474	1, 4, 5, 9, 15, 30, 32, 33
2004	175	Random, 16 m^2	0.280	1, 4, 5, 9, 15, 30, 32
2007	105	Random, 16 m^2	0.168	1, 4, 5, 9, 18, 30, 33
2017	300	Random, 16 m^2	0.480	1, 4, 5, 6, 7, 8, 9, 14, 18, 19, 29, 30, 32, 33
	Shearwater Stream			
1988	7	Fixed, 100 m2	0.070	1, 2, 3, 4, 5
1993	5	Fixed, 100 m2	0.050	1, 2, 4, 5
2007	31	Random, 20m2	0.062	1, 2, 4, 5

[a] Burrow densities were measured from 1986 to 1988 (Sherley 1992)

During the 2017 fieldwork burrow densities in Kowhai Valley were measured following the same methods as employed since the late 1990s (see Cuthbert & Sommer 2009), with 4 × 4 m quadrats randomly distributed in selected sub-colonies. Each sub-colony was traversed on foot in a rising or descending zigzag pattern through all available habitat types, with the exact location of each quadrat determined by throwing a 40 × 30 cm plastic rectangle and using its resting place as the pre-defined corner of each quadrat. Quadrat squares were made with a pre-tied length of rope with the corners pinned out flat on the sloping ground with bamboo stakes (Figure 2). Within each quadrat a team of two observers counted all shearwater burrows entrances and following previous methods all burrows that extended more than 0.4 m in length (beyond the length of a forearm) were recorded as burrows. Burrow entrances that were less than 0.4 m in length, which are unlikely to contain breeding birds, were not included in the quadrat total. When two burrow entrances joined the same tunnel they were counted as a single entrance. Burrows on the edge of the quadrats were excluded if more than 50% of the burrow entrance was judged to be outside the line. A total of 15 sub-colonies were sampled in 2017 with 20 random quadrats in each sub-colony and 300 quadrats in total (Table 1). These 15 sub-colonies had a total area of 23.42 ha (after adjusting for slope), covering nearly half (48%) of the post-earthquake area of the Kowhai Valley. The selection of sub-colonies for sampling in 2017 was based on (a) whether previous burrow density data existed for the sub-colony, (b) their representativeness of the whole colony including consideration of altitude, aspect and vegetation, and (c) the safety of the site following the 2016 earthquake. Fieldwork in the Shearwater Stream colony was not possible in 2017 due to safety concerns. As a consequence the post-earthquake reduction of burrow densities recorded in the Kowhai Valley (see results) was used as a proxy for Shearwater Stream with the assumption that the same extent of damage was likely to have occurred at both colonies. This assumption is untested, however Shearwater Stream only holds around 6% of the total breeding population of Hutton’s shearwater (see results) and consequently this assumption is unlikely to alter the main conclusions of the study.

Figure 2: Measuring burrow densities within a quadrat during fieldwork in the Kowhai Valley breeding colony, December 2017.

2.5 Calculating total population size and confidence limits

Pre and post-earthquake assessments of colony area and burrow density allow an assessment of the current population size of Hutton's shearwater and the extent of change likely to have occurred as a result of the earthquake damage. At its simplest a total population estimate for the species is provided by the product of total breeding area, average burrow density and average burrow occupancy. However, this approach ignores any potential bias in the estimation of burrow density, which may occur if densities vary systematically with factors such as vegetation type or aspect, and the inclusion of these factors may provide a more precise and accurate population assessment. In order to investigate this each of the 300 quadrats in 2017 were treated as independent sampling points and Generalized Linear Models (GLMs) were constructed with the number of burrow entrances in each quadrat as a dependent variable and with sub-colony, altitude, aspect and vegetation class as factors. Altitude was derived from handheld GPS coordinates taken for each quadrat location and these coordinates were used to determine the aspect and classify the vegetation type from aerial imagery in ArcGIS. Habitat types were simplified into "Tussock" and "Scrub" categories, with the latter containing *Hoheria* and other montane scrub species. Aspect was grouped into eight ordinal categories each of 45° in arc, consisting of 0–45° (NNE), 45–90° (ENE), 90–135° (ESE), etc. A total of 8 potential candidate models were tested with the following factors as explanatory variables: Sub-colony, Altitude, Aspect, Vegetation, Sub-colony + Altitude, Sub-colony + Aspect, Sub-colony + Vegetation and one null model with no explanatory variables to represent a baseline candidate model. The choice of models was based on their biological plausibility at influencing burrow densities and to avoid collinearity among factors (e.g. models with both altitude and vegetation type were excluded, as scrub habitat is strongly correlated with elevation as it only occur at lower elevations of the colony). The best-fitting model from the set of candidate models was assessed in an information-theoretic model-testing framework (Burnham & Anderson 2002) in program R v3.1.2 (R Core Team 2013), with the best model determined by the lowest Akaike's Information Criteria (AICc).

This analysis indicated that the best fitting model explaining most variation in burrow densities was one that included sub-colony and vegetation types, as average burrow densities varied among subcolonies and between tussock and scrub habitats (see **Annex 1** for the outputs of this model). As a consequence the post-earthquake population estimate was calculated using sub-colony specific density estimates for each sub-colony where data were available, with the assumption that the random location of quadrats through the sub-colony area and all occurring vegetation types provided an accurate estimate of overall density. For the remaining sub-colonies, where quadrats were not undertaken, the area of scrub and tussock habitat was measured from aerial imagery in ArcGIS for each sub-colony and then the mean burrow density was used for these two habitat types based on the mean value for tussock (5413 ± 1839 burrows ha^{-1}, (± 1 standard deviation), n = 251 quadrats, 95% C.I. 5185 – 5642) and scrub vegetation (4196 ± 1619 burrows ha^{-1}, n = 49, 95% C.I. 3731 – 4662) recorded from across all sampled subcolonies during the 2017 fieldwork.

A similar process was undertaken for pre-earthquake assessments of the population size using subcolony specific density estimates where these were available and the overall mean value from all quadrats for sub-colonies that were not sampled. GPS coordinates of quadrat locations were not available from earlier surveys and it was not possible to calculate vegetation specific estimates of burrow density. In order to take into account the lower and higher burrow densities in scrub and tussock vegetation in earlier surveys the ratio of burrow densities in these two habitat types was used against the overall average density of burrows recorded from across all 300 quadrats in 2017 (an overall mean density of 5214 burrows ha^{-1}), with the assumption that the same habitat specific patterns of burrow density were present in previous years (as previously observed). The resulting correction factors (1.0382 for tussock and 0.8048 for scrub areas) were then used with the mean burrow density (across all habitat types) and the area of snow tussock and scrub habitat within each sub-colony which was measured in ArcGIS from pre-earthquake aerial imagery. The distribution of scrub and tussock vegetation within the Kowhai Valley has remained unaltered since the late 1990s (authors personal observations) and the same area estimates of these vegetation types in sub-colonies were used in all calculations.

Chionochloa snow tussock is the only vegetation type at Shearwater Stream and consequently the estimate of total burrow numbers was based on mean burrow densities for each sub-colony when this was available and with overall mean burrow density used to calculate numbers in sub-colonies that were not sampled. Information from Mike Morrissey (Kaikōura DOC) who knows this site very well indicated that burrows only occur in appreciable numbers in sub-colonies 1, 2b, 2c, 3b, 3c, 4a, 5b and 5d (see Figure 7), with the remaining sub-colonies (2a, 2d, 3a, 4b, 5a and 5c) containing a few isolated burrows that “may only number in the 20s” in total (M. Morrissey *pers. comm.*). As a consequence I used burrow density and area estimates for calculating total burrow numbers in the former sub-colonies and used a fixed total of 150 burrows for the six sub-colonies with very low numbers (assuming a figure of 25 burrows within each site).

Estimates of the total number of shearwater burrows derived above, incorporating sub-colony and habitat specific estimates of burrow density and area, were multiplied by a mean burrow occupancy of 70.5% to provide an overall estimate of breeding numbers. This occupancy figure is based on ten years of monitoring within the Kowhai Valley colony from 1989–1990 to 1998–1999 (Cuthbert 2001) and is the only available estimate of the overall proportion of breeding pairs within the species breeding grounds. Measures of burrow occupancy (the proportion of burrows containing an incubating pair at the start of the breeding season) are not available for more recent years, as this parameter depends on monitoring a marked sample of study burrows from one season to the next and recording this data shortly after egg laying. Observations on the number of birds present at night in sub-colonies of the Kowhai Valley in December 2017 and from finding incubating pairs in burrows with an infra-red burrowscope in the same period indicated high numbers of shearwaters within the colony, and no grounds for considering a major change in burrow occupancy or breeding birds on the ground in comparison to previous years.

Confidence limits for population estimates were derived from a boot-strapping procedure using random sampling (with replacement) of actual burrow density measurements. Bootstrapping for sampled subcolonies was undertaken with burrow density data from the same sub-colonies, with bootstrapping for all remaining sub-colonies taken from all quadrat data in the year of sampling. These procedures were repeated 10 000 times, with the lowest 250th and upper 9750th of the resulting population sizes taken to provide a 95% confidence interval for the population estimate.

2.6 Monitoring breeding success

Breeding success has been monitored at the Kowhai Valley from the 1989/90 to the 1998/99 breeding seasons, along with further monitoring at this colony and Shearwater Stream from 2006/07 to 2015/16. As is usual for burrowing petrels that lay a single egg breeding success was defined as the proportion of incubating pairs that went on to produce a fledged chick. Burrows in the Kowhai Valley during the earlier period of monitoring were checked through study hatches dug above the nesting chamber and the use of an infra-red burrowscope to inspect the contents of the nest chamber from the burrow entrance, and with a minimum of three checks over the breeding season corresponding to the early incubation, early chick and late chick-rearing stages. The more recent monitoring was undertaken solely with the use of burrowscopes with burrows checked in the early incubation and late chick-rearing stages. Trapping for stoats was undertaken in the Kowhai Valley in two breeding seasons (1993/94 and 1994/95) and at Shearwater Stream over eight seasons (from 2008/09 to 2015/16) in order to evaluate the effectiveness of this management measure at increasing breeding success. Breeding success in the Kowhai Valley was monitored in the 2017/18 breeding season to determine if breeding success of the species had been affected by the earthquake, with a sample of 100 burrows monitored with a burrowscope in December 2017 and rechecked in March 2018. These burrows were located in subcolonies 1b and 8 (see Figure 4). Breeding success could not be monitored at Shearwater Stream due to the safety concerns outlined previously.

2.7 Evaluating changes in colony vulnerability and potential new sites

The inaccessibility of the Kowhai Valley and Shearwater Stream breeding colonies distinguish these two extant shearwater colonies from the species' former breeding sites, and the boundary areas of both remaining colonies are guarded by steep cliffs and rocky terrain which have prevented feral pigs from entering the sites (Cuthbert 2002). Areas on the true left and true right of the Kowhai River at the boundary of the Kowhai Valley colony were visited during the 2017 fieldwork in order to evaluate if the earthquake had increased the accessibility of the site to feral pigs. The accessibility of Shearwater Stream was evaluated from the air during helicopter flights to this site, as well as by visits on foot to the boundary of this area made by Mike Morissey (DOC).

Prior to and following fieldwork in the Kowhai Valley the author visited the location of former breeding colonies of Hutton's Shearwater in the Seaward Kaikōura Range. These included visits on foot to sites on the flanks of Mt Fyffe (including Big Hau and Little Hau) and in the Happy Valley, as well as a helicopter flight around the eastern and western flanks of the Seaward Kaikōura Range from north of George Saddle to south of Snowflake Peak to search for any remnant shearwater colonies and evaluate their potential for re-establishing a breeding colony. As well as visits to these sites further visits on the ground were made to areas of Mt Fyffe, Mt Alexander and the Kaikōura Peninsula. The location of these sites is shown in Figure 3. A qualitative assessment of the potential suitability of these sites for reestablishing a breeding colony of Hutton's shearwater was undertaken based on consideration of the site's accessibility; the ability to construct and maintain predator proof fencing on the site; its slope angle and area; and the proximity to the two extant breeding colonies and the flight path of birds. At three sites (on the lower true left boundary of the Kowhai Valley colony, the north western flanks of Mt Alexander, at Sandy Saddle on Mt Fyffe) soil depth was measured following previous methods (Cuthbert & Davis 2002c) using a 5 mm diameter metal probe and inserting this to its maximum depth perpendicular to the slope of the hillside. A sample of soil depths was taken from these areas through traversing the site and taking a depth sample after a set number of paces. This data was compared with previous measurements of soil depth from the Kowhai Valley colony (Cuthbert & Davis 2002c). Slope angle in these areas was measured in ArcGIS by measuring horizontal distances between vertical contour lines, as described previously in the methods.

As well as investigating the above sites in detail the helicopter flight on 15 December was used to further search the seaward and inland flanks of the Seaward Kaikōura Range in order to search the former breeding sites of the species and to look for any remaining shearwater sites in these and other areas through observations of tussock slopes within the altitudinal range of the species (1200–1700 m). This flight was undertaken in good weather with an elevation of 50 to 100 m above the ground and with a slow flight speed or hovering in any potential areas. Sites were searched with binoculars from the air and through examining photographs from the flight.

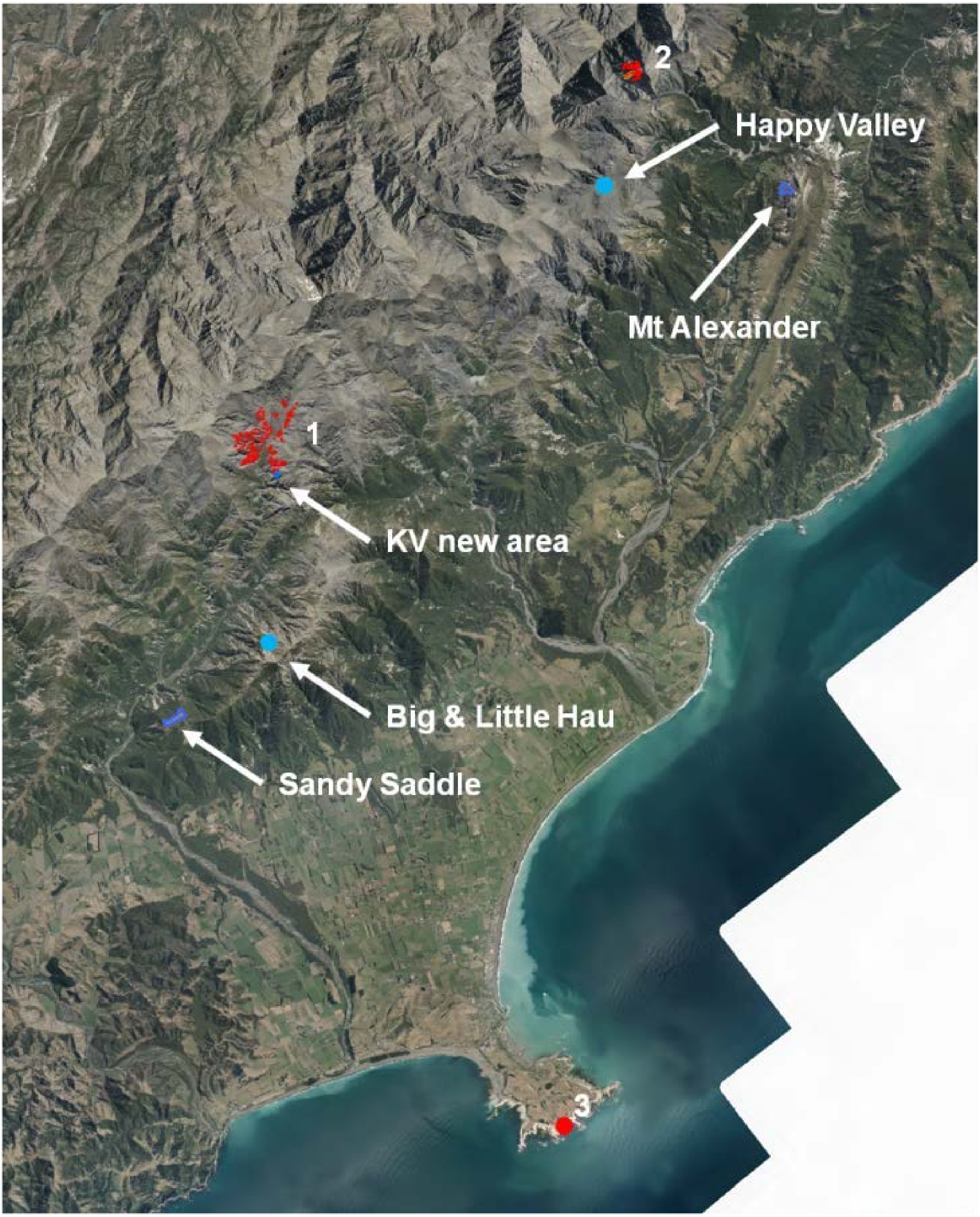

Figure 3: Aerial image of the Kaikōura region showing the location of the Kowhai Valley (1), Shearwater Stream (2) and Peninsula colonies (3), as well as the location of sites visited to assess their potential suitability as new colony areas. See Annexes 2 and 3 for more detailed images of these sites.

3. RESULTS

3.1 Colony areas and loss of breeding habitat

As was known previously from flights immediately after the 2016 earthquake the greatest damage to the shearwater's breeding grounds occurred within the Kowhai Valley from a major rock fall that occurred from near the summit of Mt Saunders and which swept down the eastern flanks of this peak and into the Kowhai Valley. This rock ‘avalanche’ completely buried sub-colony 15 and caused major destruction of sub-colonies 14, 29 and 31 (Figures 4-5). The vegetation within remaining areas of sub-colony 29 was also severely impacted by this rock slip, with considerable areas of *Hoheria* scrub lying dead and stripped of all leaves and large areas of bare soil (see Appendix 2). Prior to the earthquake sub-colonies 14 and 15 were separated from sub-colonies 16, 29 and 31 by a very steep sided stream and gorge. This has now been completely buried by rock debris transforming this area into a wide open valley of tumbled rock and scree (Figure 6). The depth of these rocks is estimated to be up to 50 to 100 m above the former surface of the ground, with the area of rock debris measuring around 1.2 km in length and 100 to 200 m in width. As well as the major damage to these sub-colonies there was also damage to further areas of breeding ground within the Kowhai Valley colony, with small changes in the area of extent of subcolonies 12, 17, 19c and 27 (Figures 4-5). A total of 7.416 ha of breeding habitat is estimated to have been destroyed in the Kowhai Valley, accounting for 13.5% of the pre-earthquake area (Table 2).

Measuring the extent of colony loss at Shearwater Stream was difficult as fieldwork could not be undertaken within this site and because the post-earthquake aerial imagery of certain sub-colonies were in deep shadow making precise estimates of these areas difficult to measure. Nonetheless site visits by helicopter to this colony and examination of photographs from the flight, along with the aerial imagery (Figure 7), revealed relatively little damage and no major rock falls/landslips. Based on this flight and aerial imagery there was an estimated 3.7% loss of colony area at this site (Table 2). The combined losses at Shearwater Stream and Kowhai Valley represent a reduction of 12.4% of the total breeding habitat of Hutton’s shearwater in comparison to area estimates from before the 2016 earthquake.

Table 2: Estimated area of breeding habitat at the Kowhai Valley and Shearwater Stream Hutton’s shearwater colonies from before and after the earthquake and the area and percentage loss of habitat from these two sites and for both sites combined. The area estimate is the surface area of the slope (i.e. incorporating slope in the calculation).

	Kowhai Valley		Shearwater Stream		Both sites	
	Before	After	Before	After	Before	After
Area (ha)	56.019	48.462	7.312	7.038	63.331	55.000
Area lost (ha)		7.557		0.274		7.831
Percentage loss		13.5%		3.7%		12.4%

The above figures are markedly different and over twice the area of previous estimates of the colony area of these two sites which Sherley (1992) previously estimated as 24.22 ha for the Kowhai Valley and 2.65 ha for Shearwater Stream. The likely cause of these major differences in area estimates is reviewed in the Discussion.

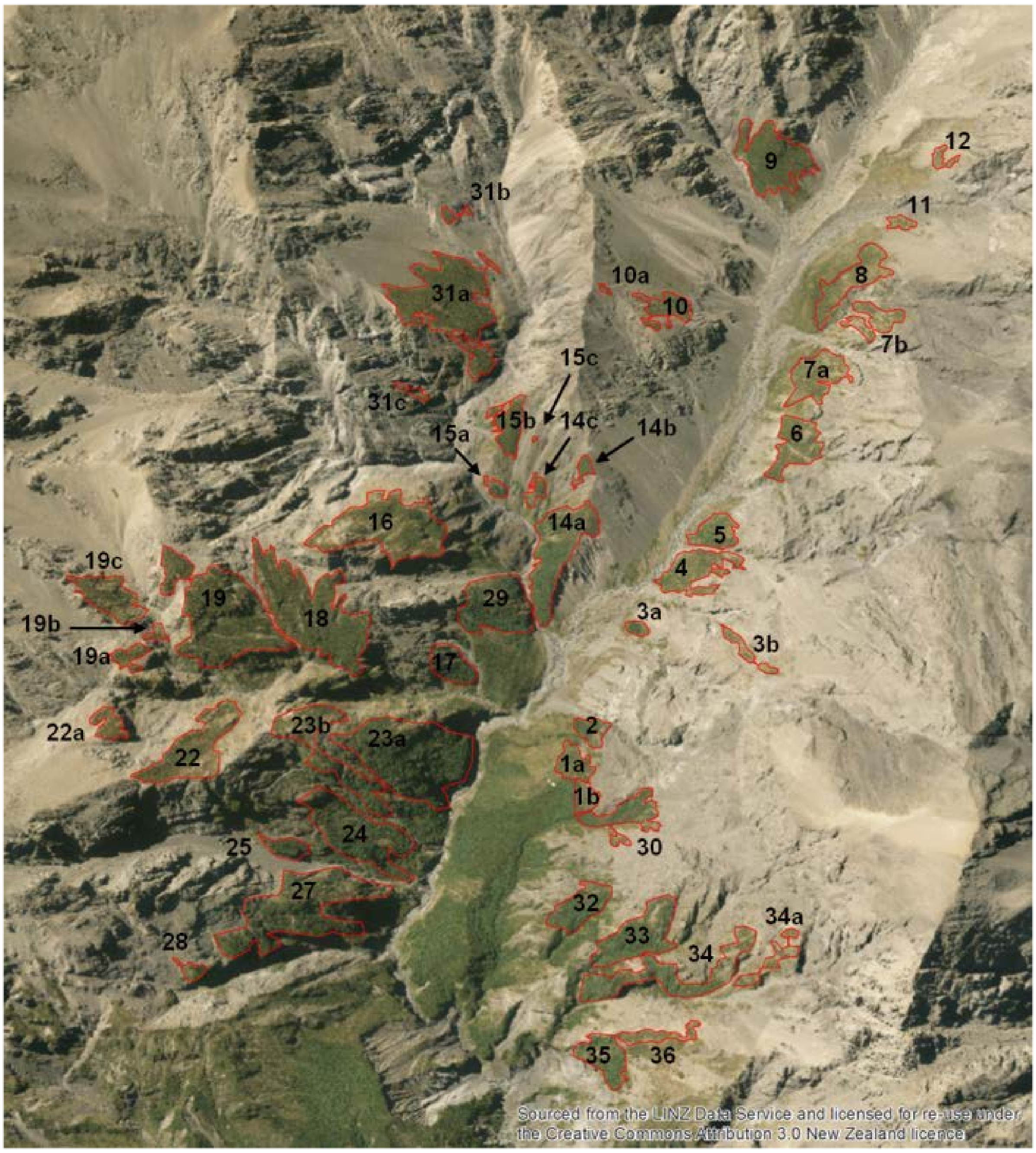

Figure 4: Hutton's shearwater breeding areas at Kowhai Valley from before the 2016 earthquake (images are from the 2014–15 summer flying season; LINZ 2016). Boundaries of individual sub-colonies are marked with red lines with labels indicating the sub-colony number.

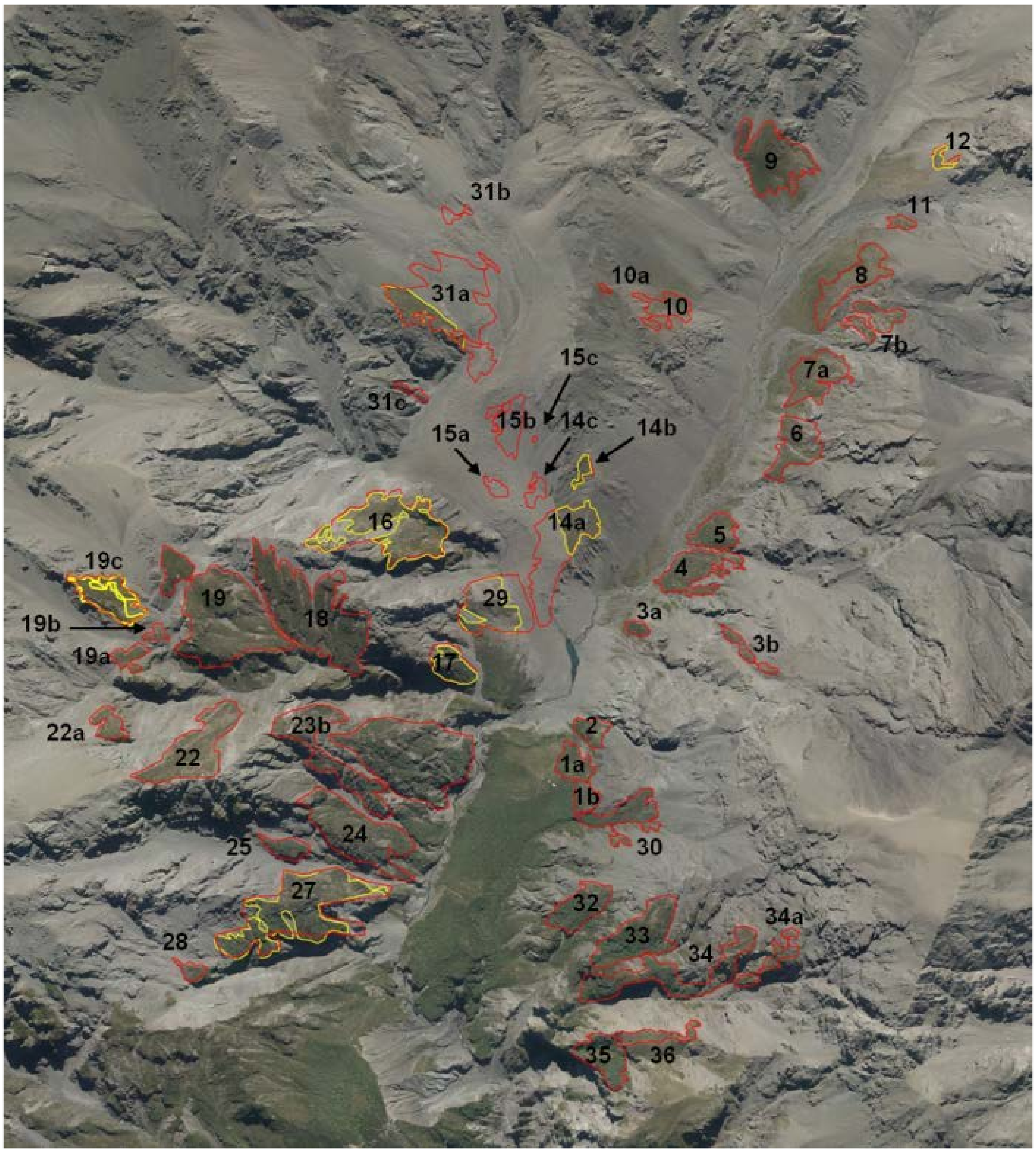

Figure 5: Hutton's shearwater breeding areas at Kowhai Valley indicating the site after the 2016 earthquake. Sub-colonies are marked with red and yellow lines to indicate pre and post-earthquake boundaries, respectively. The major areas of destruction occurred in sub-colonies 31, 15, 14 and 29, with the debris caused by the rock avalanche from Mt Saunders clearly visible in this former steep valley and ending in a small lake blocking the Kowhai River (the lake has since been eroded away by the river's flow).

Figure 6: Images of the extent of the major rock avalanche from the summit slopes of Mt Saunders into the Kowhai Valley which completely or partially buried breeding areas of the species in this colony. The bottom image was taken standing on what was previously a deep gorge and stream.

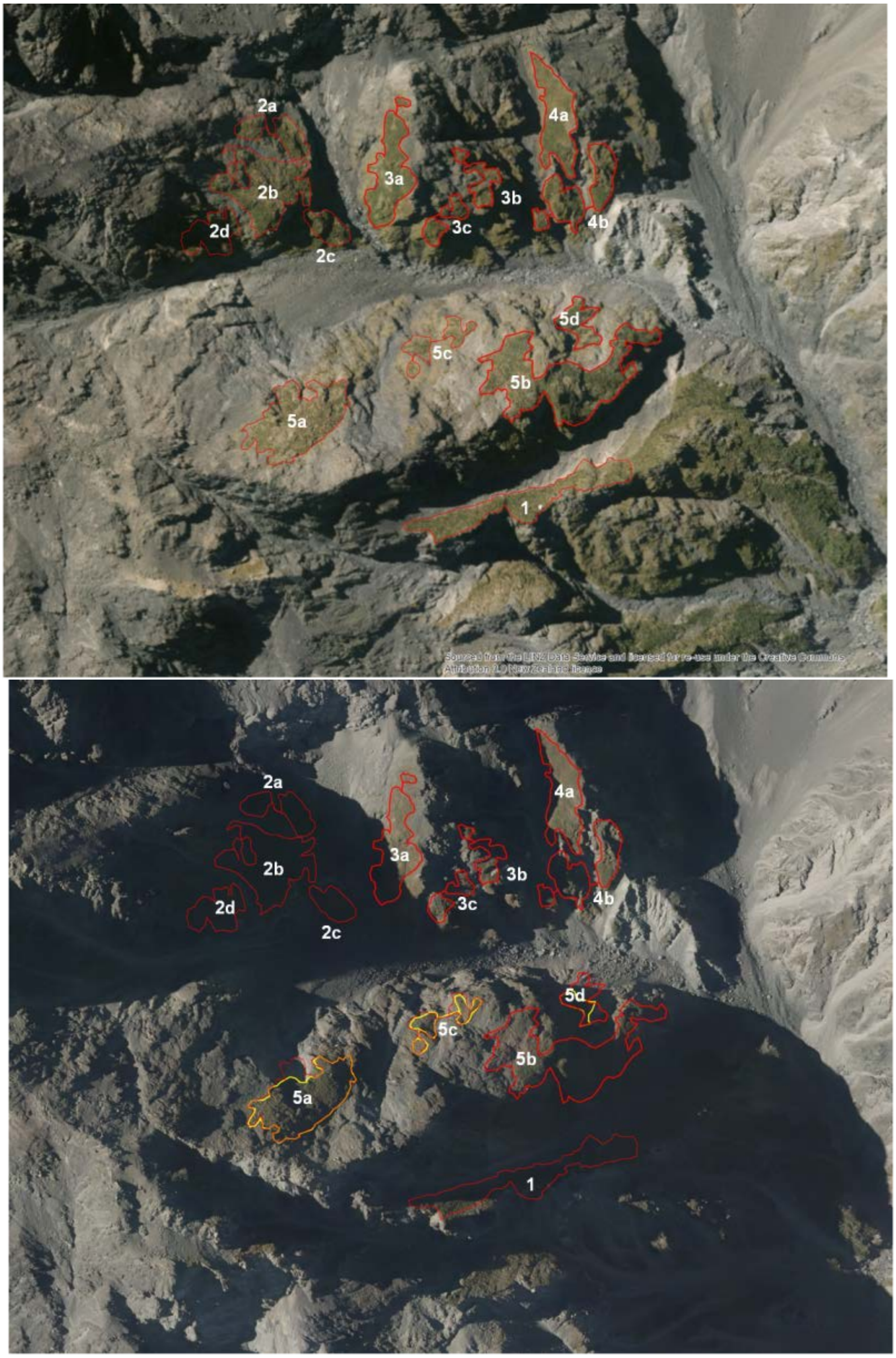

Figure 7: Hutton's shearwater breeding areas at Shearwater Stream indicating the site prior to (top) and after (bottom image) the 2016 earthquake. Sub-colonies are marked with red and yellow lines to indicate pre and post-earthquake boundaries, respectively.

3.2 Burrow densities

Comparison of pre and post-earthquake burrow numbers in the Kowhai Valley colony indicates a highly significant reduction in burrow density following the 2016 earthquake in comparison with data on burrow density collected using the same methodology in 2007 (Table 3). This reduction is apparent when comparing all 15 sub-colonies visited in 2017 against the 7 sub-colonies sampled in 2007, and when comparing the same 7 sub-colonies in 2007 and 2017. This data indicates an overall reduction in burrow density of 29.6% to 32.8% (Table 3) with the figure of 29.6% likely to be the most accurate estimate of the proportional reduction in burrow density (i.e. removing any sub-colony effect from the comparison). As stated previously, information on burrow density could not be obtained from Shearwater Stream as site visits to this site were not permitted due to safety concerns. Consequently, the same reduction in burrow density at this site (29.6%) as measured at the Kowhai Valley has been assumed for Shearwater Stream.

Table 3. Measured values of burrow density within the Kowhai Valley colony from before the earthquake (in 2007) and after the earthquake (2017) for all available data from both years of survey and a paired comparison using data from the same seven sub-colonies in both years (sub-colonies 1, 4, 5, 9, 18, 30, 33; Figure 3). Data presented indicates mean burrow density (burrows ha^{-1}) ± 1 standard deviation, with sample size of quadrats in parentheses, 95% confidence intervals (C.I.) of the mean, results of a T-test and probability (*P*) and the percentage reduction in burrow density following the earthquake.

	All available data (7 and 15 sub-colonies)		Paired sub-colonies (7 in each year)	
	Before (2007)	After (2017)	Before (2007)	After (2017)
Burrow density	7411±3774 (105)	5215±3270 (300)	7411±3774 (105)	4892±3174 (140)
95% C.I.	7289–7533	4871–5094	7289–7533	5102–5327
T-test		t=5.684, P<0.0001		T=5.482, P<0.0001
Reduction		32.8%		29.6%

3.3 Population estimates

As described in the methods, information on colony area and burrow density was obtained in 2017 following the 2016 earthquake and compared with colony area measured prior to the 2016 earthquake and with burrow density estimates from 2007 and earlier years when this was surveyed. Sub-colony specific estimates of burrow densities were used for individual sub-colonies in years that this was available, and with the overall average burrow density obtained from all surveyed sub-colonies used for the remaining areas after measuring and correcting for tussock and scrub habitat types. These calculations result in a total population estimate for the species of 312 600 pairs of breeding birds in 2007/08 (the last year prior to the earthquake where burrow density estimates were available), with the majority of these (94%) at the Kowhai Valley colony (Table 4). Following the 2016 earthquake the estimated population in 2017/18 season is 191 500 pairs, an overall reduction of 38.7% in comparison with a decade earlier. Repeating these same calculations for earlier years where burrow density estimates are available (and using the same area colony estimates) indicates a slowly increasing population over the period 1987 to 2007 (Figure 8), prior to the 2016 earthquake event.

Table 4: Estimated total number of breeding pairs of Hutton's shearwater at Kowhai Valley and Shearwater Stream breeding colonies and both sites combined from before (2007/08 breeding season) and after (2017/18) the 2016 earthquake. Values are calculated estimates with 95% confidence intervals.

	Kowhai Valley		Shearwater Stream		Both sites	
	Before (2007)	After (2017)	Before (2007)	After (2017)	Before (2007)	After (2017)
Population (pairs)	294 950	179 950	17 650	11 600	312 600	191 550
Lower 95% C.I.	272 200	169 750	15 000	9 750	287 200	179 500
Upper 95% C.I.	319 000	190 000	20 400	13 250	339 400	203 550

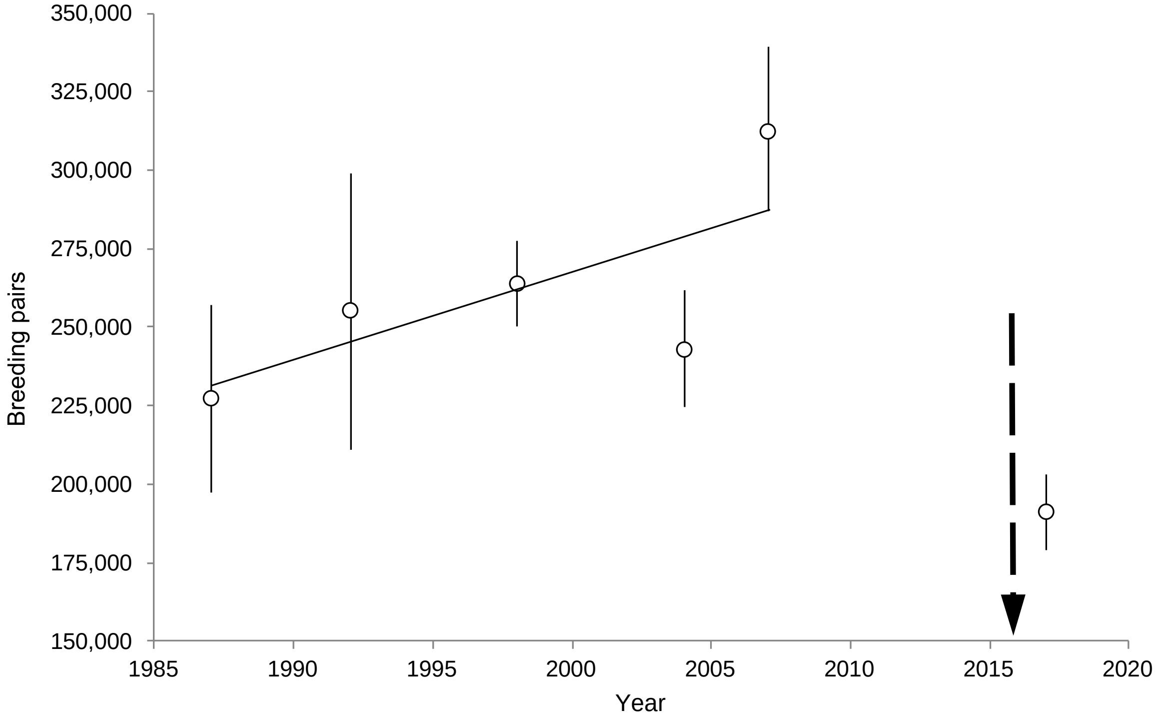

Figure 8: Total population size (number of breeding pairs) of Hutton's shearwater from 1987 to 2017, from prior to and after the 2016 earthquake. Error bars are 95% confidence intervals of each estimate and the fitted line is the best-fit linear regression for the period 1987 to 2007. The dashed arrow indicates the 2016 earthquake event.

3.4 Breeding success

Overall patterns of breeding success monitored within the Kowhai Valley and Shearwater Stream colonies are shown in Figure 9, which illustrates the high annual variability of this parameter. At the Kowhai Valley in the 2017/18 season there were a total of 71 near fledging age chicks in March 2018 from a sample of 100 burrows containing birds on eggs recorded in early December 2017. This value of breeding success (71%) compares favourably with previous years of monitoring and is in the upper range of the recorded values of breeding success (Figure 9). Breeding success averages 49.7 ± 18.4% (*n* = 20, 95% C.I. 41.1 – 58.3) in the Kowhai Valley colony and 49.9 ± 28.6% (*n* = 10, 95% C.I. 29.5 – 70.4) at Shearwater Stream. Breeding success was monitored at both colonies for eight years (from the 2008/09 to 2015/16 seasons) during which period stoat trapping was undertaken at Shearwater Stream and when there was no trapping at the Kowhai Valley site. There was no major difference in breeding success between the two sites over this period (trapped colony 61.1 ± 18.1%, *n* = 8, 95% C.I. 46.1 –

76.3; not trapped 57.8 ± 18.8%, n = 8, 95% C.I. 42.1 – 73.6) and annual breeding success at both sites was highly correlated over these two years (Pearson's r = 0.7196, n = 8, P = 0.0144).

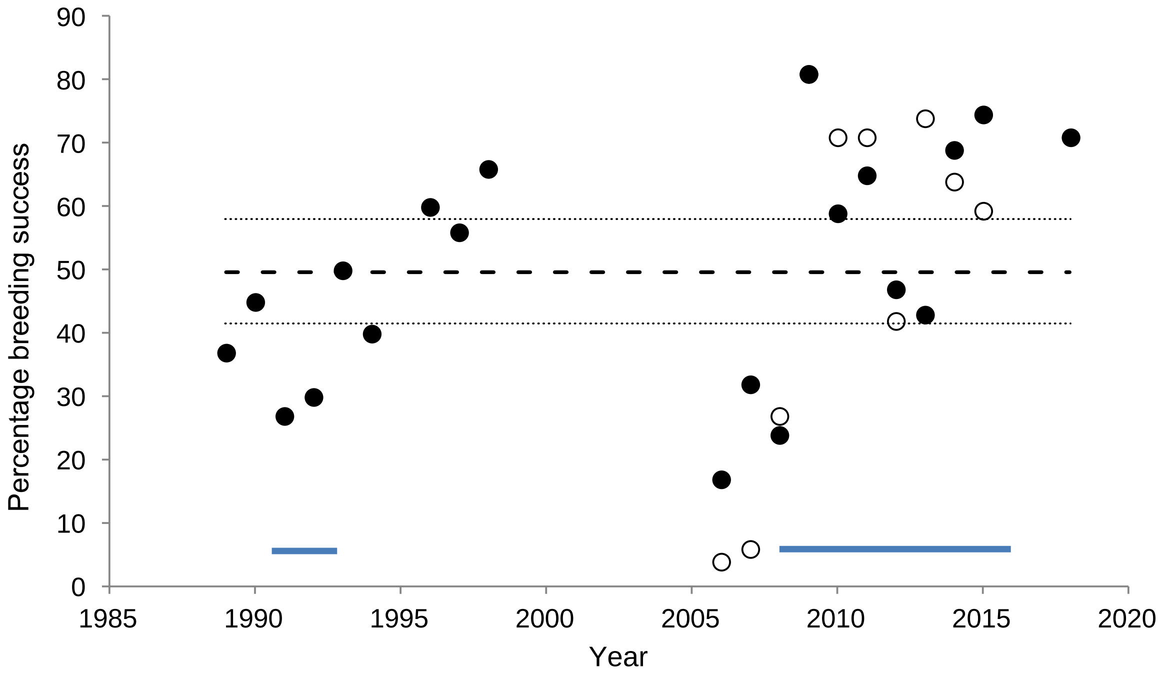

Figure 9: Measured values of breeding success from Kowhai Valley (filled symbols) and Shearwater Stream (unfilled symbols). The thick and thin dashed horizontal lines are overall mean breeding success and the 95% confidence intervals of this estimate. Blue horizontal lines represent periods of stoat trapping in Kowhai Valley (1992/93 and 1993/94 seasons) and Shearwater Stream (2008/09 to 2015/16). The single post-earthquake measure is from 2017 and at the Kowhai Valley site.

3.5 Colony vulnerability

During the visit to the Kowhai Valley colony time was spent exploring the lower boundary of the site on both the true left and true right of the Kowhai River, as steep bluffs and cliffs in these areas have provided an effective barrier for feral pigs from entering the site. The area on the true left (to the east) has remained unchanged following the earthquake and the extensive areas of scree and rock and bare open ground always made this route an unlikely point of access for pigs (although chamois *Rupicapra rupicapra* and red deer *Cervus elaphus* do traverse through these areas). The most vulnerable entry point to the Kowhai colony is on the true right of the river where a narrow (about 15 m width) and steep spur of vegetated ground comes down to near the Kowhai River just above a large waterfall (10–15 m in height) that forms a boundary to animals coming up the river. This narrow point is the usual route in and out of the colony if the site is accessed on foot and involves a steep scramble, along a narrow ledge which is also used by chamois and deer. While there was earthquake damage and new areas of scree just upstream of this access point the waterfall and spur have remain unaltered by the earthquake (Figure 10) and this remains a barrier for pigs entering the site. While chamois and deer do use this route into the colony it is steep and over a large (more than 20 m) drop; during the December 2017 visit the carcass of a deer was present at the foot of the waterfall and it is likely to have slipped from this access point (Figure 10). The Shearwater Stream colony is guarded by steep cliffs that rise from the stream bed of a branch of Happy Valley Stream on which there are fixed ropes to allow DOC staff and other researchers to access the colony. These features were unaltered following the 2016 earthquake and the site remains inaccessible to pigs.

Figure 10: Images of the lower reaches of the Kowhai Valley shearwater colony indicating the steep spur and access point on the true right of the valley just above the waterfall into the Kowhai River. The pre and post-earthquake boundaries of sub-colony 27 are indicated with red and yellow lines, respectively, along with the rock debris in the river bed from these areas following the 2016 earthquake. The bottom image is from above the waterfall with a deer carcass at its base (indicated by the yellow arrow).

3.6 Prospective colony areas

Potential new areas for extending or establishing new areas of breeding colony for Hutton's shearwater were explored during December 2017. These included a site adjacent to existing areas of burrowed ground within the Kowhai Valley, old extinct colonies at Big Hau and Little Hau on Mt Fyffe and in the headwaters of Happy Valley near Shearwater Stream, and potential new sites at Sandy Saddle near Mt Fyffe and Mt Alexander (see Figure 3), as well as visits to the Kaikōura Peninsula colony. Both Big Hau and Little Hau were excluded from further investigation due to the small remaining areas of tussock habitat present and the difficulty in protecting these sites. Similarly, the headwaters of the Happy Valley area were excluded due to the very steep and unstable terrain present, which would make fencing and protecting these sites in the long-term a very difficult proposition. Further information was collected from a small area of ground on the furthest true left area of the Kowhai Valley colony, as well as at Sandy Saddle and Mount Alexander. Attributes of these sites are summarised in Table 5 below. The potential prospect for these sites as future colonies is considered in more detail in the discussion.

The helicopter on the 15 December revealed no evidence of shearwater colonies remaining in the Seaward Kaikōura Range. As outlined in the methods areas of shearwater burrowed ground in snow tussock slopes can be swiftly recognized, both in the field and from aerial imagery, by its darker green and lusher vegetation, and despite careful searching there was no evidence of any burrows. This confirms previous assessments (Sherley 1992), as well visits on foot by deer and goat culling teams in the Kaikōura Ranges over the last two decades (M. Morrissey *pers. com*).

Table 5: Characteristics of potential breeding new breeding sites within the Kowhai Valley (new area), the Peninsula Colony, Sandy Saddle and Mount Alexander, along with information in the first column on slope angle and soil penetrability measured within burrowed areas of the Kowhai Valley (Cuthbert & Davis 2002c). Values in parentheses are 95% confidence intervals.

	Kowhai Valley		Peninsula	Sandy	Mount
	Existing areas	New area	Colony	Saddle	Alexander
Elevation range (m a.s.l.)	1200–1700	1320–1400	70–90	780–860	800–1000
Flight path		Yes	No	Yes	Probable
Accessibility		Difficult	Good	Moderate	Good
Fencing		Not needed	Completed	Possible	Possible
Slope angle (º)	35.4 (30.2–40.6)	28.9	25.6	24.3	35.2
Soil penetrability	34 (25.6–42.4)	35.1 (26.7–43.5)	Not measured (but low)	19.4 (14.1–24.6)	20.8 (14.9–26.7)
Area of habitat (ha)		0.8	1.8	12.2	6.6
Potential population (pairs)[1]		1700–2500	4000–6000	26000–40000	14000–21000

[1]The potential population size of these areas was calculated based on colony densities at Kowhai Valley recorded in 2007 and assuming that between 50 – 75% of the available habitat is occupied by breeding pairs.

4. DISCUSSION

The major purpose of this study was to assess the impact of the 2016 Kaikōura earthquake on the population of Hutton's shearwaters and to assess potential ongoing threats and limits to recovery for the species. As part of this assessment the study has undertaken a new assessment of the total breeding population of the species, using accurate aerial imagery along with modern spatial software techniques, as well as assessing the population size and trends prior to and following the earthquake. The implications of the earthquake and the species' remaining breeding areas are reviewed both in the context of the damage caused by the 2016 earthquake and in terms of potential management options for the species that are required to secure the long-term security of the species and reduce the level of threat from future earthquakes or any other major event (such as a large avalanche or landslip) that could impact the remaining breeding sites. The population size and impact of the earthquake on the species and future management options are discussed separately below.

4.1 Population size and impact of the Kaikōura earthquake

As outlined in the introduction, previous estimates of the total population size of Hutton's shearwater have calculated a population of around 134 400 pairs (Sherley 1992), using measures of burrow density and colony area, with this figure being revised down to 106 000 pairs based on an average burrow occupancy figure of 70.5% (Cuthbert & Davis 2002). The latter figure did not involve recalculating burrow densities or area estimates, and predicted population trends of Hutton's shearwater have relied on new burrow density estimates alone (Cuthbert & Sommer 2009; Sommer et al. 2009). The current study, using highly accurate aerial imagery and GIS software, re-measured the area of the two mountain breeding colonies both before and after the earthquake and combined these new area estimates with pre-existing burrow density estimates from both sites along with new measures of burrow density recorded in 2017 from Kowhai Valley. These calculations estimate that there were around 312 600 pairs of Hutton's shearwater in 2007. Following the 2016 earthquake and the destruction of breeding areas and reduction in burrow density, the species population is estimated to be around 191 550 pairs in 2017.

These figures are considerably larger than the previous population estimates obtained for the species, with the pre-earthquake population of 312 600 pairs nearly three times the size of the former estimate of 106 000 pairs. This major difference in population size is a consequence of the measured differences in the area of the species' breeding habitat, as the same burrow density estimates from 2007 and earlier years were used in the new assessment. Sherley (1992) measured the colony area as 24.22 ha for the Kowhai Valley colony and 2.65 ha for Shearwater Stream, which contrast with new pre-earthquake measurements of 55.88 ha and 7.04 ha, respectively. The major difference in the methods employed in previous population estimates in comparison with the new analysis is the use of highly accurate aerial imagery; readily available and sophisticated spatial software for calculating sub-colony areas; and the use of surface area estimates, that take account of the slope, as opposed to planimetric areas. The latter point increases the total area estimate by around 30% in comparison to the planimetric area alone, however the estimated planar areas as measured in 2017 (43.57 ha for the Kowhai Valley and 5.06 ha for Shearwater Stream) are still nearly double the area estimates calculated by Sherley (1992). These large differences in area are most likely to be down to a scaling error in the original maps used by Sherley, which due to the squaring effect of area calculations will result in far a larger area error and estimates that are nearly half the actual area [1]. The colony area estimates obtained in 2017 were independently measured and assessed using an alternative GIS software package and produced the same area estimates for the species as presented in this report (J. Preece, *pers. com*). Consequently, these area estimates and resulting population estimates can be confidently used as a more accurate measure of the total population than previous estimates for the species.

Further evidence to support the revised and larger population estimate of the species is provided by a separate and independent measure of the number of individual Hutton's shearwaters present off the coast of Kaikōura and calculated through a mark and re-sighting procedure (Rowe et al. in press). This method was undertaken in 2002 and 2014 when around 2000 birds were marked with a colour dye in Kowhai Valley colony over several consecutive nights. Re-sighting of marked and unmarked birds was then undertaken over several subsequent days off the Kaikōura Peninsula and a sampling model was used to calculate the total number of individuals present. These methods produce estimates of 460 000 birds (95% C.I. 435 000–485 000) in 2002 and 590 000 birds (95% C.I. 545 000–645 000) in 2014 (Rowe et al. 2018. These mark and re-sighting estimates were undertaken in September at the start of the shearwaters' breeding season when all breeding birds should be present off Kaikōura and visiting the breeding colonies during the pre-laying period. Based on information from the closely related Manx

[1] The approximate size of the linear error in the original maps can be calculated from the square-root of the previous and new estimates. Thus for the Kowhai Valley the error is $\frac{\sqrt{24.22}}{\sqrt{43.57}} = 0.746$ and $\frac{\sqrt{2.65}}{\sqrt{5.06}} = 0.724$ for Shearwater Stream. The impact of a linear error of about 0.75 is illustrated by the resulting area of a 75 x 75 m sub-colony (5625 m^2), versus the true area of a 100 x 100 m sub-colony (10 000 m^2), which is nearly double the former area estimate.

shearwater *Puffinus puffinus*, which breeds in the Northern Hemisphere, the majority of birds present at the start of the season will be breeding adults, as immature birds are recorded more frequently at the breeding grounds during later stages of the season (Brooke 1990). As a consequence, the number of birds recorded at sea in September should be around twice the number of breeding pairs (i.e. both the male and female members of the pair) estimated independently by measurements of colony area, burrow density and burrow occupancy. Support for this is shown in Figure 10 below where the number of breeding birds recorded at sea in September is within the same range as numbers estimated from the breeding grounds. As part of the wider study on the impact of the earthquake on Hutton's shearwater a further mark re-sighting exercise is planned for September 2018, which will produce an independent assessment of the post-earthquake population estimate for the species and may provide further support for the magnitude of impact of the 2016 earthquake as reported here.

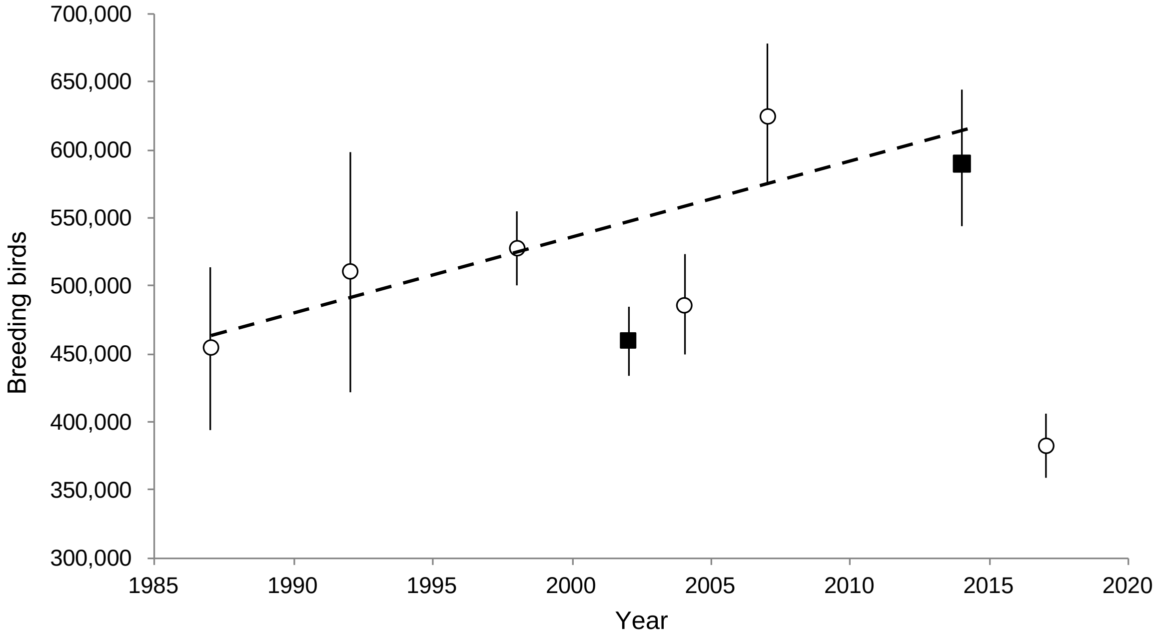

Figure 10: Comparison between the total number of breeding birds from estimates of Hutton's shearwaters obtained at the breeding grounds (unfilled circle symbols) and from an analysis of mark and re-sightings of birds off the Kaikōura Peninsula in 2002 and 2014 (square black symbols). Vertical lines are 95% confidence intervals and the dashed line is the best-fit trend line for colony estimates of breeding birds from 1987 to 2007 (excluding the post-earthquake estimate) and projected to 2014. The 2017 data point is the population estimate following the 2016 earthquake.

The estimated number of pairs in both colonies in 2017 is 191 500 pairs, a reduction of 121 000 pairs from a decade earlier prior to the earthquake and an overall reduction of nearly 40% in the breeding population. This drop in breeding numbers is a consequence of shearwaters that were killed directly by the 2016 earthquake and birds that were displaced from the colonies due to the collapse of breeding burrows within the remaining sub-colonies. Estimating the proportion of birds within these two categories is difficult, however it is likely that all birds within areas of colony that were destroyed by major rock falls and landslips were killed directly when these areas were lost. Colony areas destroyed during the earthquake total 7.043 of habitat in Kowhai Valley and around 0.131 ha at Shearwater Stream (see Table 2) and based on the average density of burrows at these two colonies in 2007 (7411 burrows ha^{-1} and 5710 burrows ha^{-1}, respectively) and a burrow occupancy value of 70.5% then these areas would have contained around 40,000 incubating birds that would have been killed during the immediate impact of the 2016 earthquake. This figure takes no account of burrows that may have contained two birds due to pairs swapping over incubation shifts, nor does this figure account for empty burrows that will have resulted from any early breeding failures. These two factors will respectively increase and decrease the resulting mortality estimate, however as they cannot be estimated to any degree of accuracy they have been excluded from the above figure.

A further reduction in breeding numbers of birds in the colonies will have resulted from the drop in burrow densities following the earthquake and the shock and tremors from the 7.8 magnitude quake would have caused the collapse of considerable numbers of shearwater burrows within areas of habitat that were affected by the earthquake (but not destroyed or swept away). This reduction in burrow density (of around 30%; Table 3) would have been likely to have killed further numbers of incubating shearwaters that either suffocated or were otherwise trapped in their burrows, although an unknown proportion of birds are likely to have dug themselves out and escaped from these collapsed burrows. Under the very worst case scenario of no birds escaping, then the collapse of burrows may have caused the mortality of a further 80 000 breeding shearwaters. The actual number of breeding birds killed in this way may be considerably less than this figure, but this proportion is difficult to assess. Fieldwork in the Kowhai Valley in December 2017 did not provide any evidence for large numbers of partially buried or decomposing shearwater carcasses within burrows or sub-colony areas that were checked and visited, although burrows that had completely collapsed with birds in them may not have been found.

One potential way of understanding the potential losses of birds killed in this manner (trapped and killed in burrows in remaining colony areas, versus killed in colony areas that were directly destroyed) will be the mark re-sighting exercise planned for September 2018 as part of this wider study, as this will provide an independent assessment of the remaining number of breeding birds. The previous two assessments undertaken in this manner corroborate the results from monitoring within the breeding grounds (Figure 10) and therefore if the September 2018 survey returns a similar figure to twice the estimated number of breeding pairs estimated from the colonies in 2017 (191 550 pairs is about 380 000 breeding birds), then it is likely that around 120 000 birds were killed during the earthquake (i.e. about 40 000 birds killed in colony areas destroyed by the quake with about a further 80 000 birds killed within burrows in remaining areas of habitat). Alternatively, if the at sea estimate obtained in September 2018 is markedly higher than about 380 000 birds then this difference may give an indication of the number of breeding shearwaters that survived, despite the loss of their breeding burrows.

4.2 Future population trends and limits to recovery

Prior to the 2016 earthquake the remaining population of Hutton’s shearwater was considered to be stable and slowly increasing in size at an annual rate of 1.7% a year based on an increase in burrow densities recorded within both the Kowhai Valley and Shearwater Stream colonies (Cuthbert & Sommer 2009) and these results are borne out in the re-analysis of population numbers undertaken in this study (Figure 8). This slowly increasing population is occurring despite the fact that the species is now restricted to just two sites within its former breeding range due to the actions of feral pigs and that introduced stoats are present within the two remaining mountain colonies but are not having a major impact on the population (Cuthbert 2002; Cuthbert & Davis 2002b). These conclusions, particularly on the impact of stoats, are further verified by the high adult survival of shearwaters recorded within the Kowhai Valley colony and values of breeding success measured at both colonies that are within the same range as other shearwater species breeding in areas free from introduced predators[2] (Cuthbert & Davis 2002a). Further support for the limited impact of stoats on breeding success is provided by eight years of data (from 2008/09 to 2015/16 seasons) when stoat trapping was undertaken in Shearwater Stream and absent from the Kowhai Valley, and where average breeding success was very similar at both sites (61.1% and 57.8%, respectively) and annual variation in breeding success was highly correlated between both sites. The latter result suggests that inter-annual variation in environmental factors, such as at-sea feeding conditions, are a far more important driver of breeding success than the impact of stoats at the colonies (Sommer et al. 2009).

[2] Breeding success of Hutton’s shearwater in Kowhai Valley and Shearwater Stream averages 49.7 ± 18.4% (n = 20 years) and 49.9 ± 28.6% (n = 10), respectively, values that are nearly identical to a 32 year study of the Short-tailed shearwater *Puffinus tenuirostris* in a predator free environment where breeding success averaged 48 ± 18% (Wooler et al. 1992).

While fieldwork in the Kowhai Valley during December 2017 established that there had been loss of considerable areas of breeding habitat and reduction in burrow densities, it also revealed no other major changes in the colony. Despite initial concerns the most vulnerable access points to the colony remained unaffected by the earthquake and this site and Shearwater Stream remain relatively inaccessible to feral pigs as previously. This is of vital importance; as if pigs were able to now enter the sites the colonies and shearwaters would be at very high risk. Observations within the Kowhai Valley also revealed that other than the major rock fall and damage to sub-colony areas on the eastern flanks of Mt Saunders that the other sub-colonies were superficially undamaged and appeared almost untouched by the earthquake. These 'undamaged' colonies and remaining areas of the valley were nearly identical in habitat and species use of these areas in comparison with the authors' time in the valley in the late 1990s. The apparent stability of ecology and habitat include observations of high numbers of shearwaters within sub-colonies at night with birds coming in to swap incubation shifts and large numbers of courting and calling birds on the surface; the same network of chamois and deer tracks within the valley and the same placement of stoat scats on rocks and beneath boulders; the same distribution of scrub and tussock in the sub-colonies; and in many places the same location of 'poised' rocks and boulders as seen 20 years ago. The only apparent difference in ecology of the valley was the low numbers of kea *Nestor notabilis* seen in December 2017, with only two adult birds recorded during this visit, whereas in the late 1990s a group of 6–12 kea were regularly seen (although absent on some days), and this observation is most likely to mirror national declines in the kea population rather than be any direct consequence of the earthquake. In addition, numbers of deer and goats, in small herds of 4–6 animals, were seen in the valley during December 2017, matching observations from 2007 that deer numbers were higher than previously observed in the late 1990s (Cuthbert & Sommer 2009).

While anecdotal, the above observations suggest that despite the impact of the 2016 earthquake the situation for Hutton's shearwater within the Kowhai Valley colony is likely to be similar to before, and that the same underlying processes will be affecting the population. Thus, I would predict that stoats will continue to have a small impact on the overall population and that Hutton's shearwater will continue to have high adult survival and high values of breeding success. The latter point is suggested by one year of breeding data from the last (2017/18) season, where breeding success measured from 100 burrows in the Kowhai Valley was 71% and in the upper range of values previously observed (see Figure 8). Further monitoring is required to verify this and as well as monitoring breeding success future monitoring should include regularly repeating quadrat counts (at a minimum of five year intervals) to monitor burrow density at both sites.

Prior to the earthquake the population of Hutton's shearwaters was slowly increasing at a rate of around 1.7% a year (Cuthbert & Sommer 2009; Sommer et al. 2009). If the impact of stoats and other factors, such as at sea feeding conditions, are the same as before then I would predict that burrow densities (and by extension the breeding population) will start to slowly increase again within the two mountain colonies as the population recovers from the earthquake's impact and increases in size. Such an increase will depend on the remaining areas of habitat still being suitable breeding grounds for shearwaters within the colonies, with no irreversible substrate damage which has rendered the soil unusable for shearwater burrows. As described above, the remaining shearwater colonies appeared almost untouched in terms of their vegetation, soil structure and use by shearwaters, despite the measured decrease in burrow densities in comparison with 2007 levels. Shearwater were observed at night actively courting and digging new burrows, and the overall impression was of a healthy population of adult and immature birds engaged in the breeding and pre-breeding behaviours, and there appears to be no fundamental change in the remaining colony areas that has rendered them unsuitable.

If, as predicted, burrow density and the breeding population recovers to the densities recorded in 2007 then the remaining area of breeding habitat within Kowhai Valley and Shearwater Stream may support around 275 000 pairs (i.e. 550 000 breeding birds), after taking into account the 12% of breeding area destroyed by the 2016 earthquake. Based on this growth rate and these densities the population may reach this size after around 20–25 years (Figure 11), assuming no other major impacts on the breeding grounds and population.

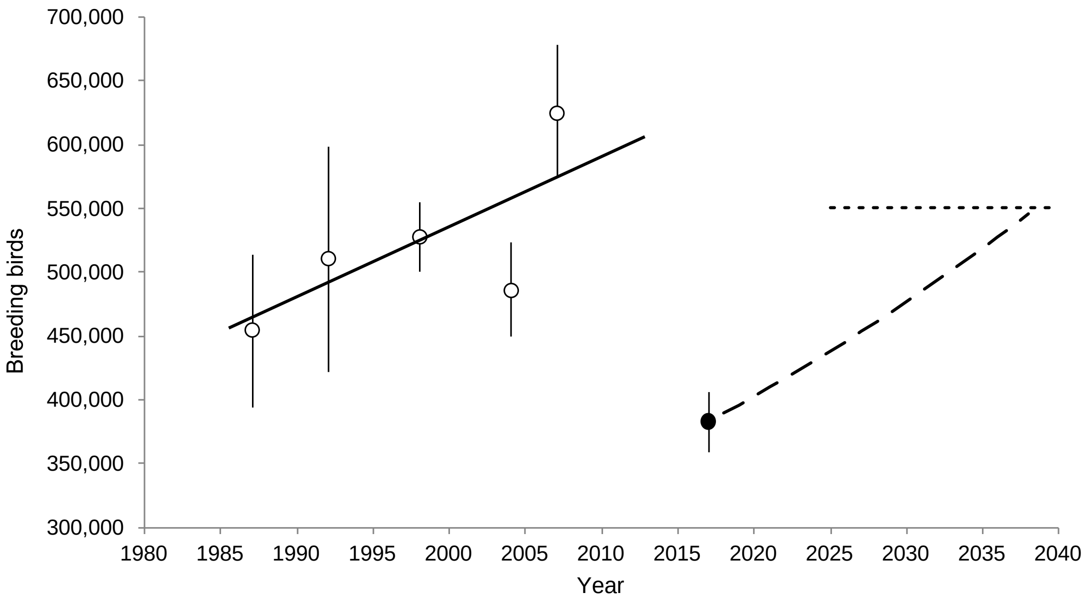

Figure 11: Schematic figure showing revised population estimates of Hutton's shearwaters at the two mountain colonies based on new calculations of colony area, burrow density and burrow occupancy (open circles) with the observed increase in the population from 1987 to 2007 (solid line), and the postearthquake population in 2017 (filled circle symbol) and a projected population growth rate of 1.7% a year (long-dashed line). The horizontal dashed line is the predicted population size if burrow densities reach the same levels as measured in the colonies in 2007.

While burrow densities and the breeding population of birds is predicted to increase, the ultimate factor that will limit the population and cause Hutton's shearwater to remain threatened is habitat availability, due to the limited areas of suitable habitat within the two remaining colonies and absence of alternative breeding localities (Cuthbert 2001; Cuthbert & Sommer 2009). Suitable areas of breeding habitat remain throughout the Seaward and Inland Kaikōura ranges, including within former colonies, however birds are unable to reoccupy these sites as the factor that caused their extirpation (feral pigs) is still present in these areas. Moreover, even if pigs were eliminated colonies of shearwaters would not be able to re-colonise because there would be no "safety in numbers" and these small colonies would suffer unsustainable predation rates from stoats (Cuthbert 2002). As a consequence, the limit to recovery for Hutton's shearwater is the extent of available habitat in the remaining two colonies which together may hold around 275 000 pairs if burrow densities recover to their 2007 level. In addition, the newly established Kaikōura Peninsula colony may eventually support up to a further 4000–6000 pairs, if this site reaches the burrow densities present within the mountain sites. Consequently, the total projected population of the species may be around 280 000 pairs at two vulnerable mountain sites (with the vast majority in one locality) and one small lowland locality.

5. MANAGEMENT IMPLICATIONS

Management options for Hutton's shearwater can be divided into those actions that are required within the species' remaining breeding colonies and the potential options for establishing new and further breeding sites, and these two topics are discussed in turn below.

Despite the impact of the 2016 earthquake the main areas of breeding habitat remain within both Kowhai Valley and Shearwater Stream, and over time the density of burrows and population of birds is predicted to increase. This prediction will need to be assessed over the coming years in order to ensure that population trends can be monitored and to ensure that no further unforeseen factors are impacting the species following the earthquake. Independent assessments of the population size through mark re-sighting of birds at sea should also be repeated in conjunction with on the ground monitoring, to provide an independent measure of population trends. It is recommended that such monitoring be undertaken every five years, as a minimum frequency. Ongoing monitoring of breeding success should be undertaken at both sites (safety permitting at Shearwater Stream) to ensure that this parameter remains within its normal range, while recognizing that there is a large degree of interannual variation in values. Previous reports (Cuthbert 2001) have recommended monitoring adult survival of Hutton's shearwater as well as breeding success, as the population is most sensitive to changes in survival (Cuthbert et al. 2001). Such an approach would require additional effort and the need to re-establish a marked population of birds and would take at least five years before a reliable survival figure could be estimated. Nonetheless it would provide a sensitive and early estimate of larger scale changes that may be affecting the population.

Of key importance for the survival of the species is the fact that the steep rock features and waterfalls on the boundaries of both colonies remain intact and the colonies remain difficult for feral pigs to access. If further reduction of the risk of pigs gaining access to the sites is desired, then efforts to hunt pigs on the boundaries of both colonies should continue along with maintenance and regular checks of the existing 'walk in' pig trap near the boundary of the Kowhai Valley. Similarly if reduced numbers of deer and goats are desired (important for reducing trampling damage in colony areas as was observed in December 2017 and also for preventing large numbers of deer or goats from making the colony areas more accessible for pigs by creating more open paths), then ongoing control of deer and goats within both colonies should be undertaken. Any deer and goat control in the colonies would be likely to have least secondary impacts in the spring and early summer rather than later in the season (ideally with culling completed by December), in order to avoid leaving non-decomposed carcasses in the colony which may act as a food source for stoats during the winter months[3.]. Evidence to date suggests that control of stoats within the mountain colonies has relatively little influence on shearwater breeding success; however there is no suggestion that this activity is detrimental and if resources permit it may have wider conservation benefits in the region.

As outlined in the introduction and discussion the ultimate factor likely to be limiting the current population of Hutton's shearwater is the number of remaining breeding colonies and the availability of habitat within these sites. Currently the species' is restricted to two vulnerable mountain sites and one small lowland locality, with 94% of the species' population occurring in less than 50 ha of suitable habitat within the Kowhai Valley. Earthquakes are a geological feature of New Zealand and over the coming 50 to 100 years there will almost certainly be other earthquake events within the Kaikōura region that may have further devastating impacts on the remaining breeding sites. As well as earthquakes, breeding sites could suffer other potential catastrophe events, such as the impact of a '100 year' avalanche within either colony. As with many other species the long term risk and threat to Hutton's shearwater will remain high, as long as the species remains restricted to a very limited number of small sites. Previous reports have recommended the establishment of further breeding colonies in order to secure the long-term future of Hutton's shearwater (Cuthbert 2001) and management interventions will be needed to establish further sites if this action is to proceed. Such an action has already been undertaken on the Kaikōura Peninsula where the translocation of about 100 chicks per year over four years has resulted in a small population becoming established within a fenced predator proof area. This population is growing slowly, including chicks fledged from the site now returning to breed, and the site held around 25 breeding pairs during the 2017/18 season. This successful translocation has been very important for verifying that the methods can work for this species, in refining techniques, and for increasing awareness and knowledge of the species with the Kaikōura community and more widely. The Peninsula colony remains highly important as a third breeding site for Hutton's shearwater, however the likely maximum total number of birds (about 4000– 6000 pairs) within the existing site remains too small to safeguard the species' future. Potential new sites for increasing and establishing new areas are listed in Table 5 and include one site on the boundary of the Kowhai Valley colony (see

[3] Stoat numbers in the shearwater colonies are limited by their territorial behaviour and the absence of food during the winter period, when surviving stoats are forced to scavenge on prey remains and over-winter mortality is likely to be high (Cuthbert et al. 2000; Cuthbert & Sommer 2002).

Appendix 3), as well as two potential completely new areas at Sandy Saddle (Mt Fyffe) and Mount Alexander. The former area in the Kowhai Valley already contains a few scattered shearwater burrows and is adjacent to a small area of burrowed ground (sub-colony 36) which has become established over the last 20 years (Cuthbert & Sommer 2009). Hutton's shearwaters may eventually colonise this adjacent area on their own accord, however the digging of 'starter burrows' (i.e. an approximately 30–40 cm deep tunnel) in the area and broadcasting shearwater calls from the site at night during September to December may encourage the more rapid settlement of this area. The other two potential new areas are recommended based on observations and quantification of the area of available habitat, likely or known proximity to existing shearwater flight paths (as new sites may 'pull in' non-breeding birds from the existing colonies), and crucially their accessibility and the ability to erect and maintain predator proof fencing which will be needed in the long-term or until there is step change in predator control within New Zealand. Details of these sites are laid out in Table 5 as well as images in Appendix 3 and Appendix 4. As well as these two sites there is also may be potential for establishing further breeding sites on the Kaikōura Peninsula in areas of suitable terrain and slope. Such an option could be considered as part of wider ecological restoration and conservation initiatives for the Kaikōura Peninsula, such as establishing the peninsula as a predator free area and supporting this as part of a long-term economic and biodiversity recovery plan for the region. Options for these potential sites will need to be developed in full and include careful evaluation of the feasibility and costs involved in providing accessibility to the site, constructing predator proof fencing, the time and costs of shearwater translocations, the long-term maintenance and upkeep of the sites and fencing, and the support of the wider community. This detailed evaluation is beyond the scope of this report, but is strongly recommended in order to secure the long-term safety of the species through establishing further and secure breeding colonies.

In summary, key recommendations for monitoring and management of Hutton's shearwater are to:

- Monitor population size and trends of the species through repeating established methods for measuring burrow density and colony areas in the breeding grounds in conjunction with repeating mark re-sighting methods at sea,
- Monitor breeding success of shearwaters within both colonies (if possible) and consider reestablishing measurements of adult survival,
- Ensure there are low numbers of feral pigs around the boundaries of the colonies through hunting and the maintenance and checking of walk in traps,
- Reduce deer and goat numbers within the two sites with culling taking place early in the year,
- Dig starter burrows and set up a speaker system to encourage birds into non burrowed areas on the boundary of the existing Kowhai Valley colony,
- And, undertake a comprehensive and costed assessment on the potential for establishing new and large-scale shearwater breeding colonies in the Kaikōura region.

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APPENDIX 1 GLM model results

Table A1: Results for a Generalized Linear Model (GLM) on the density of burrows within quadrats and covariates, indicating the model, number of parameters (K), Akaike's Information Criterion (AICc), difference between current and top model (Delta AICc), relative likelihood of the model (Mod Weight), cumulative model weight (Cum Weight) and maximised value of the loglikelihood function (LL).

Model	K	AICc	Delta AICc	Mod Weight	Cum Weight	LL
Sub-colony + Vegetation	17	1826.86	0.00	0.48	0.48	-895.35
Aspect	8	1828.89	2.02	0.17	0.65	-906.20
Sub-colony + Aspect	20	1828.90	2.03	0.17	0.82	-892.94
Sub-colony	16	1829.42	2.55	0.13	0.95	-897.75
Sub-colony + Altitude	17	1831.47	4.61	0.05	1.00	-897.65
Vegetation	3	1843.60	16.74	0.00	1.00	-918.86
Altitude	3	1845.58	18.72	0.00	1.00	-919.76
Null Model	2	1847.31	20.45	0.00	1.00	-921.63

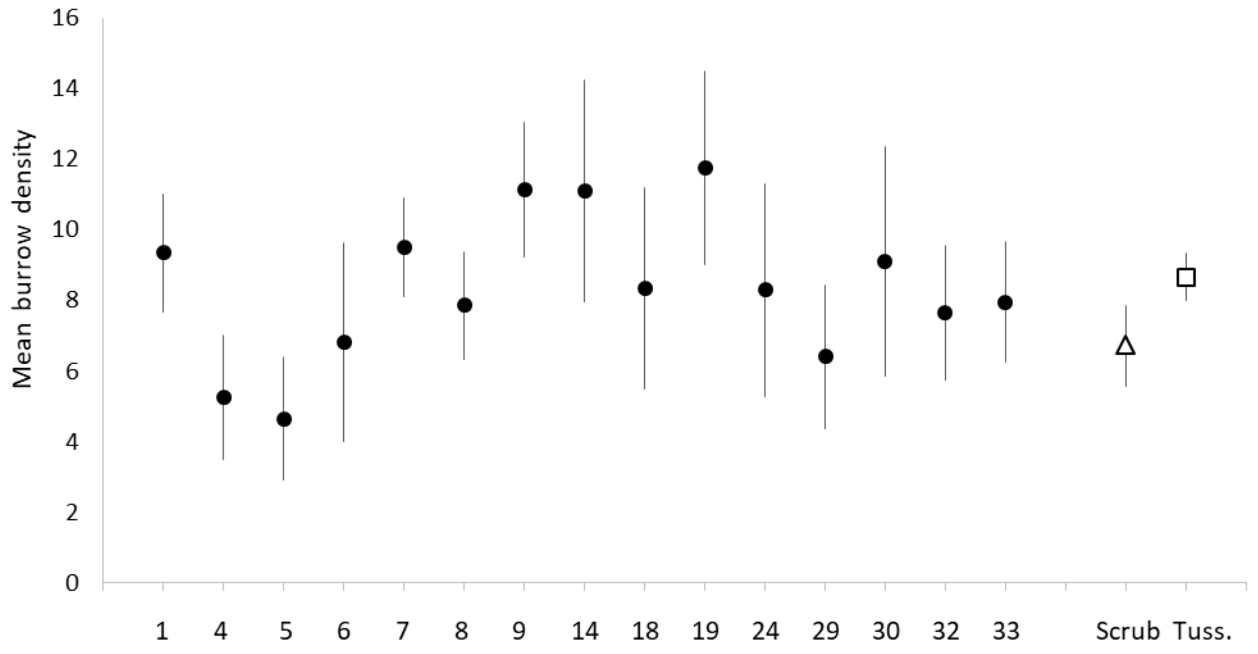

Figure A1: Mean burrow density within 4 × 4m quadrats during the 2017 field season for each of the 15 sampled sub-colonies (round filled symbols with sub-colony numbers labelled on the X axis) and overall mean density in scrub (unfilled triangle symbol) and tussock (unfilled square symbol) vegetation types. Error bars are 95% confidence intervals.

APPENDIX 2 Images of earthquake damage

Figure A2: Further mages of the extent of the major rock avalanche in the Kowhai Valley indicating the magnitude of the slip. The top image and insert shows the dead areas of *Hoheria* scrub presumed to have been destroyed by the wind blast from the rock 'avalanche'.

APPENDIX 3 Aerial images of potential new colony areas

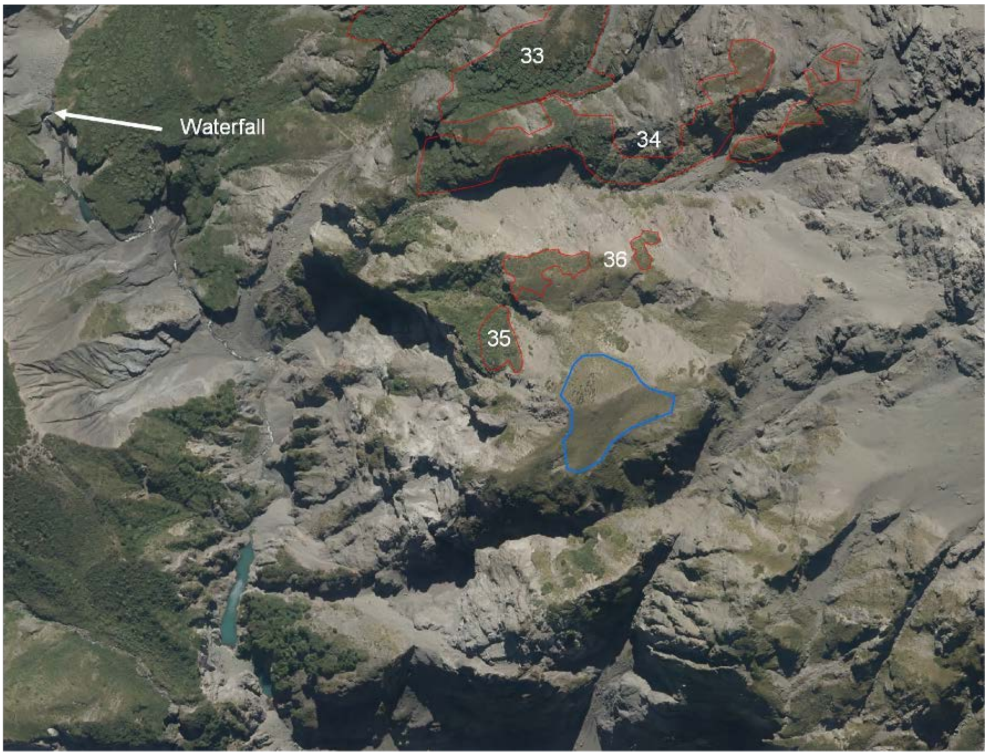

Figure A3a: Imagery of the lower reaches of the Kowhai Valley colony showing the potential new area of shearwater habitat (blue line), along with sub-colony numbers and the main waterfall.

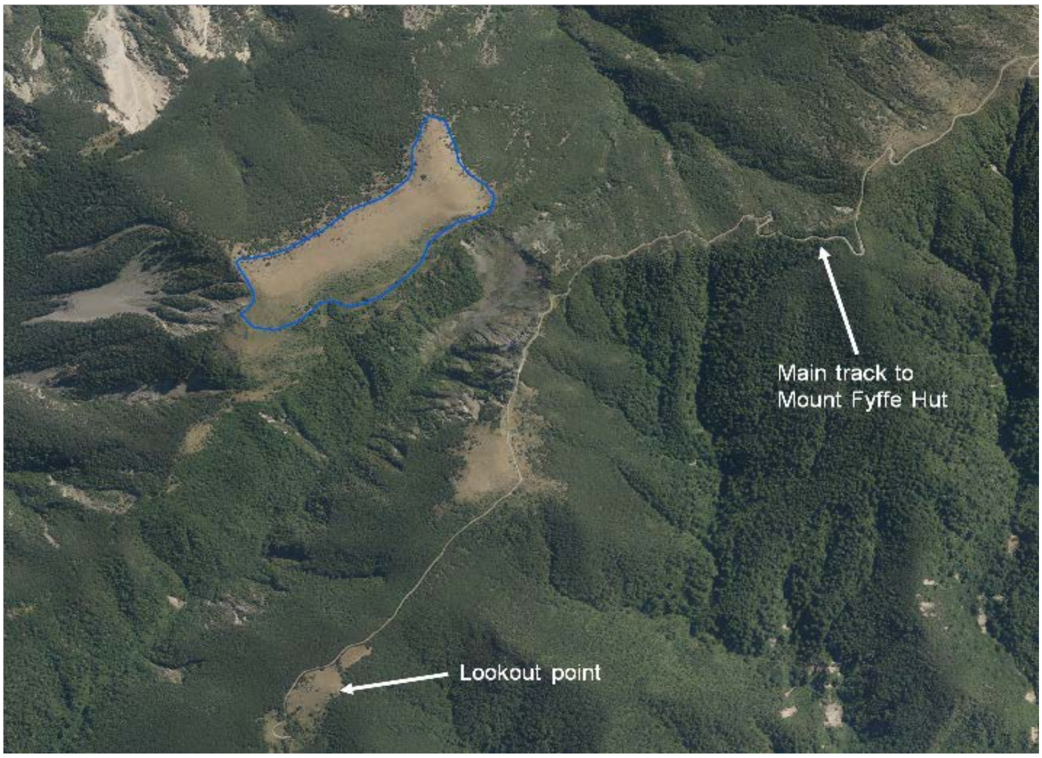

Figure A3b: Imagery of the potential Sandy Saddle area (blue line) on Mt Fyffe.

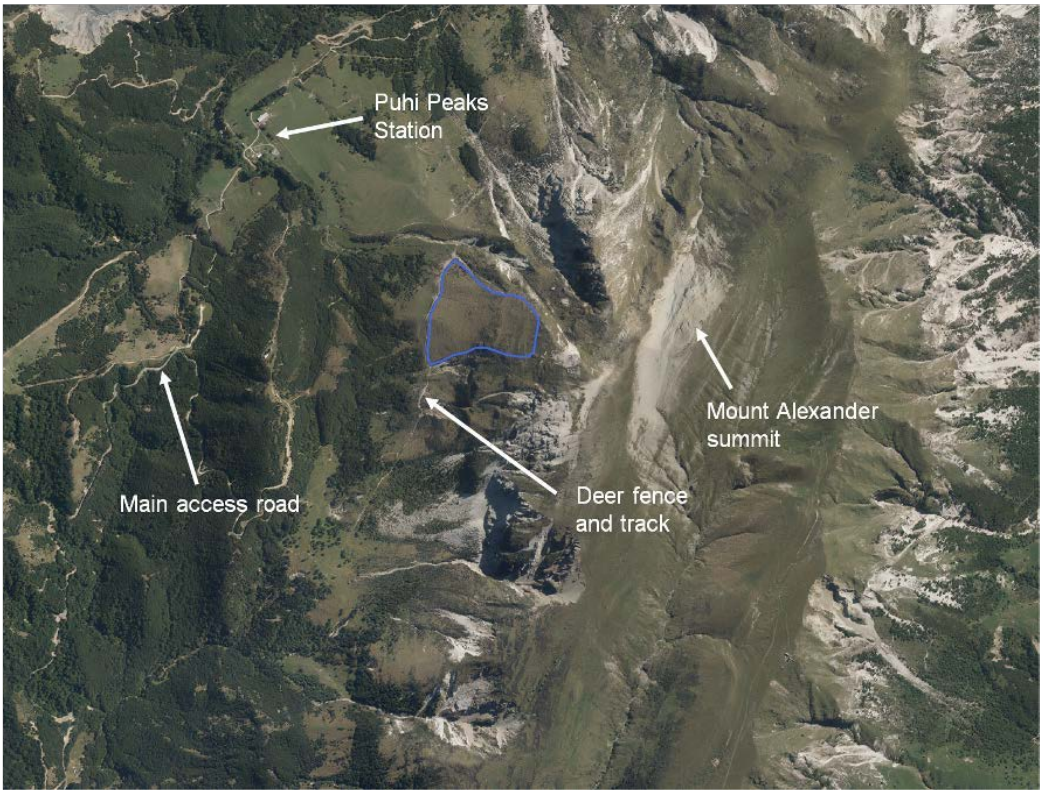

Figure A3c: Imagery of the potential Mount Alexander area (blue line) near the Puhi Puhi Station

APPENDIX 4 – Photos of Sandy Saddle and Mount Alexander areas

Figure A4a. Photographs of Sandy Saddle, from high up on Mt Fyffe, indicating the general area and tussock habitat. Mount Manakau (with snow) at the head of the Kowhai Valley shearwater colony is visible in the bottom image and the site is on the shearwater's flight path.

Figure A4b. Photographs of the north western slopes of Mount Alexander and tussock habitat present. The potential colony area is on the sloping tussock areas in the left central mid region of the upper photograph.