Review of current and future predicted distributions and impacts of Bennett's and dama wallabies in mainland New Zealand

Final Report

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Executive Summary

This study summarised the historical and current distributions of Bennett’s wallaby (*Macropus rufogriseus*) and dama (or tammar) wallaby (*M. eugenii*) in mainland New Zealand. Based on these distributions, we estimated rates of spread and predicted distributions at 5, 10, 20 and 50 years into the future. We also estimated suitable habitat for Bennett’s wallaby in the South Island and dama wallaby in the North Island. Finally, we reviewed wallaby impacts and, where possible, derived economic costs associated with their impacts. This economic valuation focused on (1) impacts to agricultural production values and (2) natural capital assessed through ecosystem services (the only two impacts for which there are some data) under the following scenarios: (a) status quo of low or no control, (b) widespread remedial control, in which control occurs after wallabies have spread into a future predicted distribution, and (c) defensive control for containment, in which wallabies are intensively managed around the periphery of the current distribution (i.e. the invasion front).

At present, it is estimated that Bennett’s wallabies occupy c. 5322 km^2 in the South Island (centred on the Hunters Hills, South Canterbury); however, the large number of confirmed sightings and animals shot outside this area suggest that they may currently occupy as much as 14 135 km^2. Based on current estimated rates of spread, the distribution of Bennett’s wallaby in 50 years is likely to be between 9621 km^2 and 20 631 km^2, but possibly as large as 44 226 km^2. The last value includes known illegal liberations and represents almost one-third of the South Island or an increase of 700% with respect to the current known distribution.

At present, it is estimated that dama wallabies occupy c. 2050 km^2 in the North Island (centred on the Rotorua lakes in Bay of Plenty); however, the large number of confirmed sightings and animals shot outside this area suggest that they may currently occupy as much as 4126 km^2. Based on current estimated rates of spread, the distribution of dama wallaby in 50 years is likely to be between 3265 km^2 and 11 070 km^2, but possibly as large as 40 579 km^2. This last value represents more than one-third of the North Island or an increase of 1700% with respect to the current known distribution.

Habitat suitability models suggest that high- to moderate-densities of wallabies are likely to occur throughout the New Zealand mainland, if allowed to spread. Models predict that the primary areas from which they will be absent are high elevations, urban areas, and high production exotic grassland (e.g. dairy).

Wallabies in mainland New Zealand impact agriculture by competing with livestock for pasture species and consequently reduce stocking rates of livestock. They can also foul pasture, damage fences, destroy agricultural crops, contribute to erosion, and browse/kill seedlings of some plantation forest species. Both species, but particularly dama wallabies, have been shown to have significant unwanted impacts on native vegetation, especially preventing the regeneration of most palatable native plant species and reducing plant diversity. Anecdotally, vehicle collisions with wallabies may be problematic in areas with high vehicle use and high wallaby numbers (although this is currently believed to be minor), and collisions may increase if wallabies extend their ranges. Currently, wallabies appear to pose little risk to human or animal health.

The current total gross annual economic benefit of avoiding the impacts of Bennett’s wallaby in the South Island were estimated to be c. $23.7 million (which includes c. $22.2 million in avoided lost revenue to agriculture and c. $1.5 million to ecosystem services and natural

capital). If Bennett’s wallabies were allowed to spread without any active management, we estimated that the total gross annual economic benefit of avoiding their impacts in 10 years would increase to c. $67 million. If widespread remedial control was applied to reduce their densities within their predicted distribution in 10 years, the avoided lost revenue would be c. $27.7 million. This suggests that there is a large net benefit (c. $39.3 million) of doing management to control their unwanted impacts as opposed to doing nothing (i.e. status quo/no control). The net benefit of containing Bennett’s wallabies would be even greater. That is, intensive widespread control and surveillance within a containment buffer would cost c. $6.2 million. This represents one-third the expenditure and revenue lost if wallabies were allowed to expand for 10 years and then controlled ($18 million), or one-seventh the revenue lost if wallabies were allowed to expand in the absence of management ($43.4 million).

The current total gross annual economic benefit of avoiding the impacts of dama wallaby in the North Island was estimated to be c. $4.2 million (which includes c. $1 million in avoided lost revenue to agriculture and c. $3.2 million to ecosystem services and natural capital). If dama wallabies were allowed to spread without any active management, we estimated that the total gross annual economic benefit of avoiding their impacts in 10 years would increase to c. $16.5 million. If widespread remedial control was applied to reduce their densities within their predicted distribution in 10 years, the avoided lost revenue would be c. $11.4 million. This suggests that there is a net benefit (c. $5.1 million) of doing management to control their unwanted impacts as opposed to doing nothing (i.e. status quo/no control). As for Bennett’s wallaby, the net benefit of containing dama wallabies would be even greater. That is, intensive widespread control and surveillance within a containment buffer would cost c. $3.4 million. This represents half the expenditure and revenue lost if wallabies were allowed to expand for 10 years and then controlled ($8.6 million), or one-third the revenue lost if wallabies were allowed to expand in the absence of management ($12.3 million).

The current total gross annual benefit of avoiding the impacts of wallabies to agriculture and ecosystem services on mainland New Zealand is c. $28 million. If they are allowed to expand, the annual benefit of avoiding their impacts is predicted to increase to c. $83.5 million in 10 years (2025). Clearly these benefits will be much larger if estimated at periods beyond 10 years; however, the uncertainty of these long-term estimates would be so large (due to unpredictable changes in land uses and market trends) they would likely be highly unreliable.

There is an obvious net benefit to controlling wallabies, particularly with the intention of containing them to prevent impacts to areas that could become invaded. Regional councils affected by wallabies have attempted to contain them to delineated containment areas. This has not been entirely successful, because new populations of both Bennett’s and dama wallabies have been detected well outside current containment areas. Furthermore, illegal liberations outside containment areas have resulted in a number of established populations, adding to the complexity of the wallaby expansion problem. New surveillance and detection tools and further information relating to biological knowledge gaps, applied within an appropriate control or eradication framework, may help to halt current wallaby range expansions.

1 Introduction

Five species of wallabies have been present in New Zealand for over 140 years, with extant populations centred on South Canterbury, the Rotorua lakes, and Kawau Island. Since their initial releases, some species have increased in numbers and distribution and, similar to the situation in parts of their native range in Australia (Di Stefano 2004), they have had unwanted impacts in invaded areas (Warburton 2005a, b). In New Zealand, impacts to agriculture, plantation forests, and indigenous vegetation have been reported as being of greatest concern (Warburton 2005a, b). This report updates the status of the two wallaby species that occur on mainland New Zealand, Bennett's wallaby (*Macropus rufogriseus*) and dama (or tammar) wallaby (*M. eugenii*) and our subsequent use of the term wallaby refers to these two species, not the other three species that occur on Kawau Island.

In South Canterbury, South Island, Bennett's wallaby has been recognised as an agricultural pest since the 1940s (Warburton 1986). They compete with domestic livestock for food (McLeod 1986), foul pasture, and damage agricultural crops (Warburton 1986). Bennett's wallaby also damage plantation forests, native scrub and tussock habitats, and prevent the regeneration of palatable plant species within indigenous forests (Warburton 1986). Since the 1950s, various agencies – starting with the Department of Internal Affairs, then the New Zealand Forest Service, and followed by the South Canterbury Wallaby Board – have been tasked with reducing the unwanted impacts of this species (Choquenot & Warburton 2006; Warburton et al. 2014).

A similar history exists for dama wallaby in the Bay of Plenty, North Island. This species prefers pasture–forest margins, but is well suited to living in forest interior, particularly compared to Bennett's wallaby (Williamson 1986; Warburton 2005a). Dama wallaby can damage pasture and may travel up to c. 500 m through forest to feed on pasture (Williamson 1986). They also occasionally browse young plantation forest species (e.g. *Pinus radiata*); however, of far greater importance are the impacts that their browsing has on indigenous vegetation in native forests (Knowlton & Panapa 1982; Williamson 1986; Llewellyn 1988a). Serious attempts to curb the impacts of dama wallaby in the Rotorua district started in the early-1960s with the use of aerial 1080 operations covering all land tenures (Warburton 1986). Subsequent control was restricted to rateable land, and comprised spotlight shooting and occasional use of 1080 poison carried out by the local pest destruction board (Warburton 2005a). The Department of Conservation (DOC) has also carried out two aerial control operations targeting dama wallabies (Llewellyn 1988b).

Wallaby populations are currently being actively managed by Environment Canterbury, Bay of Plenty Regional Council, and Waikato Regional Council (as this region is also becoming increasingly invaded by dama wallabies). It is important to note, however, that it is not just affected regions that include wallabies in their Regional Pest Management Plans (RPMP), but also regions that do not currently have wild populations of wallabies. These plans have objectives to keep wallabies at low abundances, prevent spread outside containment areas, and eliminate isolated populations outside these areas. The responsibility for wallaby control on private land lies with the landowner and, if necessary, this is imposed through rules in RPMPs. Notably, regional councils issue 'notices of compliance' to landowners when wallaby numbers on their properties are assessed and found to be too high.

Despite management efforts, wallabies continue to persist (sometimes at high densities) within the containment areas delineated within Canterbury and Bay of Plenty, and have progressively expanded out of these areas (Warburton 2005a, b). Bennett's wallabies have crossed the Waitaki River at the southern edge of their currently designated containment area and are thought to have established a low density breeding population on the south side of that river, an area which includes the northern part of Otago Region (Warburton et al. 2014). Similarly, sightings and known or suspected breeding populations of dama wallaby continue to emerge from outside the containment area, and well into the Waikato Region (Bay of Plenty Regional Council and Waikato Regional Council, unpubl. data). The impacts of these expansions on agriculture, the environment, and possibly other values are not known, but could be significant.

2 Objectives

Because of concern about the potential spread of wallabies and uncertainties about their impacts, the Ministry for Primary Industries (in collaboration with regional councils affected by wallabies on mainland New Zealand) requested Landcare Research to do the following:

- Summarise the historical and current distributions of Bennett's wallaby and dama wallaby and, based on these distributions, estimate rates of spread and predict future distributions (these analyses assumed control that is insufficient to contain populations).
- Identify suitable habitat for Bennett's wallaby in the South Island and dama wallaby in the North Island to provide an overall 'picture' of what areas within each island might ultimately be occupied by wallabies.
- Based on current and future distributions, provide a quantitative assessment of the current (2015) and future (2025) estimated benefit of avoiding the impacts caused by Bennett's and dama wallabies to agricultural production values and natural capital assessed through ecosystem services. Insofar as is possible, this analysis will account for the impacts of sympatric introduced herbivores. This analysis yields the gross annual benefit of avoiding wallaby impacts in the presence of current levels of control/management intervention.
- Estimate the cost of broad-scale control of wallabies in current (2015) and future (2025) predicted distributions (i.e. widespread remedial control) and determine if there is a net benefit of controlling them for agricultural production values and natural capital and ecosystem services.
- Compare the costs associated with the 'widespread remedial control' scenario with those associated with preventing spread from their current distribution (i.e. a 'defensive control for containment' scenario), and then estimate which scenario yields the greatest benefits. That is, to clarify which of these two scenarios is likely to be the most cost-effective method of managing wallabies.
- Provide a qualitative/descriptive assessment of other potential impacts caused by wallabies and, if possible, estimate the costs of those impacts.
- Identify significant knowledge gaps that might (a) improve management for remedial control, containment or eradication and (b) improve estimates of the economic valuation of the impacts of wallabies.

3 Methods

3.1 Wallaby distributions

Historical and current distributions for Bennett's wallaby and dama wallaby are based on qualitative and quantitative surveys conducted by Environment Canterbury (also see Warburton et al. 2014) and Bay of Plenty Regional Council, respectively (Figures 1 and 2).

We used empirical estimates of natural rates of spread to predict future distributions of wallabies under two scenarios, 'best-case' and 'worst-case'. The best-case scenario used the 'known distribution' of breeding populations in North and South islands and is based on current distributional polygons delineated by councils. The worst-case scenario used the numerous confirmed sightings and kills (excluding extreme outliers, which were assumed to have resulted from illegal liberations, i.e. human-assisted spread as opposed to natural spread) from outside the known distribution to delineate current distributional polygons and assumes that these polygons represent 'probable distributions' of breeding populations. It may be particularly important to use the boundary of the probable distribution as a starting point for predicting future distributions, because this is likely to include individuals dispersing at the invasion front (e.g. Lindström et al. 2013). These individuals likely occur at low numbers, making it difficult to detect them, and thus they are likely to be omitted from the known distribution. As has been shown for cane toads (*Rhinella marina*; Lindström et al. 2013), this omission may massively underestimate actual rates of spread at the leading edge of the invasion front because estimates are based on residents, not dispersers. Accordingly, we use the terms 'known distribution' and 'probable distribution' to differentiate between these in the sections below.

We used the most recent estimates of natural rates of spread (as opposed to historical ones) to predict future wallaby distributions because these estimates are derived under a level of control that is likely to be sustained (if not intensified) in the future. However, it is important to note that these control efforts often occur within the centre of wallaby distribution, where their numbers, and thus their impacts, are highest. Control within some areas of the invasion front is likely to result in lower rates of spread, but this is likely to be variable around the front. In summary, if future distributions were modelled using rates of spread in the absence of any control efforts, both the estimated rates of spread and future distributions would be larger than predicted in this report.

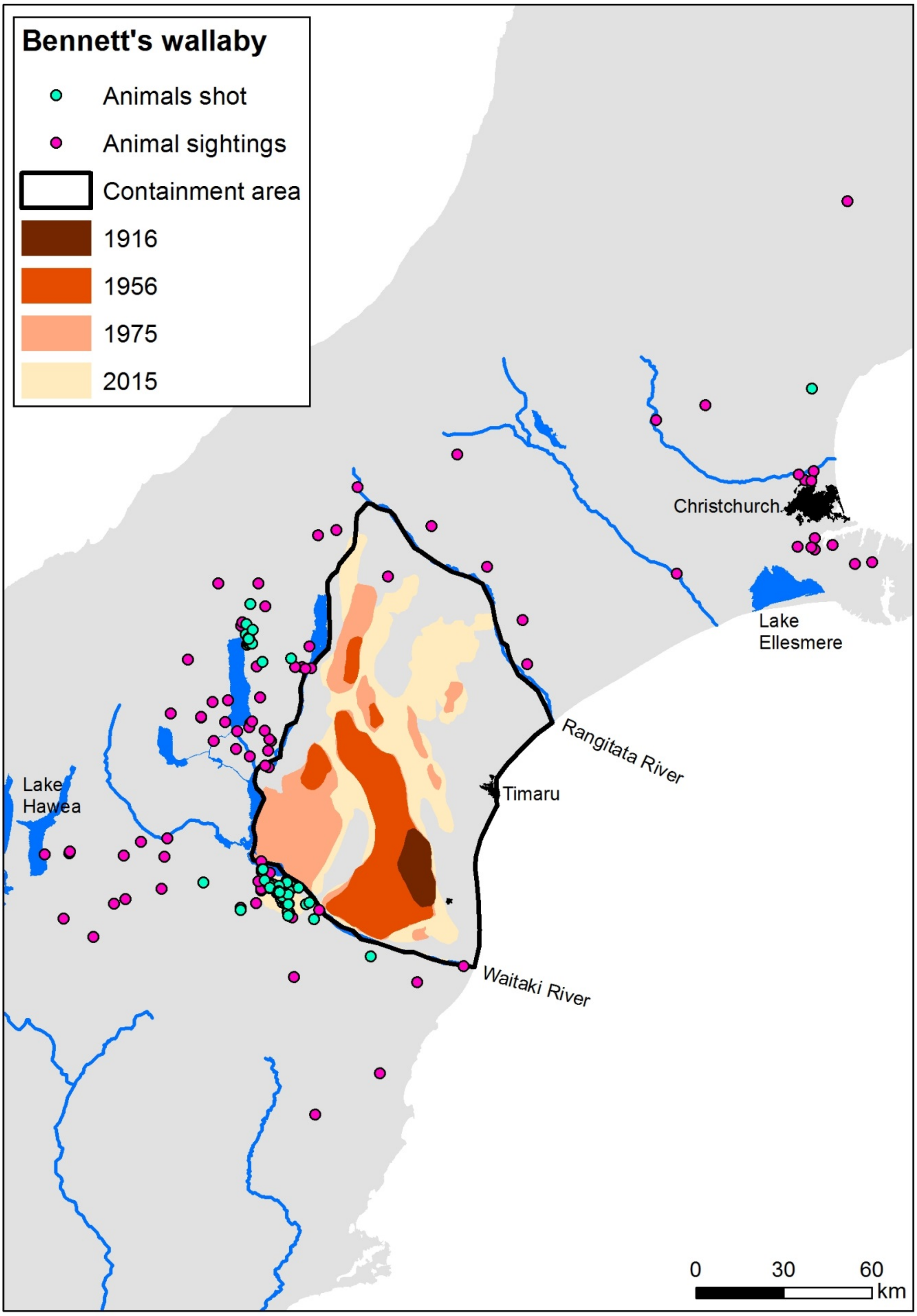

Figure 1: Historical and current distribution and confirmed sightings and kills (since 2000) of Bennett's wallabies in South Island, New Zealand.

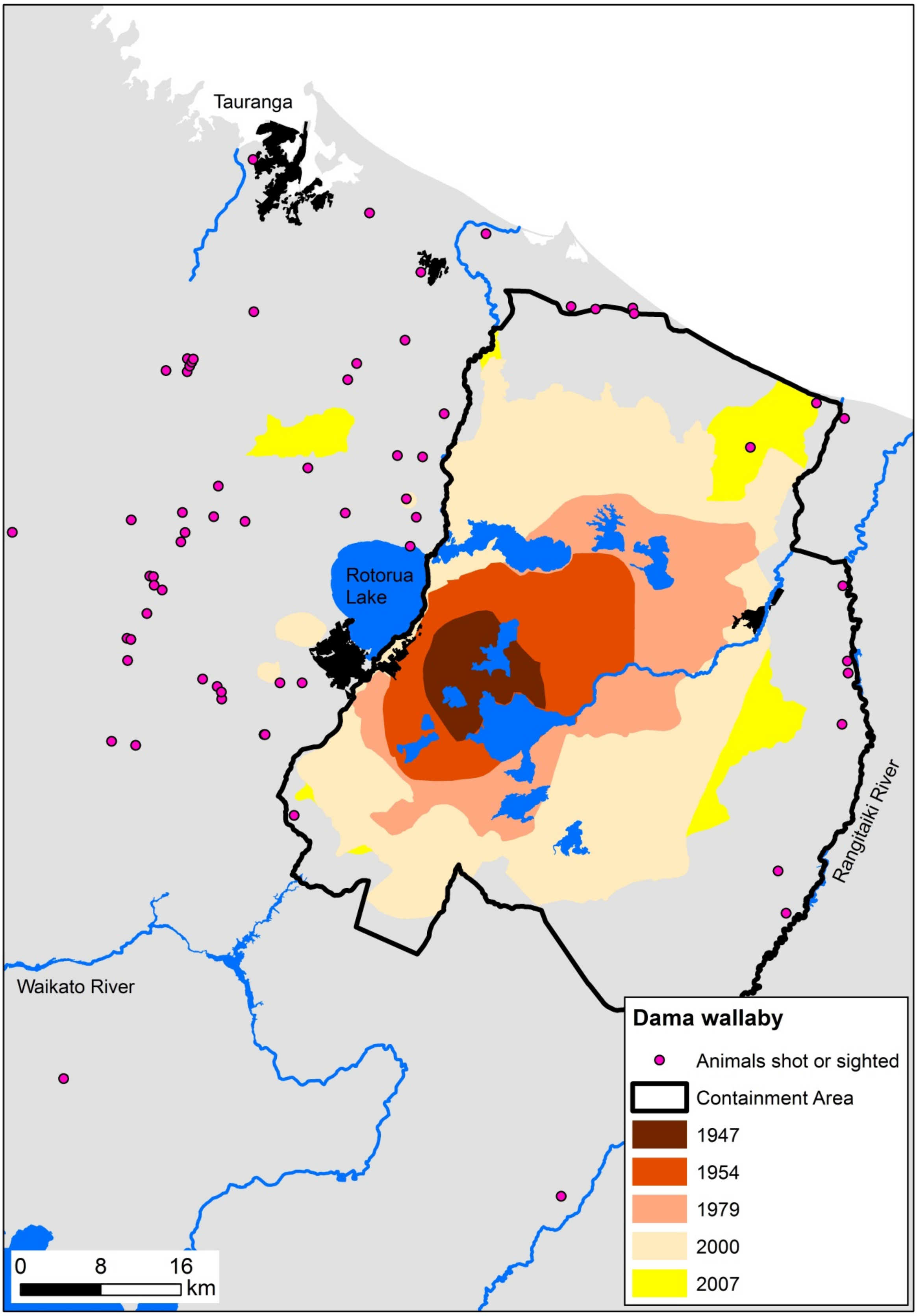

Figure 2: Historical and current distribution and confirmed sightings and kills (since 2000) of dama wallabies in North Island, New Zealand.

3.1.1 Bennett’s wallaby, South Island

We calculated natural rates of spread (m/yr) for Bennett’s wallaby for each of the three time periods for which we have been provided with ‘known distributions’: 1916–1956, 1956–1975 and 1975–2015 (Figure 1). Rate of spread for the period 1916–1956 was estimated by calculating the straight-line distance between the polygon boundaries depicting these two time periods. Because wallaby range expansion does not occur at the same rate around the polygon boundaries, we used 3154 points located at 100-m intervals along polygon boundaries to sample the distance between the two polygons. This provided a mean (and distribution) of the rate of spread for Bennett’s wallabies from 1916–1956. This was repeated for the 1956–1975 and 1975–2015 time periods using 5211 and 8228 sampling points, respectively. We assumed that the polygon at the northern end of Lake Pukaki resulted from an illegal liberation and so did not use it to estimate natural rates of spread (but we did include it in our predictive models, see below). The summary statistics for natural rate of spread based on the known distribution are presented in Table 1.

We predicted range expansion from the known distribution using two scenarios (see the two values highlighted bold, ‘known distribution’, Table 1) to represent a more conservative and a less conservative future distribution:

1. First quartile annual rate of spread estimated from 1975–2015 (16.5 m/yr) and using the 2015 polygon boundary as the starting range.
2. Third quartile annual rate of spread estimated from 1975–2015 (181.7 m/yr) and using the 2015 polygon boundary as the starting range.

Table 1: Bennett’s wallaby natural rates of spread (m/yr) for known and probable distributions, South Island, New Zealand. We estimate best-case (known distribution) and worst-case (probable distribution) rates of spread (see descriptions in Methods).

Period	No. of years	Minimum	1st quartile	Median	Mean	3rd quartile	Maximum
			Known distribution				
1916–1956	40	0.3	318.8	697.3	727.8	1067.0	1703.5
1956–1975	19	0.2	27.2	244.9	396.0	620.5	1555.3
1975–2015	40	0.0	16.5	61.3	122.5	181.7	647.5
			Probable distribution				
1975–2015	40	178	353.5	515.0	609.0	827.8	1232.5

We used 265 reported wallaby sightings and kill locations from Canterbury and Otago to construct a 95% kernel density estimator (KDE), and used this polygon as a ‘worst-case’, current ‘probable distribution’. This estimate excluded locations around Lakes Hawea and Wanaka, south-west of the Hawkdun Range and north of the Rakaia River, because it is thought that these resulted from illegal liberations rather than from natural spread (G. Sullivan, Environment Canterbury, pers. comm.). As was done for the known distribution, we constructed a distribution of rates of spread by calculating the straight-line distance from 4884 points on the 2015 worst-case boundary (i.e. the 95% KDE) to the nearest point on the 1975 boundary. The summary statistics for natural rate of spread based on the probable distribution are presented in Table 1.

We predicted range expansion from the probable distribution using two scenarios (see the two values highlighted bold, ‘probable distribution’, Table 1) to represent a more conservative and a less conservative future distribution:

1. First quartile annual rate of spread estimated from 1975–2015 (353.5 m/yr), but using the 2015 probable distribution boundary (as estimated from 95% KDE around sighting and kill locations) as the starting range.

2. Third quartile annual rate of spread estimated from 1975–2015 (827.8 m/yr), but using the 2015 probable distribution (as estimated from 95% KDE around sighting and kill locations) as the starting range.

All four scenarios (two for the known distribution and two for the probable distribution) were run for 5, 10, 20 and 50 years to estimate Bennett’s wallaby distribution at each of those time periods.

To include biological realism in the modelling process, we constructed layers that biased rates of spread using a geographic information system (GIS). These included a ‘barrier to movement’ layer that completely prevented the extension of the range polygon. The features that we included in this barrier layer included the South Island main divide; major rivers (Waitaki, Rakaia, Rangitata, Clutha, and Waimakariri); man-made canals in the Canterbury High Country; large lakes (Tekapo, Pukaki, Benmore, Ohau, Wanaka, Aviemore, Hawea, Coleridge, and Wakatipu); and large towns. However, we allowed spread to occur through this barrier layer at bridges and dams, (i.e. wallabies could extend their distribution beyond some barrier features) but it was biased towards and slowed by crossing features (Figure 3). In addition to hard barriers, we also included a semi-permeable barrier for mountain ranges (excluding the main divide which we assumed was a hard barrier) ≥1500 m a.s.l. This layer allowed wallaby range expansion to occur across these high elevations, but the rate of spread was set at half that of elevations below 1500 m a.s.l. That is, we assumed that bluffs, scree slopes, a high terrain ruggedness index, and sparse vegetation associated with higher elevations would slow but not prevent wallaby spread.

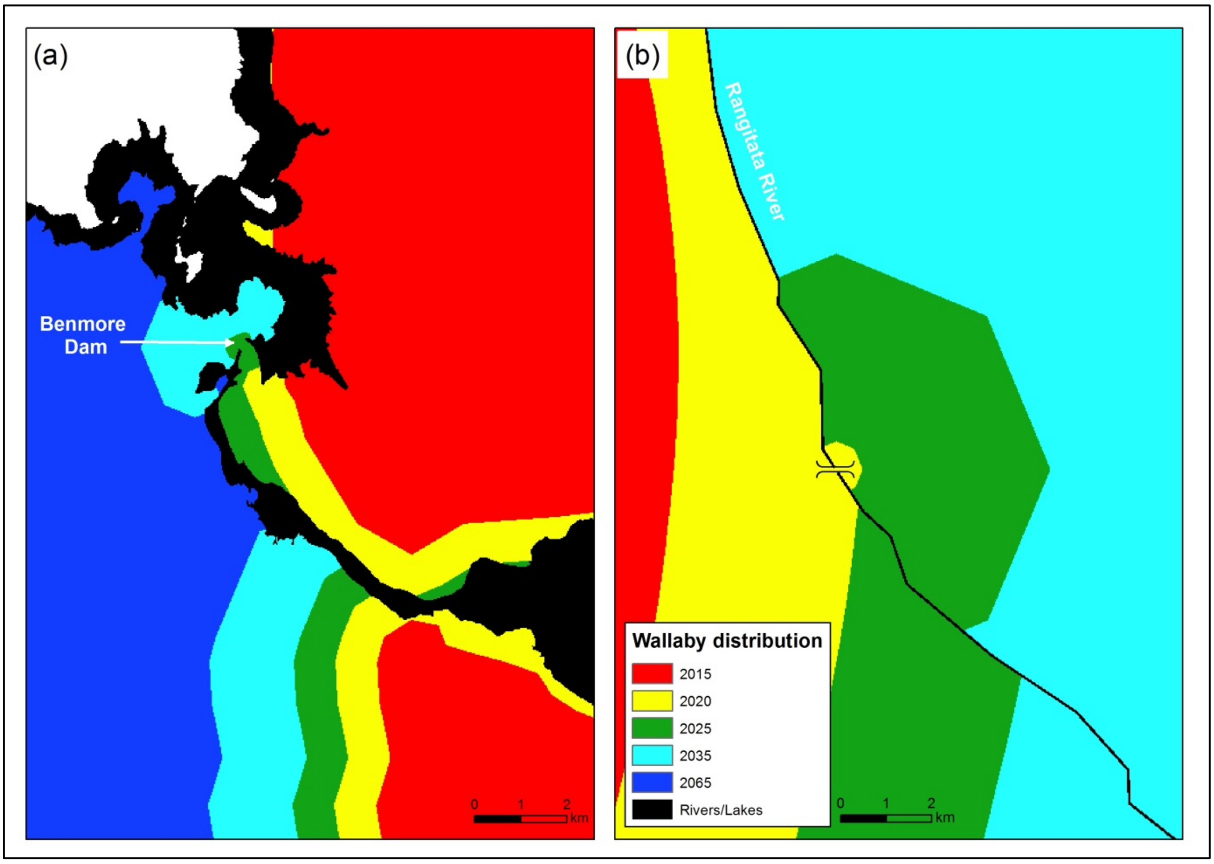

Figure 3: Two examples of how we biased spread in our models to restrict the range expansion of Bennett's wallaby at hard barriers (e.g. lakes and large rivers). We allowed wallaby range expansion to occur at structures that enabled wallabies to cross these features, e.g. (a) dams and (b) man-made bridges.

We did not include habitat biases in our range expansion modelling for Bennett's wallabies, but rather assumed that individuals could disperse through all habitats other than those associated with the hard and semi-permeable barriers described above. This assumption results in a future predicted distribution (i.e. first-order selection; Johnson 1980) that may include both good and poor quality habitat for Bennett's wallaby, a pattern that is realistic for most species. That is, this analysis predicts geographic range boundaries at four future time periods, not habitat preferences or associated wallaby densities within future invaded areas (see Habitat suitability model below for estimated wallaby habitat preferences).

Finally, we used recent confirmed sightings and kills (Figure 1) that occurred distally to the area included in the 95% KDE analysis to estimate the possible impact of illegal liberations on the future distribution of Bennett's wallaby. We assumed that illegal liberations in North Otago District, northern Queenstown Lakes District, northern Central Otago District, southern Mackenzie District, Banks Peninsula, and the Ashley Forest and Mount Oxford areas had resulted in established breeding populations. The total area of the 2015 KDE and the area occupied by illegally-liberated wallabies was 15 229 km^2. Using this area, we predicted future distribution at 5, 10, 20 and 50 years using the less conservative rate of spread from the probable distribution (third quartile, 827.8 m/yr).

3.1.2 Dama wallaby, North Island

We calculated natural rates of spread (m/yr) for dama wallaby for each of the four time periods for which we have been provided with estimated ‘known distributions’: 1947–1954, 1954–1979, 1979–2000 and 2000–2007 (Figure 2). To do this, we used the same methods described for Bennett’s wallaby in the South Island. The summary statistics for natural rate of spread based on the known distribution are presented in Table 2.

We predicted range expansion from the known distribution using two scenarios (see the two values highlighted bold, ‘known distribution’, Table 2) to represent a more conservative and a less conservative future distribution:

1. First quartile annual rate of spread estimated from 2000–2007 (3.1 m/yr) and using the 2007 polygon boundary as the starting range.
2. Third quartile annual rate of spread estimated from 2000–2007 (92.9 m/yr) and using the 2007 polygon boundary as the starting range.

Because there has not been a recent (2015) update for the distribution of dama wallabies, we had to project expansion from the 2007 polygon boundary, using first and third quartile natural rates of spread from 2000–2007 (i.e. cells highlighted bold, ‘known distribution’, Table 2), to estimate the 2015 boundaries from which we then modelled the 5, 10, 20 and 50 year future distribution scenarios.

Table 2: Dama wallaby natural rates of spread (m/yr) in the North Island, New Zealand. We estimate best-case (known distribution) and worst-case (probable distribution) rates of spread (see descriptions in Methods).

Period	No. of years	Minimum	1st quartile	Median	Mean	3rd quartile	Maximum
			Known distribution				
1947–1954	7	246.7	521.7	657.9	821.6	1057.6	1857.1
1954–1979	25	0.5	84.1	192.0	191.5	273.4	523.6
1979–2000	21	0.8	160.8	300.2	312.9	450.9	773.3
2000–2007	7	0.0	**3.1**	3.5	117.4	**92.9**	976.9
			Probable distribution				
2007–2015	8	22.3	**592.9**	1106.6	1398.8	**1981.3**	3883.8

We used 82 reported wallaby sightings and kill locations from Bay of Plenty and Waikato to construct a 95% KDE, and used this polygon as a ‘worst-case’, current (2015) ‘probable distribution’. As was done for the known distribution, we constructed a distribution of rates of spread by calculating the straight-line distance from 5882 points on the 2015 worst-case boundary (i.e. the 95% KDE) to the nearest point on the 2007 boundary. The summary statistics for natural rate of spread based on the probable distribution are presented in Table 2.

We predicted range expansion from the probable distribution using two scenarios (see the two values highlighted bold, ‘probable distribution’, Table 2) to represent a more conservative and a less conservative future distribution:

1. First quartile annual rate of spread estimated from 2007–2015 (592.9m/yr), but using the 2015 probable distribution boundary (as estimated from 95% KDE around sighting locations) as the starting range.
2. Third quartile annual rate of spread estimated from 2007–2015 (1981.3 m/yr), but using the 2015 probable distribution (as estimated from 95% KDE around sighting locations) as the starting range.

All four scenarios (two for the known distribution and two for the probable distribution) were run for 5, 10, 20 and 50 years to estimate dama wallaby distribution at each of those time periods.

To include biological realism to the modelling process, we constructed layers that biased rates of spread using GIS. These included a ‘barrier to movement’ layer that completely prevented the extension of the range polygon. The features that we included in this barrier layer were guided by Williams (1997) and included major rivers (Waikato, Wairoa, Kaituna, Rangitaiki, Tarawera); large lakes (29 in total, including the Rotorua lakes, Taupo, and Karapiro); and large towns. However, we allowed spread to occur through this barrier layer at bridges and dams (i.e. wallabies could extend their distribution beyond some barrier features), but it was biased towards and slowed by crossing features. As was done for Bennett’s wallaby, we also included a semi-permeable barrier for mountain ranges ≥1500 m a.s.l. for dama wallaby (this primarily included the Central Plateau and Kaimanawa Mountains).

Because dama wallabies prefer pasture/forest margins (Williamson 1986), there has been speculation that they might avoid intensive, high production exotic grassland (e.g. dairy) with no or minimal cover. However, it is unclear whether this agricultural land presents a hard barrier to their movement or would induce more rapid movement rates (and potentially higher rates of population spread) in search of more suitable habitat. This question requires data on dama wallaby habitat selection and movement patterns in relation to land use. It also requires fine-scale landcover data that captures potential movement corridors through, for example, dairy farms, such as hedgerows, riparian corridors, and other patches of scrub and forest. Currently, the landcover datasets available do not capture this level of detail and thus we were precluded from modelling the influence of dairy farms and associated movement corridors on wallaby rates of spread. We acknowledge that this might result in future predicted distributions that include some habitats unsuitable for dama wallabies. Consequently, we calculated the area of flat to rolling (<100 m a.s.l.), high production exotic grassland, assuming that this comprised mostly dairy farms and, based on this, provide an estimate of the percentage of land within the 2065 worst-case scenario distribution that might be unsuitable for dama wallabies. Additionally, we estimated dama wallaby habitat preferences for the entire North Island using a habitat suitability model (see Habitat suitability model below).

We did not estimate the possible impact of illegal liberations on their future distribution of dama wallaby because the worst-case scenario resulted in a distribution that already included all extreme outlying observations of that species.

3.1.3 Habitat suitability model

We identified potentially suitable habitat for Bennett’s wallaby and dama wallaby using Maxent 3.3.3 (Phillips et al. 2006). Maxent is a program for modelling species distributions from presence-only species records, and has been shown to perform as well, or better than, other methods for modelling these kind of data (Elith et al. 2006). In addition to presence data, Maxent uses a number of randomly selected points (called ‘pseudo-absences’), which are then combined with biophysical covariates to construct an index of habitat suitability for each cell ranging from 0 (least suitable habitat) to 1 (most suitable habitat). Presence-only data for each wallaby species were obtained from regional councils and DOC as incidental sightings or locations where animals had been shot. These sightings were located outside the known distributional ranges (Figures 1 and 2); thus, we sampled 300 locations for each species within their current range polygons to depict presence within their current ranges. For Bennett’s wallaby, we also incorporated the locations of 27 pellet transects surveyed since 1993 and a further 11 transects surveyed since 2008, all of which have had wallaby sign recorded. These data provided us with a total of 631 and 349 presence-only records for Bennett’s wallaby and dama wallaby, respectively.

We identified 14 biophysical variables as potentially important predictors of wallaby distribution in New Zealand (Table 3). These variables were generated from three different datasets: LENZ (Leathwick et al. 2003), LCDB v4.1 (www.lcdb.scinfo.org.nz), and a digital elevation model (DEM) of New Zealand. All these datasets were in raster format except for LCDB, which was converted to a 25-m resolution raster prior to analyses. Biophysical variables were collected within 1 km^2 cells; this cell size was chosen as a compromise between estimates of home range size for wallabies in New Zealand (Bennett’s wallaby: no published data; dama wallaby: c. 0.4 km^2) and a practical unit size for conducting field surveys.

Table 3: Biophysical covariates used in modelling habitat suitability for Bennett’s and dama wallabies using Maxent.

Layer	Source	Source pixel (m)
Average annual temperature (°C)	LENZ	100
Average elevation (m)	DEM	25
Average slope (°)	LENZ	100
Distance to cover (m)	LCDB	25
Distance to river (m)	LCDB	25
Minimum temperature of coldest month (°C)	LENZ	100
Percent agriculture in flat areas (0–100 m asl)	LCDB	25
Percent cover (forest, shrubs, tall tussock)	LCDB	25
Percent forest	LCDB	25
Percent pasture/grasses	LCDB	25
Percent pasture/grasses in hill and high country (>100 m asl)	LCDB	25
Percent shrubs	LCDB	25
Percent urban	LCDB	25
Percent water	LCDB	25

Model performance was assessed by determining how well the model discriminates between unsuitable and suitable habitat over a range of thresholds. To do this, we estimated the area under the receiver operating characteristic curve (ROC-AUC), which represents the probability that a randomly chosen presence site will be ranked as more suitable than a randomly chosen pseudo-absence site (Fielding & Bell 1997). A model with AUC = 0.5 performs no better than random, whereas a model with AUC = 1 has perfect discrimination. An additional measure of performance is the regularised training gain, which describes how much better the Maxent distribution fits the presence data compared to a uniform distribution.

3.2 Wallaby impacts

We estimated the economic value of the impacts caused by Bennett's and dama wallabies, primarily to primary industries but (insofar as possible) also to natural capital assessed through ecosystem services (i.e. there have been no attempts to assign a monetary value to natural capital other than through their ecosystem services). We worked with council experts to determine appropriate values for control and surveillance costs and to account for the impacts of sympatric herbivores on natural capital. This analysis represents a first attempt to understand the total potential economic benefits of avoiding the impacts caused by wallabies. It may be necessary to conduct a more detailed cost/benefit analysis to underpin decisions on control strategies.

Using information about the economic value of the impacts caused by wallabies and per hectare costs of wallaby control, we estimate the cost of doing nothing (or more correctly, the status quo of insufficient control to prevent their spread, which we define as 'no control') versus the cost of widespread remedial control (i.e. control that occurs after wallabies have expanded and which aims to reduce their abundance within an invaded area). To do this, we apply a per hectare cost of control to the distribution of a wallaby species for a snapshot in time, we then estimate the annual cost of the impacts that control avoids within that distribution, and calculate the net benefit based on the difference between these two values. We also compare the costs associated with the 'widespread remedial control' scenario with those from a 'defensive control for containment' scenario (i.e. preventing spread from their current distribution), and estimate which scenario yields the greatest savings (or smallest financial loss). Because there are insufficient (or no) data from New Zealand to estimate population responses following control, we were unable to estimate the annual economic value of the impacts of wallabies over a control period (i.e. the period of time from initial knockdown to recovery to pre-control densities). Additionally, determining how the value of an ecosystem service affected by wallaby impacts recovers over a control period is, given the current lack of data, purely speculative.

Although wallabies may impact other values, we did not include them in the economic valuation because of a lack of data. However, we provide a short summary describing other potential impacts of wallabies in New Zealand based primarily on Warburton's reviews and references therein.

3.2.1 Bennett's wallaby, South Island

We base the estimated value of the impacts caused by Bennett's wallaby to primary industries on a reduction in sheep equivalents and assume that this also reflects relative reductions in beef cattle, dairy and crop production. We used Warburton and Frampton's (1991) estimate that the dry matter intake of 3.8 Bennett's wallabies is equivalent to one ewe. This ratio is based on an analysis of diet preferences that showed that the two species did not differ significantly in the food consumed and concluded that both species were non-selective grazers (McLeod 1986). We assumed an average density of 0.15 wallabies/ha in high productivity pasture (i.e. dairy and intensive crop production; classified as flat to rolling land) and 2 wallabies/ha in hill and high country. The latter value is lower than the >2–3/ha reported by Warburton (2005b) and aims to capture spatial variability in intensity of control (i.e. none to high). We assigned a lower density estimate to flat to rolling land based on the understanding that this is poorer quality habitat for wallabies and they are more easily detected and killed in this habitat compared to scrub covered hill country (Warburton & Frampton 1991). We followed Morris (2013) and assigned values of stock units per hectare (where one stock unit equals one breeding ewe) of 14, 7.5, and 0.7 in flat to rolling, hill country, and high country regions, respectively. This assumes that all farmers are maximising their stocking rates. We delineated flat to rolling, hill country, and high country regions within a GIS assuming elevations of 0–100 m, 101–300 m, and >300 m, respectively. We applied a live weight value of $100 per ewe, which is a rough average for the gross revenue from meat and wool per sheep stock unit, which has fluctuated between $65–$118 in the hill country since 2006 (Beef and Lamb New Zealand; http://www.beeflambnz.com/information/on-farm-data-and-industry-production/sheep-beef-farm-survey/nsi/). Thus, for one hectare of hill country for example, the stock units would be reduced from 7.5 to 7 (i.e. 3.8 wallabies equal 1 ewe or 0.5 ewe equals 2 wallabies) and a gross revenue loss of $50 would be incurred.

We present the estimated economic value of avoiding the impacts caused by Bennett's wallaby to primary industries for agricultural production landscapes within the known current distribution (5322 km^2) and the predicted future distribution (based on the 2015 probable distribution) in 10 years (i.e. 2025; 17 444 km^2; Table 4), assuming current market values. The 2025 estimate represents the likely revenue loss for primary industries in 10 years if current management does not prevent wallaby spread from the containment area (i.e. it is the future revenue loss from doing nothing). We compare this estimate with that of a widespread remedial control scenario. To do this, we assumed that wallabies will be controlled only on hill and high country agricultural land at a per hectare cost of $15 (which is an approximate average for all accepted control methods at current market value (e.g. Choquenot & Warburton 2006), and that this control will achieve a reduction to a density of 0.2 wallabies per hectare (i.e. achieving a 90% reduction in wallaby numbers; Warburton 1990). We assumed that no wallaby control was required on flat to rolling country because the density of wallabies there was already below the threshold for control.

The impacts of Bennett's wallaby extend beyond agricultural production landscapes. They damage seedlings in plantation forests (usually within 50–100 m of the bush edge; Warburton 1986), native vegetation, and are expected to impact some ecosystem services other than those related to agricultural production landscapes. However, estimating the economic value of avoiding the impacts that wallabies or any other invasive species have on ecosystem services is complex and often constrained by a lack of data (e.g. Costanza et al. 1997; Patterson & Cole 2013). Further, disentangling the impacts of wallabies from those of sympatric browsing and grazing mammals (domestic livestock, wild deer (*Cervus elaphus* and *Dama dama*), feral pigs (*Sus scrofa*), brushtail possums (*Trichosurus vulpecula*), hares (*Lepus europaeus*), and rabbits (*Oryctolagus cuniculus*)) is difficult (Warburton & Frampton 1991). Nevertheless, we provide a rough estimate of the economic value of wallaby impacts to relevant ecosystem services by using the benefit transfer values presented by Patterson and Cole (2013) for New Zealand's land-based ecosystems.

Based on findings that show that wallabies at high numbers can impact soils and native vegetation (McLeod 1986; Warburton et al. 1995), the ecosystem services that we included in our calculations were (1) erosion control and sediment retention and (2) cultural services (i.e. aesthetic, educational, and scientific opportunities provided by ecosystems such as native tussock, scrub and forest). We used the values from Tables 5 (scrub ecosystems), 7 (forest–scrub ecosystems), and 8 (forest ecosystems) in Patterson and Cole (2013) to produce a combined economic value of ecosystem services from land dominated by native scrub and native and plantation forests (i.e. habitats used by wallabies). This combined value was corrected to account for the area of each of these ecosystems within the known current distribution and the 2025 future predicted distribution of Bennett's wallaby. Further, we assumed that impacts to ecosystem services by wallabies and other sympatric herbivores only reduced the economic value of that service by half. In this sense, we acknowledged that invasive herbivores do not completely destroy a given ecosystem service, and that they may provide benefits to society via ecosystem services related to recreation, such as recreational hunting and aesthetic value (i.e. some people enjoy seeing them) (Patterson & Cole 2013).

To account for the impacts of sympatric herbivores on ecosystem services, we made a number of assumptions. Domestic livestock are mostly absent from native scrub and forest ecosystems, and thus we excluded them from our analyses. The impacts of hares (because of their low density) are minor compared to wallabies (Warburton & Frampton 1991) and thus were excluded from our analyses. Brushtail possums do not directly contribute to erosion but do impact cultural values. Conversely, rabbits, particularly at high densities, contribute to erosion (Lough 2009), but we assumed their impacts to shrub and forested habitats were negligible compared to wild deer, feral pigs, brushtail possums, and wallabies. Thus, for erosion control and sediment retention services, we assumed relative impacts of rabbits (0.5) > feral pigs (0.3) > Bennett’s wallabies (0.1) = wild deer (0.1). For cultural services provided by native scrub and forested habitats, we assumed relative impacts of Bennett’s wallabies (0.24) = wild deer (0.24; because of perceived comparatively low densities in this area; Nugent & Asher 2005; Nugent & Fraser 2005) = feral pigs (0.24) = brushtail possums (0.24) > rabbits (0.04). Finally, we compare the loss in the economic value of ecosystem services due to wallaby impacts with the cost of their control in natural ecosystems; for the latter we assumed a cost of control of $15/ha (Choquenot & Warburton 2006) and that once reduced to low densities, wallabies have negligible impacts on ecosystem services.

We compared the net benefit of remedial control of wallabies within the area invaded from 2015 to 2025, with the net benefit of intensive control and surveillance at the current invasion front (i.e. defensive control for containment). We based this analysis on the 2015 and 2025 distributional boundaries derived from the 95% KDE and a third quartile rate of spread (827.8 m/yr). We did not consider the impacts or management costs of wallabies within the 2015 boundary in this analysis, but rather focused on control and surveillance costs and avoided impacts within the ‘donut’ resulting from the expansion of wallabies from 2015 to 2025. We assumed that management aimed at containment occurred within a 5-km buffer around the 2015 boundary and was more expensive on a per hectare basis than remedial control within the wider 2015–2025 ‘donut’. That is, we applied per hectare costs of $25 for intensive control plus $500 per person per day for surveillance of every 500 hectares (or $1/ha; G. Sullivan, Env. Canterbury, pers. comm.) and assumed that these costs resulted in residual wallaby densities that were sufficiently low to prevent dispersal from the containment area.

Finally, we performed a simple probabilistic risk assessment to compare, in relative terms, the four distributional scenarios we simulated (Lindley 1985). To do this, we estimated the total revenue lost from agriculture and impacts to ecosystem services of each predicted wallaby distribution in 10 years under the status quo of low or no control). We then estimated risk as the ratio of the revenue lost under each scenario relative to that of the worst-case scenario (2015 probable distribution as a starting polygon and fast rate of spread). This estimates the level of certainty managers ought to have regarding a given scenario to justify not planning for the worst-case scenario and thus risk having to incur its associated revenue loss.

3.2.2 Dama wallaby, North Island

We used the same approach to estimate the economic value of the impacts caused by dama wallaby as we did for Bennett's wallaby; however, we parameterised calculations based on our understanding of the impacts caused by dama wallaby to habitats within their North Island distribution. First, we assumed that dama wallabies are on average one-third the weight of a Bennett's wallaby (Williamson 1986), and thus 11.4 dama wallabies are equivalent to one ewe. Because there are no estimates of density for dama wallabies (Warburton 2005a), we assumed a density of 0.15 wallabies/ha in high productivity pasture (i.e. dairy and intensive crop production; classified as flat to rolling land) and 2 wallabies/ha in hill and high country (as was done for Bennett's wallaby; Warburton 2005b).

We present the estimated economic value of avoiding the impacts caused by dama wallaby to primary industries for agricultural production landscapes within the 2015 distribution (2051 km^2, based on third quartile rate of spread from the 2007 known distribution; Table 5) and the predicted future distribution in 10 years (i.e. 2025; 8649 km^2; Table 5), assuming current market values. We used the same per hectare costs of control and estimate of percentage kill used for Bennett's wallaby (also see Williams 1997).

We estimated the economic value of avoiding dama wallaby impacts to ecosystem services (erosion control and sediment retention and cultural) using the information provided in Patterson and Cole (2013). We used the same set of assumptions as for Bennett's wallaby to account for the impacts of sympatric species; however, we altered the weight given to the impacts of sympatric herbivores based on known or suspected impacts by each species within dama wallaby range. Thus, for erosion control and sediment retention costs, we assumed relative impacts of feral pigs (0.3) = wild deer (0.3) > rabbits (0.25, i.e. the region is less rabbit prone than the area occupied by Bennett's wallaby; Allen et al. 1995; Lough 2009) > dama wallabies (0.15). For cultural opportunities provided by native scrub and forested habitats, we assumed relative impacts of wild deer (0.3) = brushtail possums (0.3) = feral pigs (0.3) > dama wallabies (0.1) (based on values presented in Llewellyn 1988a and Williams 1997).

We used the same methods as described for Bennett's wallabies to assess the benefits associated with the widespread remedial control scenario relative to those of a defensive control for containment scenario, but using the predicted distribution in 2025 based on the probable current distribution and third quartile rate of spread (1981.3 m/yr). Similarly, we performed a simple probabilistic risk assessment for dama wallabies following the same methods described for Bennett's wallabies (Lindley 1985).

4 Results

4.1 Wallaby distributions

4.1.1 Bennett's wallaby, South Island

The predicted distributions (based on five time periods) of Bennett's wallaby in the South Island are shown in Figure 4 and Table 4. Currently, they occupy c. 5322 km^2. Assuming a slow (and arguably overly conservative) rate of spread (16.5 m/yr) estimated using the known distribution (Table 1), the distribution is predicted to increase by c. 500 km^2 over 50 years (i.e. a 10% increase, Figure 4a). Assuming a third quartile rate of spread of 181.7 m/yr, the distribution is predicted to increase by c. 4300 km^2 (i.e. an increase of 80% compared to the 2015 estimate, Figure 4b).

Table 4: Predicted distributions (km^2) of Bennett's wallabies at five time periods using four different estimates of rate of spread (RS, in m/yr) and three different current range polygons. Note: current range polygons (2015) were derived from empirical data as opposed to modelled using rates of spread.

Year	2015 'known distribution'		2015 'probable distribution'		2015 'probable distribution', with illegal liberations
	1st quartile (RS = 16.5)	3rd quartile (RS = 181.7)	1st quartile (RS = 353.5)	3rd quartile (RS = 827.8)	3rd quartile (RS = 827.8)
2015	5322	5322	14 135	14 135	15 229
2020	5395	5947	14 925	15 949	18 328
2025	5443	6477	15 703	17 444	21 529
2035	5553	7434	17 018	20 257	28 048
2065	5883	9621	20 631	28 447	44 226

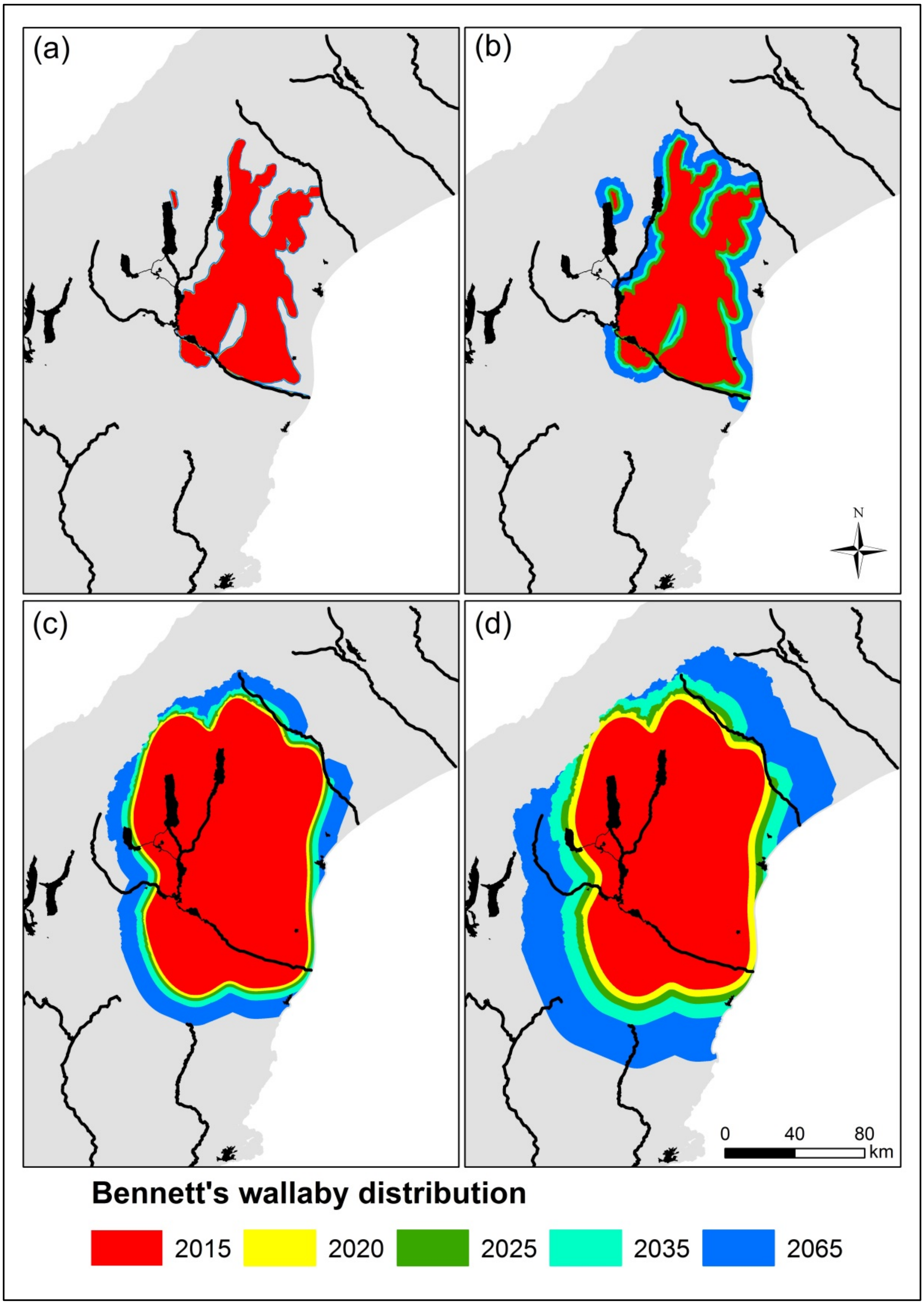

Figure 4: Predicted distributions of Bennett's wallaby in South Island, at five time periods using four different estimates of rate of spread. (a) and (b) use the estimated 'known distribution' from 2015 as the starting point for wallaby spread and these expand using either (a) the first quartile annual rate of spread (16.5 m/yr) or (b) the third quartile annual rate of spread (181.7 m/yr). (c) and (d) use the estimated 'probable distribution' from 2015 (estimated from a 95% KDE around confirmed sighting and kill locations) as the starting point for wallaby spread and these expand using either (c) the first quartile annual rate of spread (353.5 m/yr) or (d) the third quartile annual rate of spread (827.8 m/yr).

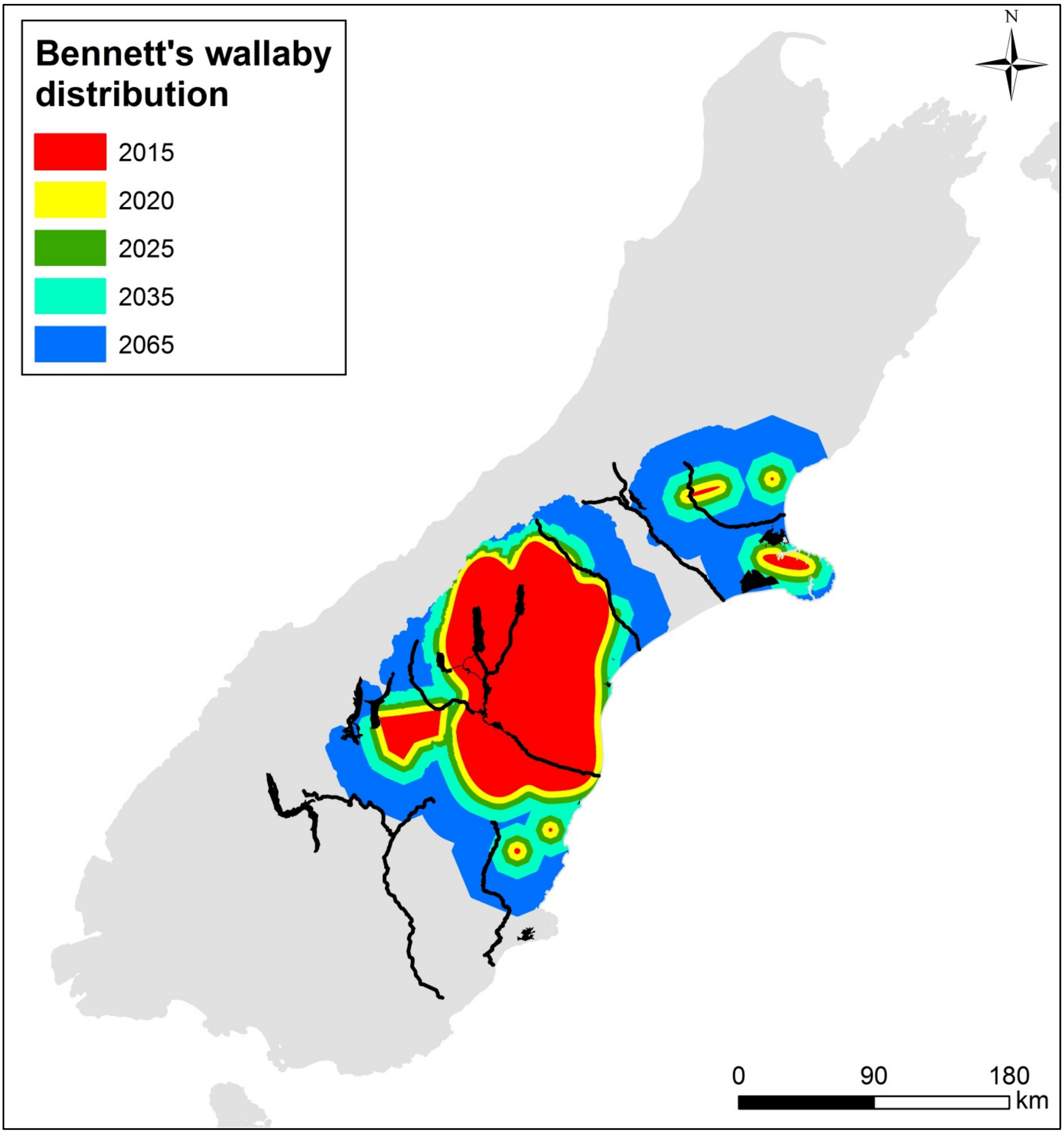

Figure 5: Predicted distributions of Bennett's wallaby in South Island at five time periods. These predictions use the estimated 'probable distribution' from 2015 as the starting point for wallaby spread, but also include confirmed sightings from six locations outside the 'probable distribution' that are believed to have originated from illegal liberations. We expanded probable and illegally liberated distributions using the third quartile annual rate of spread (827.8 m/yr). The map shows that, assuming illegal liberations establish, wallaby range expansion will occur far more rapidly compared to a solely natural spread scenario.

The current probable distribution is 14 135 km2, which is almost three times larger than the known distribution (Figure 4, Table 4). Based on the probable distribution, wallaby range over the next 50 years is predicted to increase to 20 631 km2 assuming a slower rate of spread (353.5 m/yr; Figure 4c) or to 28 447 km2 assuming a faster rate of spread (827.8 m/yr; Figure 4d).

Incorporating illegal liberations into estimated distributions at 5, 10, 20 and 50 years resulted in large predicted range expansions in northern Otago and mid-Canterbury (Figure 5, Table 4). The distribution in 50 years under this scenario is predicted to be 44 226 km2 or 55% larger than under the maximum (28 447 km2) predicted by a solely natural spread scenario.

4.1.2 Dama wallaby, North Island

The predicted distributions (based on five time periods) of dama wallaby in the North Island are shown in Figure 6 and Table 5. As of 2007, dama wallabies occupied c. 1864 km^2 in the North Island. Projecting the 2007 known distribution to 2015 (using the first quartile rate of spread, 3.1 m/yr) resulted in a negligible increase in wallaby distribution (total of c. 1865 km^2). This slow (and arguably overly conservative) rate of spread is predicted to increase wallaby distribution very little (c. 50 km^2) over 50 years (Figure 6a). Projecting the 2007 known distribution to 2015 (using the third quartile rate of spread, 92.9 m/yr) resulted in an increase in wallaby distribution from c. 1864 km^2 to 2051 km^2. This estimated rate of spread is predicted to increase the distribution of dama wallabies by 60% (total of c. 3265 km^2) over 50 years, compared with the 2015 estimate (Figure 6b).

The area of the current probable distribution was 4126 km^2, which is more than double that of the known distribution estimate (Figure 6, Table 5). The probable distribution of dama wallabies over the next 50 years is predicted to increase to 11 070 km^2 assuming a slower rate of spread (592.9 m/yr; Figure 6c) or to 40 579 km^2 assuming a faster rate of spread (1981.3 m/yr; Figure 6d). Within the worst-case predicted distribution (using the probable distribution as a starting polygon and third quartile rate of spread) at 50 years, c. 5983 km^2 (15%) is flat to rolling high production exotic grassland (i.e. possible dairy farms) and thus may not be suitable habitat for dama wallabies.

Table 5: Predicted distributions (km^2) of dama wallabies at five time periods using four different estimates of rate of spread (RS) and two different current range polygons.

Year	2015 'known distribution'		2015 'probable distribution'	
	1st quartile (RS = 3.1)	3rd quartile (RS = 92.9)	1st quartile (RS = 592.9)	3rd quartile (RS = 1981.3)
2015	1865	2051	4126	4126
2020	1873	2165	4789	6335
2025	1881	2283	5489	8649
2035	1887	2508	6780	13 988
2065	1912	3265	11 070	40 579

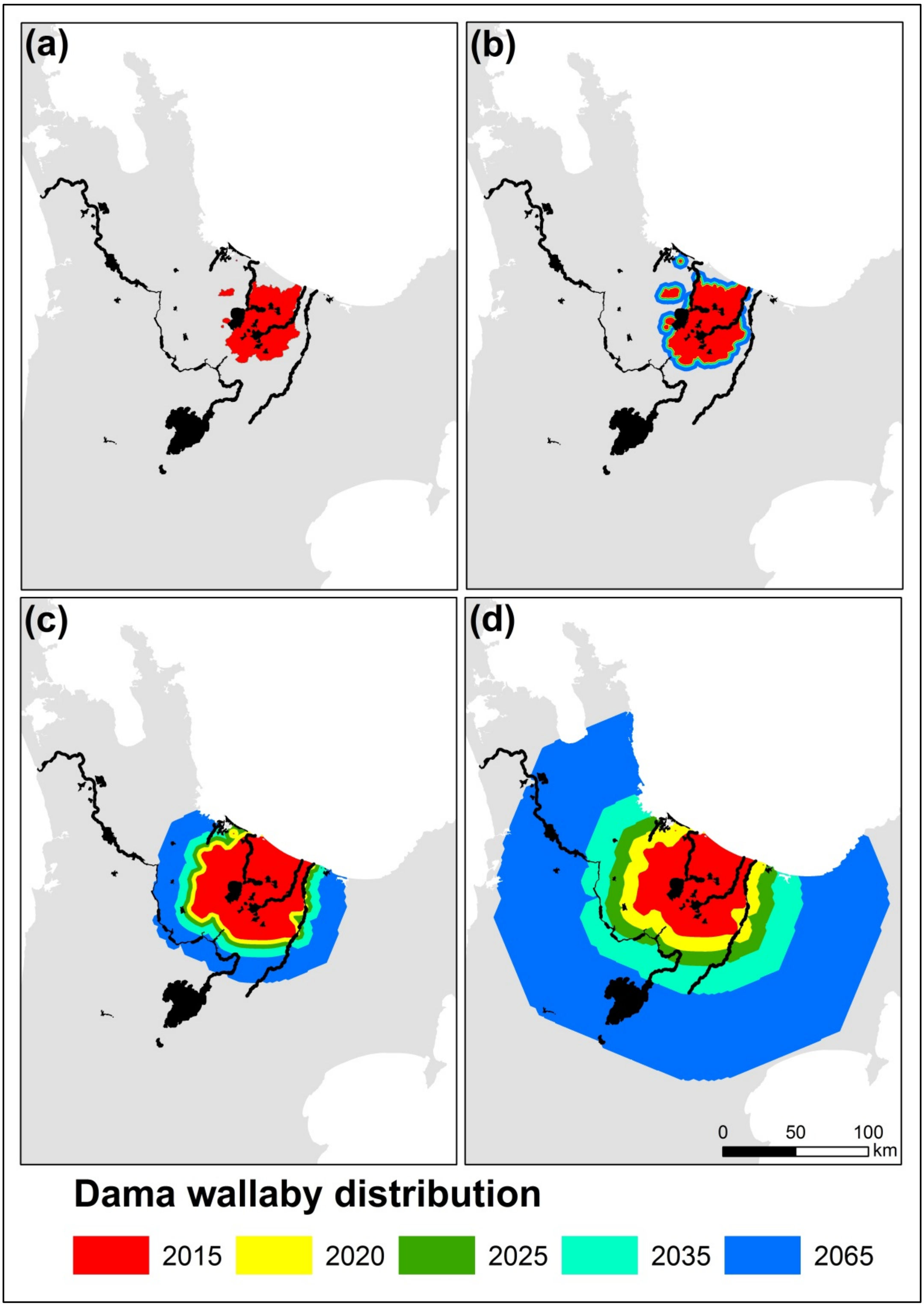

Figure 6: Predicted distributions of dama wallaby in North Island at five time periods using four different estimates of rate of spread. (a) and (b) use the estimated ‘known distribution’ from 2015 as the starting point for wallaby spread and these expand using either (a) the first quartile annual rate of spread (3.1 m/yr) or (b) the third quartile annual rate of spread (92.9 m/yr). (c) and (d) use the estimated ‘probable distribution’ from 2015 (estimated from 95% KDE around sighting and kill locations) as the starting point for wallaby spread and these expand using either (c) the first quartile annual rate of spread (592.9 m/yr) or (d) the third quartile annual rate of spread (1981.3 m/yr).

4.1.3 Habitat suitability model

The map derived from the Maxent model for Bennett’s wallaby predicts abundant suitable habitat within most of the eastern parts of the South Island and some suitable habitat in West Coast and Southland regions (Figure 7a). The primary lower elevation areas from which wallabies are predicted to be absent are associated with high production exotic grassland (e.g. dairy) and larger urban areas. Similarly, the model predicts low habitat suitability at high elevations in the South Island’s mountains – but note that most valleys are predicted to provide at least moderately suitable habitat for Bennett’s wallaby. Three variables (minimum temperature of coldest month, percent pasture in hill and high country, and average slope) had a combined relative contribution of 84% (Table 6). The AUC (0.92) and Gain (1.31) values indicate that the Maxent model for Bennett’s wallaby had a high discriminatory power.

The map derived from the Maxent model for dama wallaby predicts abundant suitable habitat within most central parts of the North Island (Bay of Plenty, Waikato, and Manawatu–Wanganui), much of Hawke’s Bay and Gisborne regions, and smaller, but not insignificant parts of Northland, Auckland, Taranaki and Wellington regions (Figure 7b). As for Bennett’s wallaby, high production exotic grassland (e.g. dairy) is the primary variable responsible for predicted dama wallaby absence at lower elevations. The model also predicts low habitat suitability at high elevations and around major urban centres. Four variables (minimum temperature of coldest month, average slope, percent forest and average annual temperature) had a combined relative contribution of 85% (Table 6). The AUC (0.96) and Gain (1.72) values indicate that the Maxent model for dama wallaby had a high discriminatory power.

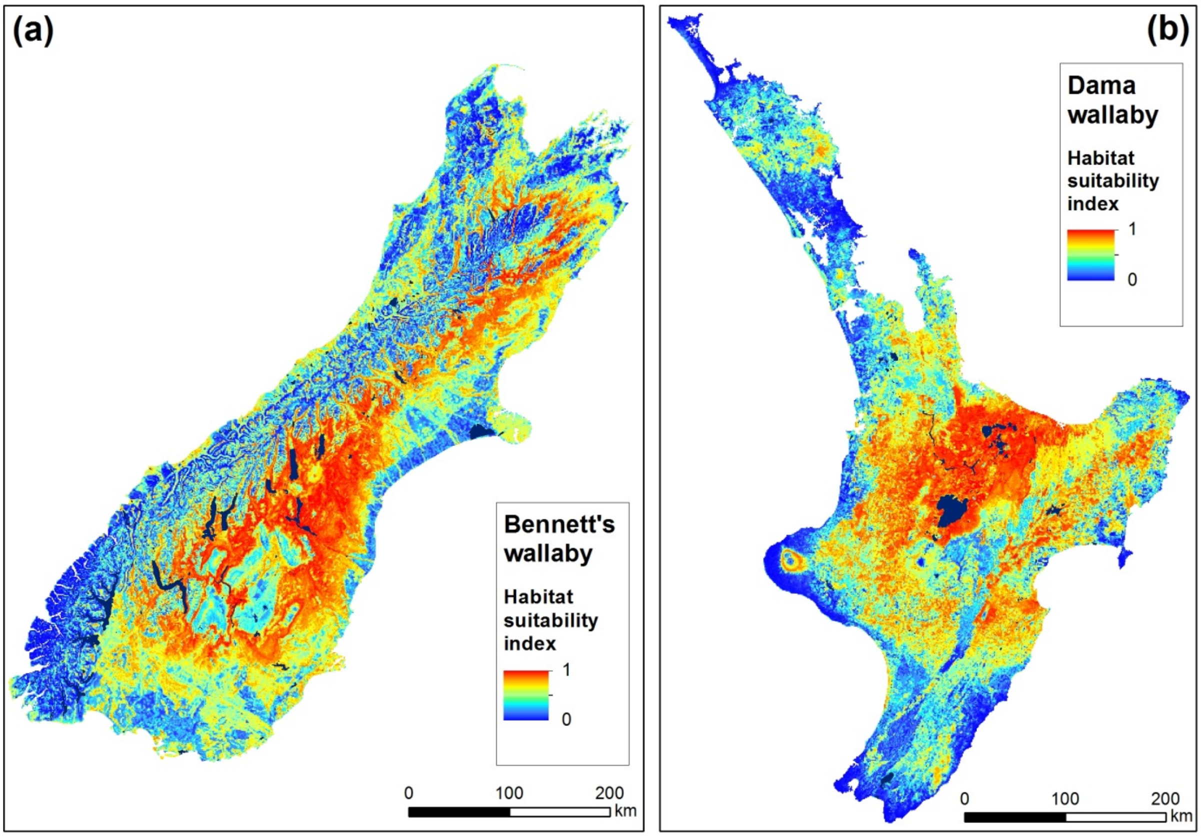

Figure 7: Predictions of habitat suitability derived using Maxent for (a) Bennett's wallaby in the South Island and (b) dama wallaby in the North Island, estimated using incidental observations of wallabies (i.e. presence-only data). Bright red and orange colours indicate areas predicted to be excellent to good wallaby habitat (1); pale blue indicates moderately suitable habitat; and dark blue represents poor habitat (0).

Table 6: Relative contributions of each variable included in the Maxent model fitted using incidental observations of Bennett's and dama wallabies in the South and North Islands, respectively.

Variable	Percent contribution	
	Bennett's wallaby	Dama wallaby
Average annual temperature	3.2	12.6
Average elevation	0.9	5.0
Average slope	16.9	21.0
Distance to cover	3.2	0
Distance to river	0.2	0.8
Minimum temperature of coldest month	48.9	33.0
Percent agriculture in flat areas	0.1	0.1
Percent cover	5.7	0.3
Percent forest	1.6	18.4
Percent pasture in hill and high country	18.0	2.7
Percent pasture/grasses	0.4	4.3
Percent shrubs	0.5	0.2
Percent urban	0.2	0.3
Percent water	0.2	1.3

4.2 Wallaby impacts

4.2.1 Summary of wallaby impacts

There are three primary documented impacts caused by Bennett's and dama wallabies: damage to agriculture, seedlings within exotic plantation forests, and native vegetation. We directly estimated the economic value of avoiding wallaby impacts to agricultural production (see results in Sections 4.2.2 and 4.2.3) using available empirical data. Conversely, although there have been studies on wallaby diet in native forests (Knowlton & Panapa 1982; Williamson 1986; Llewellyn 1988a; Warburton 2005b), there have been no attempts to specifically estimate the economic value of avoiding wallaby damage to native forest vegetation. Similarly, quantitative information on the economic value of the impacts of wallabies on plantation forests in New Zealand is sparse. We were therefore precluded from directly estimating the economic value of avoiding wallaby impacts in forest ecosystems and to the forestry industry. Instead, we assessed costs to forest ecosystems indirectly by estimating the reduction in the value of the ecosystem services provided by scrub and forest ecosystems as a result of wallaby impacts (see results in Sections 4.2.2 and 4.2.3).

Warburton (2005b) states that Bennett's wallaby have been recognised as a pasture pest since the 1940s. The majority of the plant species that form the bulk of their diet are the same as those grazed by sheep (McLeod 1986), meaning that Bennett's wallabies compete with sheep for available food and, if allowed to reach moderate-to high-densities, they can reduce the stocking rates of sheep (and presumably beef cattle grazed on the same type of pasture). Anecdotally, they have also been reported driving sheep from preferred feeding areas (but see McLeod 1986), fouling sheep feed, damaging fences, and destroying agricultural crops (Warburton 1986). Similar to the Bennett's wallaby, the dama is primarily a grazer; up to c. 70% of their diet comprising pasture species (Williamson 1986; Williams 1997). Although they are better adapted to living in forest interior than Bennett's wallabies, forest dwelling dama wallabies tend to be smaller and have lower kidney fat reserves than individuals with ready access to grassed clearings or pasture (Williamson 1986). Despite this, there have been few reports of major damage to agriculture, even though they are considered a pastoral pest (Warburton 2005a). This might be due to the serious attempts to control dama wallabies on rateable lands since the early 1960s (Warburton 2005a). If dama wallabies were to increase in numbers on or near farmland, it is likely that their impacts to agriculture would similarly increase.

Both species of wallaby are known to browse seedlings of some plantation forest species in New Zealand, notably *Pinus radiata* (possibly because it is the most widely planted exotic tree, representing 91% of the planted production forest estate (Statistics New Zealand 2002)); however, limited quantitative information is available. Warburton (1986) reported that Bennett's wallabies removed the apical buds and up to 20% of needles from *Pinus radiata* seedlings, and that some seedlings were killed in Waimate State Forest. Although the damage was locally severe, it was usually restricted to within 50–100 m of the forest edge (Warburton 2005b). Dama wallabies similarly browse seedlings of *Pinus radiata*, but plantation forests are primarily used for cover from which they access grass and weeds along roadsides, in young plantations, and nearby pasture (Warburton 2005a). Although eucalyptus trees represent less than 3% of New Zealand's planted production forests (Statistics New Zealand 2002), research from Australia suggests that Bennett's wallabies could impact these species by browsing on seedlings. However, eucalypts are less palatable than many other plant species and are only eaten when preferred species are uncommon (DPIPWE 2011).

Bennett’s wallabies reportedly browse a number of native species including broadleaf (*Griselinia littoralis*), fivefinger (*Pseudopanax aboreus*), lemonwood (*Pittosporum eugenioides*), bush lawyers (*Rubus* spp.), mingimingi (*Coprosma* spp.), wineberry (*Aristotelia serrata*), mataī (*Prumnopitys taxifolia*), and various fern and tussock species (McLeod 1986). They contribute significantly to the depletion of forest understorey and prevent regeneration of palatable species (e.g. in Matata, Nimrod, and Tasman Smith Scenic Reserves, and Gunn and Hook Bush Conservation Areas; Warburton 2005b). Although dama wallabies prefer edge habitats, they are able to live solely within podocarp/mixed hardwood forests (Williamson 1986). In forested habitats with few grassy clearings, the diet of dama wallabies comprises a high percentage of native plants. For example, Williamson (1986) reported that only 3% of the diet of forest interior dama wallabies was composed of grasses, whereas kāmahi (*Weinmannia racemosa*) and māhoe (*Melicytus ramiflorus*) together made up c. 50% of their diet. Other frequently browsed plants include hangehange (*Geniostoma ligustrifolium*), *Coprosma* spp., pigeonwood (*Hedycarya arborea*), mānuka (*Leptospermum scoparium*), kānuka (*Kunzea ericoides*), various fern species, supplejack (*Ripogonum scandens*), rangiora (*Brachyglottis repanda*), tree fuchsia/ kōtukutuku (*Fuchsia excorticata*), pāte (*Schefflera digitata*), fivefinger, and broadleaf (*Griselinia* spp.). Knowlton and Panapa (1982) showed that browsing by dama wallabies prevented the regeneration of the most palatable of these species in a vegetation survey in the Okataina Scenic Reserve. Further, measurements of vegetation in and outside exclosures established in 1984 in the same area have shown that plant species diversity was 57% higher where only dama wallabies were excluded (Wallace 1996). Benes (2001) concluded that although deer probably have greater unwanted impacts on native forests than dama wallabies, regeneration of the most palatable plant species will require the removal of both deer and wallabies.

Bennett’s wallabies impact soils and accelerate erosion rates in forested and tussock habitats (Warburton et al. 1995). These impacts occur primarily in areas with high wallaby densities (a Guilford score of 4 or higher) and in response to over-grazing/over-browsing and well-worn trails that prevent seedling regeneration. Although the impacts of wallabies on soil are less severe than those of high numbers of domestic livestock (Warburton et al. 1995), they may be sufficiently large to cause moderate erosion within conservation areas from which livestock have been excluded if wallaby numbers are not kept at low levels. To our knowledge, less is known about the impact of dama wallabies on soils in Bay of Plenty and Waikato. However, they are believed to have contributed to erosion, soil compaction, and altered soil moisture levels on Kawau Island (Shaw & Pierce 2002).

Currently, the risk of vehicles colliding with wallabies is comparatively low. For example, in 2012 c. 1% of vehicle collisions that resulted in human injury (excluding death) involved “stray or wild animals” (Ministry of Transport 2013). Although not reported, we suspect that wallabies contributed little to this statistic. However, vehicle collisions with wallabies, particularly those that cause vehicle damage but not necessarily human injury do occur (B. Warburton, pers. obs.), and would likely become more common if wallabies (particularly the much larger Bennett’s wallaby) extended their geographic distributions and became more common within those distributions. In Australia, the probability of macropod–vehicle collisions increases exponentially with traffic volume, particularly night-time traffic (e.g. Klöcker et al. 2006), and we would predict a similar scenario in New Zealand if wallaby numbers increased in areas with a high traffic volume.

Wallabies are unlikely to be vectors of tuberculosis in New Zealand or Australia (Duignan et al. 2004). There has been one report of a captive tuberculosis dama wallaby in India (Rao et al. 1991), but of post-mortems conducted on 98 dama wallabies in the Bay of Plenty, no macroscopic splenic or hepatic lesions were found (Lentle et al. 1999). Duignan et al. (2004) reported that based on an assessment of 10 dama wallabies and 20 parma wallabies (*Macropus parma*) on Kawau Island, there was no evidence of brucellosis, chlamydiosis, leptospirosis, salmonellosis, and Johne’s disease. However, they also reported that four of seven wallabies assessed tested positive for *Yersinia enterocolitica*, a bacterium that can cause zoonotic infections in a wide variety of vertebrate taxa and is regarded as an emerging disease (Duignan et al. 2004). Common symptoms in humans include watery or bloody diarrhoea and fever. In addition, there has also been one report of a captive wallaby in New Zealand that died from toxoplasmosis (Ministry of Agriculture and Forestry 1974) and one captive individual in Hamilton with an intestinal coccidiosis infection (McKenna 2003).

4.2.2 Economic valuation of Bennett’s wallaby

Within the known current (2015) distribution of Bennett’s wallaby, 80% of the land is deemed suitable for some level of agricultural production. Of this land, 1% is flat to rolling, 14% is hill country, and 85% is high country. Over this area, we estimate that the annual revenue lost from reduced stocking rates as a result of wallabies competing with livestock is c. $22.2 million. This value represents the estimated revenue loss to agriculture of the current approach to wallaby control (i.e. status quo: patchy control by landowners in Canterbury that attempt to keep wallabies below a Guilford score of 4). Doing widespread control (at an average cost of $15/ha) to achieve a reduction of c. 90% in wallaby density across all agricultural land in the known current distribution would cost c. $8.5 million (this includes the cost of control plus the estimated revenue lost from reduced stocking rates at 0.2 wallabies/ha). This suggests that there is currently a substantial net annual benefit (c. $13.7 million) to agriculture of controlling wallabies to low numbers. Additionally, widespread control might also prevent or minimise the estimated spread from the current 2015 range, and thus reduce future predicted economic impacts to invaded agricultural land.

Within the predicted future distribution (based on the 2015 probable distribution and third quartile rate of spread) of wallabies in 2025 (17 444 km^2, Figure 4d), 76% of the land is deemed suitable for some level of agricultural production (assuming no changes in landcover), with 9% of this pastoral land being flat to rolling, 15% being hill country, and 76% being high country. Over this area, we estimated that the annual revenue lost from reduced stocking rates as a result of wallabies competing with livestock will be c $63.7 million. This value represents the likely revenue loss to primary industries in 2025 if no wallaby control were to occur (i.e. it is the cost of doing nothing). Conversely, we estimated that doing widespread remedial control within this predicted future distribution would cost c. $24.8 million. Thus, the net annual benefit for agriculture of remedial wallaby control would be c. $38.9 million.

The known current (2015) wallaby distribution comprises 16% native scrub and forest landcover classes. Within this area, we estimated that the gross annual economic benefit of avoiding wallaby impacts on ecosystem services was c. $1.5 million (this estimate is based solely on the impacts of wallabies), whereas the cost of controlling them within these natural ecosystems would be c. $1.3 million. Within the predicted future distribution in 2025 (based on the 2015 probable distribution and third quartile rate of spread), we estimated that 11% of the land will be native scrub and forest (assuming no changes in landcover). We estimated that the gross annual economic value of avoiding wallaby impacts on ecosystem services in 2025 will be c. $3.3 million, whereas the cost of controlling them within these natural ecosystems will be c. $3 million. These estimates suggest that in addition to the net benefit of controlling wallabies on agricultural production landscapes, there might also be a modest net benefit to controlling them in native scrub and forested habitats.

Within the 2015–2025 ‘donut’ invaded by Bennett’s wallabies, the gross annual benefit of avoiding their unwanted impacts was $43.4 million. The annual cost of widespread remedial control was $18 million, resulting in a net benefit of $25.4 million. The annual cost of defensive control for containment was $6.2 million, resulting in a net benefit of $37.2 million. Thus there is a greater benefit from preventing their spread than controlling them once they have spread.

Assuming no widespread control occurs, the impacts caused by Bennett’s wallabies in 2025 (see predicted distributions in Figure 4) would result in annual revenue losses for agriculture and degraded ecosystem services of: c. $24.2 million (4a), c. $28.4 million (4b), c. $61.6 million (4c), c. $67 million (4d). Managers might be uncertain about which of these predictions is likely to be most realistic, with some being sceptical about the worst-case scenario where wallabies occupy about one-fifth of the South Island (depicted by the 2025 polygon shown in Figure 4d). To assess this in relative terms, managers must be almost three times more certain that the depiction in Figure 4a will be the ‘true’ distribution of wallabies in 10 years, compared to that shown in Figure 4d. It is important to assess this critically, because revenue losses associated with the worst-case scenario and wallaby management within this area will be significantly higher (c.f. the best-case scenario in Figure 4a). Similarly, managers need to be 2.5 times more certain about the 2025 wallaby distribution shown in Figure 4b, compared to that in Figure 4d, to justify not planning for the worst-case scenario. Revenue losses in 2025 for the wallaby distribution shown in Figure 4c were similar to those from Figure 4d, suggesting similar levels of certainty regarding the relative risk of these two scenarios. The magnitude of the relative risks would be even greater after 50 years (2065) of geographic spread in the absence of widespread control.

4.2.3 Economic valuation of dama wallaby

Within the known current (2015) distribution of dama wallaby, 31% of the land is deemed suitable for some level of agriculture production. Of this land, 8% is flat to rolling (0–100 m), 22% is hill country (101–300 m), and 70% is high country (>300 m). Over this area, we estimate that the annual revenue lost from reduced stocking rates as a result of wallabies competing with livestock is c. $1 million. This value represents the estimated revenue loss to agriculture of the current approach to wallaby control. Doing widespread control (at an average cost of $15/ha) to achieve a reduction of c. 90% in wallaby density across all agricultural land in the known current distribution would have a cost of c. $950,000 (this includes the cost of control plus the estimated revenue lost from reduced stocking rates at 0.2 wallabies/ha). This suggests that there is currently a marginal net annual benefit (c. $50,000) to agriculture of controlling wallabies to low numbers. Additionally, widespread control might also prevent or minimise the estimated spread from the current 2015 range, and thus reduce future predicted economic impacts to invaded agricultural land.

Within the predicted future distribution (based on the 2015 probable distribution and third quartile rate of spread) of wallabies in 2025 (8649 km^2, Figure 6d), 40% of the land is deemed suitable for some level of agricultural production, with 30% of this pastoral land being flat to rolling, 27% being hill country, and 43% being high country. Over this area, we estimate that the annual revenue lost from reduced stocking rates as a result of wallabies competing with livestock will be c. $4. 3 million. This value represents the likely revenue loss to primary industries in 2025 if no wallaby control were to occur (i.e. it is the cost of doing nothing). Conversely, we estimated that doing widespread remedial control within this distribution will cost c. $4. 1 million. Thus, the net annual benefit for agriculture of remedial wallaby control would again be marginal at $200,000.

The known current (2015) wallaby distribution comprises 62% native scrub and forest (including plantation forest) landcover classes. Within this area, we estimated that the gross annual economic benefit of avoiding wallaby impacts on ecosystem services was c. $3.2 million (this estimate is based only on the impacts of wallabies), whereas the cost of controlling them within these natural ecosystems would be c. $1.9 million. Within the predicted future distribution in 2025 (based on the 2015 probable distribution and third quartile rate of spread), we estimate that 56% of the land will be native scrub and forest (assuming no changes in landcover). We estimate that the gross annual economic value of avoiding wallaby impacts on ecosystem services in 2025 will be c. $12.2 million, whereas the cost of controlling them within these natural ecosystems will be c. $7.3 million. These estimates suggest that in addition to the (marginal) net benefit of controlling wallabies on agricultural production landscapes, there might also be a substantial net benefit to controlling them to protect ecosystem services associated with native scrub and forested habitats.

Within the 2015–2025 ‘donut’ invaded by dama wallabies, the gross annual benefit of avoiding their unwanted impacts was $12.3 million. The annual cost of widespread remedial control was $8.6 million, resulting in a net benefit of $3.7 million. The annual cost of defensive control for containment was $3.4 million, resulting in a net benefit of $8.9 million. Thus there is a greater benefit from preventing their spread than controlling them once they have spread.

Assuming no widespread control occurs, the impacts caused by dama wallabies in 2025 (see predicted distributions in Figure 6) would result in annual revenue losses for agriculture and degraded ecosystem services of c. $3.8 million (6a), c. $4.6 million (6b), c. $10.4 million (6c), or c. $16.5 million (6d). Managers might be uncertain about which of these predictions is likely to be most realistic, with some being sceptical about the worst-case scenario where wallabies occupy more than one-third of the North Island (depicted by the 2025 polygon shown in Figure 6d). To assess this in relative terms, managers must be more than four times more certain that the depiction in Figure 6a will be the ‘true’ distribution of wallabies in 10 years, compared to that shown in Figure 6d. It is important to assess this critically, because revenue losses associated with the worst-case scenario and wallaby management within this area will be significantly higher (c.f. the best-case scenario in Figure 6a). Similarly, managers need to be 3.5 and 1.6 times more certain about the 2025 wallaby distributions shown in Figures 6b and 6c, compared to that in Figure 6d, to justify not planning for the worst-case scenario. The magnitude of the relative risks would be even greater after 50 years (2065) of geographic spread in the absence of widespread control.

5 Discussion

5.1 Wallaby distributions

Empirical estimates of rate of spread associated with the known distributions were highly variable for both species. Additionally, we found that there was a temporal decay in rates of spread, with historical rates of spread usually being far greater than more recent estimates. This could arise from three non-mutually exclusive factors. First, rates of spread could have slowed as the wallaby invasion front hit unsuitable habitat. Second, control, particularly at the invasion front, may have been adequate to halt or minimise dispersal and thus population spread. This seems unlikely (at least) for Bennett's wallaby, because they are believed to have increased in distribution and numbers since the disbandment of the dedicated wallaby control unit in South Canterbury in 1992 (Choquenot and Warburton 2006). Third, estimates of rate of spread associated with the known distributions may be representative of movement by individuals that reside on the proximal edge of the core breeding population, rather than of movement by dispersers (that generally occur at low densities) at the invasion front (Lindström et al. 2013). Interestingly, we found that the rates of spread estimated from the probable distribution were comparable to the earliest historical estimates for both species, suggesting that estimates from the current known distribution do not accurately depict dispersal behaviour/movement at the invasion front. Estimated rates of spread for several wild ungulate species introduced into New Zealand are either much larger (e.g. 8690 m/yr, chamois *Rupicapra rupicapra*; 1770 m/yr, red deer (with the exception of the third quartile annual rate of spread (1981.3 m/yr) used for dama wallabies)) or comparable (e.g. 805 m/yr, fallow deer; Caughley 1963) to the more extreme values that we used to predict future wallaby distributions.

High variation in estimated rates of spread created difficulty in determining appropriate values with which to predict future distributions – as reflected by the disparity in projections, which span orders of magnitude. We consider that projections using the minimum rates of spread from the known distributions are unrealistic. They do not reflect recent average rates of spread, nor do they account for the large number of recent confirmed sightings and kills outside the known distributions. In the absence of widespread future control, they are at best, optimistic.

It is unclear whether it is more appropriate to model future wallaby distributions using the known breeding distributions delineated by councils or (what we term) the probable distributions using 95% KDEs (i.e. using the large number of confirmed sightings and kills that occur outside council delineations). If the increasingly large numbers of locations outside the known distributions represent breeding populations, even at low densities, then the use of the higher estimated rates of spread to model future distributions (see Figures 4c, d and 6c, d) may provide more realistic projections. New surveillance methodology may help confirm the presence of low density breeding populations outside containment areas, and thus refine estimates of rates of spread. In the absence of these data, we speculate that future wallaby distributions are likely best represented by Figures 4b, c and 6b, c. Although not worst-case scenarios, these represent significant range increases for both species. For example, in 50 years the distributions of Bennett's wallaby and dama wallaby are predicted to increase between 81–288% and 75–494%, respectively. If existing illegal liberations (assuming they are established breeding populations) are included into the estimate for Bennett's wallaby, then the distribution at 50 years is predicted to increase by c. 730%. Note that we did not create a model that specifically assessed the effect of existing illegal liberations on the future predicted distributions of dama wallaby, because the primary new liberation (Papamoa Hills) was already included in known and probable distributions.

Further evidence for potential large increases (under current control levels, which appear insufficient to contain populations) in the distributions of both wallaby species comes from studies that suggest there is ample good quality habitat for wallabies to invade. Bennett's wallaby have been confirmed south of the Waitaki River, occurring on the south side of that river both in Canterbury and Otago (Warburton et al. 2014). These authors argue that given the availability of suitable habitat for wallabies invading southwards, it is likely that their range will increase substantially in the absence of control. Given that there is also ample suitable habitat north of the current distribution of Bennett's wallaby, we foresee no reason why they should not continue to expand in that direction in the absence of control (assuming that they can cross major rivers at bridges). The habitat suitability model for Bennett's wallaby supports these predictions, with this species likely to occupy most of the South Island if allowed to expand. Similarly, the predicted continued expansion of dama wallabies into Mamaku and Horohoro, and invasion of places like Oropi and Te Urewera, seems reasonable given that forest types around these locations are similar to those already occupied by dama wallabies, and thus should provide suitable habitat (Williamson 1986). Although the beech and podocarp dominated forests on the upper slopes of Te Urewera may be less suitable habitat, lower altitude forests dominated by kāmahi (*Weinmannia racemosa*) and māhoe (*Melicytus ramiflorus*) are likely to be suitable habitat for dama wallabies (Williamson 1986). Again, the habitat suitability model for dama wallaby supports these predictions, with this species likely to occupy most of the North Island (except for areas heavily influenced by intensive agriculture) if allowed to expand.

Rate of spread models predict future distributions of Bennett's wallaby and dama wallaby at five different time periods. This is important for management agencies because it incrementally illustrates the extent of each region likely to be impacted by wallabies if they are not sufficiently controlled. However, these models were not designed to assess habitat preferences, occupancy or densities within future predicted distributions. These are different questions for which detailed data are required to parameterise models. We acknowledge that the future predicted increases in wallaby distributions in this report will probably overestimate the actual area occupied by wallabies at each period. For example, dama wallabies are believed to avoid areas of intensive dairying with inadequate scrub/forest cover and thus this should be subtracted from their predicted range, that is, 15% (5983 km^2 of 40 579 km^2) of their predicted range in 50 years is likely to be unsuitable habitat for them. Importantly, even accounting for high production exotic grassland (dairy), dama wallaby are still predicted to increase by c. 1750% under a worst-case scenario (i.e. using the probable distribution and third quartile rate of spread). Ideally it would have been useful to clip habitat suitability models by future distributions predicted by rate of spread models to estimate the actual area predicted to be impacted by wallaby spread at various points in the future. However, we did not do this because habitat suitability is a continuous variable, meaning that we would have to arbitrarily determine a cut-off value to represent areas occupied/impacted by wallabies in the future.

In addition to estimating rates of spread, we used environmental data surrounding known sighting locations to estimate suitable habitat for Bennett's wallaby in the South Island and dama wallaby in the North Island. These analyses provide an indication of areas that may be affected by wallabies in the future if they are not sufficiently controlled. Because these analyses used environmental data from wallaby presences (i.e. within their current ranges), they are biased towards predicting similar habitats elsewhere in each of the islands as being the most suitable. For areas that have not been invaded by wallabies yet, it is difficult to predict the suitability of those habitats because of a lack of data. Thus, habitat suitability models should be considered to represent the minimum area likely to be occupied by wallabies if allowed to expand throughout each island. Nevertheless, it is also important to note that both models performed well (based on AUC), and thus we can be confident that the models have highlighted areas where wallabies are highly likely to be in the future if they are not sufficiently controlled. High to moderate densities of wallabies are likely to occur throughout the New Zealand mainland, with the exception of high elevations, urban areas, and high production exotic grassland (e.g. dairy). However, we speculate that the models might have underestimated suitable habitat in high production exotic grassland because the lack of fine-scale vegetation data meant that refugia (patches of scrub, hedgerows, and riparian corridors) within these areas could not be easily identified.

Data collected from future systematic occupancy surveys and/or faecal pellet transect surveys will improve our knowledge about good versus poor habitats and relative abundances within current and future predicted distributions. Global positioning system (GPS) radio-collars deployed on wallabies would provide fine-scale spatial and temporal information about habitat use and potentially dispersal (which ultimately results in population spread) (Latham et al. 2015). However, given the high cost of GPS deployment and subsequent data analysis (Latham et al. 2015), key questions relating to wallaby management would need to be identified to justify its use (and in any case, fine-scale environmental data necessary to supplement these data would still need to be acquired). In our opinion, available funding would be better spent on surveillance monitoring at the invasion front, particularly methods that provide comparatively high confidence that if wallabies (even at low densities) are present in an area, they are detected, and, if eradication has been attempted, that no wallabies remain.

5.2 Wallaby impacts

Our estimates of wallaby impacts are broadly in line with previous findings (Warburton 2005a, b). That is, in the absence of control, Bennett’s wallaby are predicted to have significant economic impacts on agricultural production values, estimated to be about $63 million in 2025. If we factor in expenditure for remedial control, we estimate that the net benefit of controlling Bennett’s wallabies for agriculture is about $39 million. Conversely, we estimated that the future annual revenue lost because of the impacts caused by dama wallaby to agriculture is substantially less (c. $4 million in 2025) than those caused by Bennett’s wallaby, with only a marginal net benefit to controlling dama wallaby for agricultural production values. This is supported by Warburton (2005a) who states that so far there have been no reports of major damage to agriculture by dama wallaby.

Estimated benefits of controlling both species hinge on a number of assumptions regarding parameter estimates for which there are currently sparse or no data. We used average density estimates of 2 and 0.15 wallabies/ha in hill and high country, and high productivity pasture, respectively. Two per hectare is based on an empirical estimate for Bennett’s wallaby (Warburton 2005b) – which we also used for dama wallaby given the lack of empirical estimates for that species – and is higher than the <1/ha predicted by Choquenot and Warburton (2006). Clearly, estimated costs are sensitive to this parameter; however, we estimate that the average density could be more than halved and there would still be a net benefit of controlling Bennett’s wallaby for agriculture. Given that hill country can stock 7.5 ewe units per hectare (Morris 2013), we see no reason why, in the absence of control, the same habitat cannot maintain a density of at least 1–2 Bennett's wallaby/ha. Similarly, if the dry matter intake relationship between wallabies and sheep (Warburton & Frampton 1991) has changed since it was calculated, particularly because of selective breeding of sheep, then the estimated impacts to agriculture would also change. Finally, estimates are also sensitive to the per hectare cost of control. For example, if the cost of achieving a 90% reduction in wallaby numbers is greater than $15/ha, then the estimated net benefit of control will be reduced.

The marginal net benefit (c. $200,000) from controlling dama wallabies on agricultural land (c.f. Bennett's wallaby) may be conservative if the density estimate used for this species is biased low. They are about one-third the size of Bennett's wallaby (Williamson 1986), and given ecological carrying capacity relationships predicted by Choquenot and Warburton (2006), there is some justification for using a higher density estimate. Increasing the density of dama wallabies would obviously result in a larger net benefit from control (based on a static per hectare cost of control, i.e. $15/ha regardless of wallaby density). Ideally however, empirical estimates of dama wallaby density are needed to yield more robust estimates of the revenue losses as a result of their impacts to agriculture and the environment. The estimates of dama wallaby impacts to agriculture are also related to the greater number of dama wallabies (11.4) per ewe equivalent (c.f. 3.8 Bennett's wallabies). That is, the smaller size of dama wallaby means that their density would need to be about three times higher than that of Bennett's wallaby for the magnitude of the impacts to be roughly comparable. Recent data suggest that some pasture–forest-edge dwelling dama wallabies outside the core range can weigh c. 12 kg (P. Commins, pers. comm.). If this is the case for other dama wallaby populations outside the core range, it follows that we may have underestimated the costs of the impacts caused by dama wallaby by assuming that all populations are about one-third the size of Bennett's wallaby (c. 15 kg; Warburton 2005b).

We estimated potential economic losses incurred from impacts of wallabies to natural capital and ecosystem services using the values provided in Patterson and Cole (2013), whilst simultaneously attempting to account for the impacts of sympatric introduced herbivores. Given the huge number of uncertainties involved in attempting to obtain a precise estimate of the value of ecosystem services and how they are impacted by vertebrate pests (Costanza 1997; Patterson & Cole 2013), our crude estimates need to be taken cautiously and should not be used as robust values. Nevertheless, we argue they are a useful starting point for determining whether wallaby impacts on natural capital and ecosystem services might be sufficiently important to warrant more detailed investigations.

Our results suggest that the impacts of wallabies, particularly those of dama wallaby, represent significant economic losses to the ecosystem services that we assessed (erosion control and sediment retention, and cultural). If we factor in expenditure for widespread remedial control, we estimate that the net benefit of controlling dama wallabies to mitigate their future impacts on ecosystem services may be about $5 million in 2025. The net benefit of controlling Bennett's wallaby to avoid costs to ecosystem services is estimated to be more modest; however, our results suggest that at least in high risk erosion areas and/or high priority conservation sites there could be an economic benefit to widespread remedial control. Importantly however, our results strongly suggest that containing wallabies within their current known or probable distributions is a more cost-effective management strategy than remedial control once they have spread into a new area (although the latter is more cost-effective than no management intervention).

Presently, Environment Canterbury’s annual budget for Bennett’s wallaby management includes c. $66,000 for compliance inspections, c. $16,000 for faecal pellet transect monitoring, and c. $20,000 for incursion response (G. Sullivan, pers. comm.). Similarly, Bay of Plenty and Waikato Regional Councils have a joint dama wallaby management programme with a combined annual budget of c. $210,000, plus an additional contribution of c. $10,000 from DOC. This expenditure does not include control work paid for by landowners that are affected by wallabies. We do not have estimates for landowner expenditure for wallabies because the costs of control vary widely depending on the control method used. The combined council and agency budget of c. $320,000 per year for control and surveillance of wallabies in mainland New Zealand has probably been effective at slowing their rate of spread; however, it has not contained them within their designated containment boundaries. We estimate that the cost of controlling wallabies to low numbers and containing them with their current (2015) distributions would cost c. $10 million (calculated on a per hectare basis). Notwithstanding the unknown expenditure by landowners, this estimate suggests that significantly more funding and a well-coordinated strategy are needed to prevent further geographical spread of wallabies.

As described in Section 5.1, empirical estimates of rate of spread were highly variable for both species. This created disparity in projections estimating future wallaby distributions. We have attempted to quantify the costs related to this uncertainty using a probabilistic risk assessment. That is, managers might disagree about which projection is most likely to be the ‘true’ future scenario and, particularly, over optimism (i.e. assuming that there will be minimal spread of wallabies in the future) may result in significant future economic losses being incurred if the chosen scenario on which management is based proves to be incorrect. For example, we estimated that managers would need to be about three times more certain about the smallest predicted range increases (Figures 4a or 4b) being the true depiction of Bennett’s wallaby distribution in 10 years, rather than the worst-case scenario (i.e. Figure 4d). Similarly, we estimated that managers would need to be about four times more certain about the smallest predicted range increases (Figure 6a or b) being the true depiction of dama wallaby distribution in 10 years, rather than the worst-case scenario (i.e. Figure 6d). Note that estimated distributions in 2025 in Figures 4 and 6 are delineated by the green polygon boundary, and that there have already been confirmed sightings of Bennett’s and dama wallabies within these polygons (Figures 1 and 2). Thus, in the absence of widespread control, we suspect an inability to declare with any confidence that the smallest range increases (Figures 4a, b and 6a, b) – whose conservative estimated rates of spread are influenced by current levels of control – are about three or four times more likely to represent the 2025 distributions than those depicted in Figures 4d and 6d, respectively. However, given that a containment strategy will be more cost-effective than allowing wallabies to spread and then doing remedial widespread control, the accuracy of the rate of spread is not that important for selecting containment as the best management option.

5.3 Knowledge gaps

The following discussion on knowledge gaps is primarily based on an acceptance that control is needed to minimise, prevent or reverse predicted increases in distributions and reduce potential high costs associated with wallaby impacts (i.e. as predicted in the results of this report). The knowledge gaps discussed below are ordered using the following logic: managers need suitable surveillance and detection tools, strategic approaches and tactical options available to control or eradicate detected individuals or populations, a social licence with the local community and other stakeholders (a component that straddles all components of effective wallaby management), and biological knowledge that can be used to improve control and confidence in the estimated costs of wallaby impacts to primary production and natural capital and ecosystem services.

- The areas occupied by established breeding populations of Bennett's and dama wallabies are reasonably well known. However, given containment would be the most cost-effective management option, the key to preventing the spread of wallabies is early detection of dispersers and low-density breeding populations, followed by quick actions to prevent the establishment of these animals (Warburton et al. 2014). Detecting animals at very low numbers, such as the invasion front, is difficult. Further, determining whether survivors remain following an eradication attempt is also difficult. There is a need to optimise surveillance at the control front by utilising/trialling a suite of existing and novel (e.g. indicator dogs, camera traps, and thermal imaging technology) monitoring methods, and determining suitable methods for estimating probabilities of detection. Halting spread is a necessary step to preventing wallaby impacts and associated costs from worsening. These knowledge gaps are seen as the highest priorities to address.
- Public sightings yield important information about new wallaby populations (natural or illegally liberated) and lone individuals outside currently accepted distributions. If observations are reported before a new population has become well-established, attempts at elimination are more likely to be successful and less costly. However, how best to maximise the potential wealth of information provided by the public into well-structured citizen science is less obvious. Ideally, citizen science should be part of a collaborative project that assists managers to systematically survey invasion fronts or other areas where new wallaby populations are suspected to be, as well as to increase confidence (in concert with other surveillance methods) that no survivors remain following an eradication attempt.
- Optimal strategic approaches need to be developed for wallaby control, elimination of isolated populations or eradication. If eradication is the goal, then a study on the feasibility of eradicating wallabies from New Zealand needs to be completed. In any case, careful consideration needs to be given to the six strategic rules that need to be adhered to for elimination of isolated populations or eradication (e.g. Parkes & Panetta 2009). Briefly these are: (1) all target animals need to be put at risk by the methods being used, (2) wallaby populations must be killed faster than their rate of increase at all densities, (3) the risk of recolonisation must be zero or manageable, (4) socioeconomic factors must be conducive to meeting the critical rules, (5) where the benefits of management can be achieved without eradication, discounted future benefits should favour the one-off costs of eradication over the ongoing costs of sustained control, and (6) survivors should be detectable, and once detected, they should be killed before the population can increase. Of these, rules 1–4 are regarded as crucial to the success of eradication efforts, whereas rules 5–6 are considered desirable. Strategic plans to control or eradicate populations should include spatial and temporal factors, particularly as they relate to the six strategic rules above. This may include identifying areas/habitats where rates of population spread are highest (e.g. dispersal corridors) and focusing control efforts (at least initially) on these areas, and if possible incorporating hard boundaries (e.g. large rivers) into 'rolling front'-type eradication programmes. Geographic Information Systems (GIS) technology may be particularly useful in determining the most appropriate spatial approach to control or eradication. In addition, 'good-neighbour' rules can facilitate effective management of residual wallaby populations across land tenure boundaries.
- Although the tactical options for control or eradication are largely known, with few new tools available, it would be useful to revisit Morriss et al. (2000) to see what toxins are available and currently registered for use on wallabies (also see Fisher et al. 2008 and

Morriss & Warburton 2008). In a similar vein, maximising bait acceptance, particularly when wallabies occur at low densities and are thus less inclined to take artificial baits because of the high availability of natural foods, may increase the percentage of animals killed during control operations and 'initial knockdown' and 'mop-up' phases of eradication programmes. Assessing the utility of thermal imaging in ground and/or aerial shooting programmes is also highly recommended as recent technology has proved useful in increasing detections (e.g. Hart et al. 2015).

- Key to managing wallabies is managing people. Effective wallaby management will require a social licence, particularly with regards to obtaining buy-in from the local community, but also with other stakeholders. This relates to them supporting (or at least accepting) control or eradication efforts, as well as preventing future illegal liberations (if these cannot be prevented, then the obligate strategic rules necessary for successful eradication will not be met). Therefore, a key research need is a social science project that aims to determine how best to get a social licence for control/eradication. Some landowners may be reluctant to buy in to such a project. In these cases, it will be necessary to ensure that appropriate legislative and regulatory frameworks are in place so that a control or eradication programme can proceed, both in terms of ensuring control efforts are not halted and that illegal liberations are heavily punished. Although tangential to knowledge gaps, we also highlight the importance of having sufficient funding in place so that the chosen management programme can be completed as planned.
- There are a number of knowledge gaps relating to wallaby biology that could improve control. One potentially useful, but notoriously difficult to obtain, parameter is dispersal, particularly dispersal distances, frequency, and whether it is proportional or density-dependent. More reliable empirical estimates of density (particularly for dama wallaby, for which there are no current estimates) would better inform bait sowing rates in poisoning operations and allow more accurate estimates of the costs of wallaby impacts. In terms of control efforts, knowledge on wallaby behaviour at the low population densities typically achieved after control, as well as trends in population recovery post-control, would provide important information for building a long-term management strategy. Although some factors, such as habitat selection, would be nice-to-haves, key questions would need to be formulated before initiating projects that used devices such as GPS (Latham et al. 2015).
- The impacts of Bennett's and dama wallabies on agriculture and native vegetation have been assessed, although not for about 20 years. Little is known about other potential impacts of wallabies and next to nothing about the costs of those impacts. This precludes any detailed economic evaluation of the costs of the impacts caused by wallabies. Primary research on wallaby impacts was beyond the scope of this report; however, with substantial predicted increases in wallaby distributions (in the absence of organised control), it will be necessary to obtain quantitative information about the magnitude of the costs of wallaby impacts to better understand and evaluate their impacts to primary industry, natural capital and ecosystem services.
- Finally, as Warburton et al. (2014) note, attempts to eradicate wallaby populations (or subpopulations) from New Zealand will provide lessons that will be applicable to eradication of other pest species (both in New Zealand and overseas) with restricted distributions. The lessons related to technological and social challenges will also be useful for informing more aspirational goals, such as predator-free New Zealand.

6 Summary

Populations of Bennett's and dama wallabies currently persist outside containment areas and these, as well as confirmed, new out-of-containment-area sightings and kills, appear to be increasing. Based on moderate empirical estimates of rates of spread and in the absence of widespread control or containment, the distributions of both species are predicted to increase substantially over the next 50 years. They will impact agriculture, native vegetation, and contribute to soil erosion within newly invaded areas, as they do within their current distributions. If allowed to increase in distribution and numbers, they may have additional unwanted impacts through, for example, increased rates of collisions with motor vehicles. Based on our estimates, there is a clear net benefit of widespread remedial control of wallabies once they have expanded into a new area. There is, however, an even greater benefit from containing them and thus preventing their future impacts and associated costs in currently unoccupied areas. Effective management for containment will require sufficient funding in place for surveillance, detection, and control methods that are fit for purpose and these are seen as the highest priorities for future management of wallabies in New Zealand.

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