Kaweka Forest Park Mountain Beech Project

Culling and Monitoring Review

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Summary

Over 10% of Kaweka Forest Park mountain beech forest (>1500 ha of ≈14,000 ha, *Fuscospora cliffortioides*) is in a state of natural canopy collapse. After sika began to displace red deer in the 1950s, regeneration at open canopy sites was suppressed by deer browsing (Wardle, 1979; Fleury, 1980; Jenkins, 1982; Hosking and Hutcheson, 1988; Allen and Allan, 1997; Husheer et al., 2006b; Duncan et al., 2006). Deer culling by foot hunters was undertaken from 1958 up until 1988, when kill rates still exceeded one deer per hunter day (mean 563 deer killed annually; Davidson and Fraser, 1991). A trial of intensive deer culling in ≈11,000 ha of Kaweka F.P. commenced in October 1998 and ceased in November 2015 (mean 251 deer killed annually). Deer kill rates were initially high (>5 deer helicopter flying hour) resulting in the restoration of regeneration, but declined after 2009 when culling excluded stags, effort halved and was was undertaken in winter (June to November vs. September to January pre-2009). Estimates of deer density from faecal pellets appear unreliable, but suggest that densities have remained 5–20 deer km^{-2} in Kaweka and Kaimanawa F.P. for the past five decades despite commercial, government-funded and recreational deer hunting.

Between 1998 and 2000, paired 10 m × 10 m exclosure plots were established to test if long-term deer culling could reduce browsing on seedlings, and restore mountain beech regeneration at open canopy sites (Kaweka Mountain Beech Project KMB; Husheer et al., 2006a). Encouraging recreational hunters had no measurable benefit for seedling growth (Husheer and Robertson, 2005). Duncan et al. (2006) predicted that if aerial culling were maintained for two decades, canopy regeneration would occur. Deer culling intensity should have been maintained or increased, and extended to other areas in Kaweka and Kaimanawa F.P.s (Husheer et al., 2003). Instead, deer culling effort was reduced in both extent and intensity and became less effective. Monitoring of paired 10 m × 10 m exclosure plots in 2018 suggests that this decline in culling was associated with declines in survival and densities of mountain beech seedlings. Seedlings that survived outside fenced plots grew at half the rate of seedlings inside fenced plots. The benefits of the investment in seedling regeneration made in the first decade of the KMB project were lost in the second decade due to a failure of deer culling to reduce browsing by sika deer. Poor seedling regeneration at monitored sites means that without the reinstatement of intensive deer culling, canopy gaps will become more common and tall forest will be transformed into shrubland. Deer also adversely affect kāmahi (*Weinmannia racemosa*), silver beech (*Lophozonia menziesii*), red beech (*Fuscospora fusca*), black beech (*Fuscospora solandri*) and alpine grassland vegetation in Kaweka and Kaimanawa Forest Parks (F.P.; Elder, 1956; Husheer et al., 2003).

Recommendations

1. Published and peer-reviewed research has shown that sika deer need to be intensively culled for at least twenty years to allow mountain beech canopy regeneration in Kaweka F.P. (Allen and Allan, 1997; Husheer et al., 2006b; Duncan et al., 2006). From 2009, a criteria of $\leqslant$20 faecal pellet groups per transect, and a basal area of >44 m^2 ha^{-1} was used to justify cessation of aerial culling in Kaweka Forest Park, with little scientific support (Herries, 2013; Mayo, 2016). To assure regeneration of mountain beech, deer densities need to be lowered as much as possible (<5 deer km^{-2}). Initially, >5 deer km^{-2} $year^{-1}$ need to be culled from Kaweka F.P. mountain beech forests (>700 deer $year^{-1}$ in $\approx$140 km^2). If aerial culling is re-established, at least 140 hours a year of helicopter flying will be required to sufficiently reduce deer densities (and maintain low densities thereafter) in mountain beech forest in Kaweka F.P. Project costs including monitoring are likely to be in the vicinity of \$200,000–\$300,000 per annumn for twenty years.

2. To ensure maximum benefit for conservation, DOC-funded aerial deer culling should occur in association with possum culling. An OSPRI-funded aerial 1080 operation is planned for winter 2019. Although OSPRI plans to use deer-repellent covered cereal baits, there will inevitably be an unknown proportion of deer by-kill. Some aerial culling might be initiated prior to possum culling to retrain staff, re-establish contracts and to gauge deer density (see section 5.1). Immediately following possum culling, intensive aerial deer culling should be undertaken from November 2019 until March 2020 aimed at reducing the deer population to low levels (<1 deer km^{-2}).

3. The impacts of sika deer are not limited to mountain beech forest. Regeneration in red beech, silver beech, and kāmahi forest is likely to be suppressed by browsing. Succession of mānuka-kānuka forest into black beech forest in south-east Kaweka F.P. is also likely to be affected by deer browsing. Culling of these areas should also be undertaken.

4. Recreational deer hunters may kill <700 deer $year^{-1}$ ($\approx$1 deer km^{-2} $year^{-1}$) in Kaweka F.P. ($\approx$670 km^2). This is probably sufficient to avoid high rates of natural deer death in popular hunting areas, and increases in deer fecundity, size and condition, but insufficient to have measurable forest conservation benefits. The current policy of relying on recreational hunting for forest conservation in Kaweka and Kaimanawa F.P.s should be reconsidered. Managers should consider the future of recreational hunting areas in Kaweka and Kaimanawa Forest Parks. If they remain, statutory requirements for five-yearly reporting should be met.

5. Design a long-term vegetation monitoring system for Kaweka Forest Park including all beech forest types (mountain, black, red and silver beech). Any additional forest monitoring should build on existing long-term monitoring where possible (Allen et al., 2003). Plots established on randomly located lines between 1960 and 1980 in Aorangi, Tararua, Ruahine, Kaimanawa and Kaweka Forest Parks would provide decades of comparative data.

6. Once a long-term monitoring system is designed, all fencing, pegs and markers from existing plots and lines established between 1998 and 2013 should be removed.

7. Deer faecal pellet monitoring has been relied upon to gauge relative abundance in Kaweka F.P., but imprecision is apparent (Section 3.2). Potentially lower-cost, more-precise deer density monitoring systems should be considered. Alternatives such as demographic modelling (Tanentzap et al., 2009; Section 5.1) aerial surveys using visible light cameras (Linchant et al., 2015), thermal imaging using light aircraft (Haroldson et al., 2003), DNA analysis of faecal pellets (Goode et al., 2014; Yamashiro et al., 2017), and trail-cameras (Jacobson et al., 1997; Dougherty and Bowman, 2012), are under current development and might be considered once proven. If variability in pellet detection, defecation, decay and definition of what a pellet is are addressed, future development may make faecal pellet counts more useful.

Contents

1 Introduction

Red and sika deer (*Cervus elaphus* and *Cervus nippon*) have modified the composition of temperate forest understoreys world-wide, both in their natural range and where they have been introduced (e.g for reviews see Gill, 1992; Russell et al., 2001). New Zealand studies have shown that deer can modify the species composition and abundance of forest overstoreys (consisting of trees ⩾2.5 cm dbh, diameter at breast height, Husheer et al., 2003, 2005; Husheer, 2005; Husheer and Frampton, 2005; Duncan et al., 2006; Wright et al., 2012). Responses of plant communities to this new form of herbivory are still occurring (Holloway, 1950; Bellingham and Allan, 2003; Mason et al., 2010). These responses are highly variable and idiosyncratic at a variety of temporal and spatial scales (Wardle et al., 2002). Browsing by introduced deer might also have far-reaching effects on nutrient cycling, water-quality, carbon storage (Tanentzap et al., 2011, 2012; Holdaway et al., 2012) and bird populations (Leathwick et al., 1983).

Soon after colonisation of Kaimanawa Forest Park (F.P.) by sika deer, suppression of canopy regeneration was reported (Elder, 1948, 1956; Schofield, 1957; Logan, 1957; McKelvey, 1957, 1959; Husheer, 2003), whereas in Kaweka F.P. several concurrent reports noted signs of successful canopy regeneration in beech forests in the absence of sika deer (Elder, 1948, 1959; Wallis, 1967; Logan, 1968). From the late 1970s, concern for widespread mountain beech regeneration failure in Kaweka F.P. grew following sika deer colonisation (Fleury, 1979; Wardle, 1979; Jenkins, 1982; Apthorp, 1983). Red deer do not appear to prevent beech regeneration in New Zealand (Husheer et al., 2006b), but even at low densities deer browse mountain beech seedlings (Bellingham et al., 2016). From the 1960s, a network of huts and tracks was established to aid ground-based deer culling and recreational hunting to reduce deer numbers, but from the 1970s this had no notable benefit for mountain beech canopy regeneration (Allen and Allan, 1997; Husheer et al., 2006a). Similar hut and track networks were established in Aorangi, Tararua and Ruahine F.P.s to reduce conspicuous deer impacts in forests and alpine grasslands (Cunningham, 1979; Barnett et al., 2012). With the intensification of commercial helicopter deer recovery in the 1970s, deer populations declined in Ruahine and Tararua F.P.s, but not to the same extent in Kaweka or Kaimanawa F.P.s. In adjacent Kaimanawa F.P., deer also suppress forest regeneration, but culling has not been implemented there and helicopter deer recovery restricted (Elder, 1962; Husheer et al., 2003). Where sika deer are absent in Ruahine and Tararua F.P.s, there is evidence of much less regeneration failure. This may be due to a lack of deer effects or little plot re-measurement in these two parks during DOCs tenure (Husheer, 2005).

Ongoing monitoring of permanent vegetation monitoring plots is an important component of forest conservation management in New Zealand. Both Kaweka and Kaimanawa F.P. have extensive networks of monitoring plots established on randomly located lines by the New Zealand Forest Service (Husheer, 2003). These permanent plots were augmented with a set of paired exclosure plots established between 1998 and 2000 in mountain beech forest canopy gaps, which showed widespread regeneration failure (Kaimanawa four sites, Kaweka eighteen sites, Husheer and Robertson, 2005). New Zealand plot networks have repeatedly shown that five common broadleaved, hardwood species (*Griselinia littoralis*, *Melicytus ramiflorus*, *Pseudopanax arboreus*, *Schefflera digitata* and *Weinmannia racemosa*) are prevented from growing into small trees by browsing from deer (Bellingham and Allan, 2003; Husheer, 2005, 2007; Tanentzap et al., 2009; Wright et al., 2012). Upon re-measurement, paired monitoring plots are likely to show that these species are not regenerating in Kaweka F.P. along with mountain beech.

The Kaweka mountain beech project (KMB) was established in 1998 to reduce sika deer densities in central Kaweka F.P., and to trial if aerial deer culling could reduce deer densities to low enough densities to restore canopy regeneration. The trial was successful with aerial culled areas having seedling growth comparable to unfenced plots (Husheer and Robertson, 2005; Duncan et al., 2006). Annual re-measurement of paired mountain beech monitoring plots ceased in 2004, and since 2006 deer faecal pellet counting has been used to index deer densities in Kaweka F.P. Aerial deer culling was discontinued at the end of 2015 due to "low pellet densities", DOC and recreational hunters "reduced the deer population to an acceptable level for mountain beech regeneration" (Mayo, 2016), and deer densities "reduced from 35 deer/km^2 to 20 deer/km^2" (Herries, 2016). This decision was made with support from the Kaweka Hunter Liaison group (Herries, 2015). Vegetation criteria were also a consideration in the decision to cease culling and rely on recreational hunting alone: "regeneration of mountain beech looked sufficient" and "a low vegetation index" (Herries, 2015). Earlier, an FPI of 20 (Faecal Pellet Index = 18 deer km^{-2}, Herries, 2016) and a basal area of $>$44 m^{-2} ha^{-1} was used as a critical threshold to decide to cease aerial culling in central Kaweka F.P. "allows DOC to suspend deer control once deer abundance gets below a certain level, this occurred in most of the deer control block in 2008" (Herries, 2009, 2013). Currently there is no management plan for the Kaweka Mountain Beech project, or Kaweka Recreational Hunting Area.

The objectives of the Kaweka Mountain Beech project were (McNutt, 2017):

- To reduce deer densities to levels that allowed mountain beech forest to regenerate and replace itself in more open areas.
- To establish and maintain a monitoring programme to provide information on the results of deer control operations and the outcomes for mountain beech regeneration, vegetation composition and structural change. This includes palatable and unpalatable shrub species.
- To provide information to make informed decisions on the intensity of deer control required.

The objectives of the present review are to:

1. Review the last 10 years of data which informed management decisions to date.

2. Describe the current state of Kaweka mountain beech forest.

3. Estimate the impacts of sika deer browsing.

4. Determine if objectives of the Kaweka mountain beech project have been met.

5. Make recommendations for monitoring and control where required.

In the past decade DOC has increasingly fostered recreational hunter access in remote areas of Kaweka F.P. Huts have been maintained and improved for recreational hunters. The number of helicopter landing sites have been increased. A formal booking system has been introduced so that many remote huts in Kaweka and Kaimanawa F. P.s are continually occupied from November until May. With successful recreational hunter management of sika deer in Kaweka F.P., data would be expected to show several linked trends. Reductions in deer populations would be linearly related to reductions in deer faecal pellet counts, with noticeable decreases where aerial deer culling has complemented recreational hunter efforts. Reductions in deer densities would be associated with increases in mountain beech seedling growth, survival and counts in plots. These would be comparable to fenced plots and regions with lower deer densities. Sika deer have also suppressed regeneration of plant species which are more palatable than mountain beech (e.g. kāmahi, three finger – *Raukaua simplex* and broadleaf – *Griselinia littoralis*). With highly successful deer population management, there would be evidence of sub-canopy regeneration in all forest types and canopy regeneration in kāmahi forest.

2 Methods

To determine if the Kaweka Mountain Beech project has met its objectives, archived data has been searched for, error checked, compiled and analysed. These data include culling records, deer faecal pellet data and vegetation data. Field trips to Venison Tops, Manson, Spion Kop, Tussock and Te Puke areas of Kaweka F.P. were completed in 2017, and tagged seedlings measured at paired exclosure plots. A thorough literature review has been undertaken, and in some instances data obtained from unpublished internal reports or refereed papers have been used, where it has been lost in raw format.

2.1 Deer Culling

Pre-KMB project Sika deer have steadily expanded their range from liberation east of Kaimanawa F.P. in 1905 (Davidson, 1973, A3 sized map in Appendix – Map 2, Table 1). As sika deer colonised western Kaweka F.P. (1950–1970, Husheer et al., 2006b), the New Zealand Forest Service undertook ground-based deer culling beginning in the summer of 1958-59 until the establishment of DOC in 1987 (Figure 1). During the tenure of Lindsay Poole as Director General of the NZ Forest Service (1961–1971) a greater emphasis was placed on deer culling in Kaweka F.P. to reduce impacts on alpine vegetation and forest regeneration (e.g. Poole and Adams, 1963; Poole, 1973, 1983). In that time deer cullers typically shot 1000 deer year^{-1} ($\pm$300), with 500–1300 hunter days year^{-1} spent culling, at a present value of $\approx$\$64,000 year^{-1}. Records suggest that incentive hunting began in January 1968 until the early 1970s, when culler success thereafter declined (Logan, 1968; Fleury, 2017).

In Tararua and Ruahine F.P.s a hut and track system similar to Kaweka F.P. was established to support deer culling efforts, with deer culling ceasing in the late 1980s. In Kaimanawa F.P., ground-based deer culling did not reach the same intensity during the Forest Service era (Harris, 2002). In Kaweka F.P., DOC continued to undertake ground-based deer culling from January to April 1988. From 1970, commercial hunting was permitted using helicopter recovery in Kaweka F.P.. Typically 10–12 deer were recovered per flying hour using Hughes 300B aircraft (Cox, 2016). Deer processing rates were constrained by the ability of crews to transport deer carcasses, with more time being spent on recovery and transport than on hunting. Unpermitted recovery had occurred since 1965, and continued after 1975 when permits were not renewed. Between 1965 until the late 1970s, small teams of ground based hunters used helicopters and fixed wing aircraft (e.g. Manson's Cricket Pitch and Boyd airstrips) to remove carcasses. Daily recovery loads were required for some productive hunters (4–8 deer per load in a Supercub or Hughes 300). Helicopter hunting was allowed up until the mid 1980s, with typically 5–10 deer per hunting hour being shot using Hughes 300s (Wilson, 2010). Other helicopter types were used,but the Hughes 300 was the only type used from 1965 until the mid 1990s. Commercial helicopter-based deer recovery was permitted again in Kaweka F.P. in 1998 and occurred up until 2002, with records of a total of 175 deer being recovered during the KMB project using

Robinson R22 aircraft (1998-99 n=104, 1999-00 n=15, 2000-01 n=23, 2001-02 n=33). Commercial deer recovery followed a similar pattern in Kaimanawa F.P. Unpermitted venison recovery was common in the 1970s and 1980s, and commercial venison recovery was permitted in Kaimanawa F.P. from 2000. Only 177 deer were recovered by a single operator using a Hughes 300C (Husheer and Robertson, 2005). Recreational Hunting Areas were established in both Kaweka and Kaimanawa Forest Parks in 1986 (Map 1, page 34)

KMB deer culling In October 1998, helicopter-based deer culling was initiated in $\approx$12,100 ha of Kaweka F.P., this area was reduced to $\approx$11,000 ha in 2000 (Table 2). In 2009, aerial culling occurred further west and was reduced to $\approx$8,900 ha. In 2010, funding was partly diverted from culling deer to live capture for a deer tracking study (Herries, 2011; Latham et al., 2015). The culling area was reduced further from 2013 to $\approx$6,800 ha. Most deer were culled in creek heads, slips and forest openings on calm evenings within two hours of dark (Latham et al., 2017). Although, Latham et al. (2015) showed that both female and male sika deer often preferred open tussock habitats throughout daylight hours in winter and spring.

For the first decade culling was undertaken from October through to February. After 2009, hinds were primarily targeted and culling operations were also conducted in winter to allow recreational hunters less disturbed access to sika stag hunting during their preferred summer hunting periods (see appendices and Herries, 2016 for maps and descriptions). Aerial culling ceased in November 2015, and currently the only culling of deer is by recreational hunters. Data from aerial culling has been checked by DOC staff and appears reliable. The data available on recreational hunting is less reliable with low rates of return of hunting statistics from unsuccessful hunters (Simmons and Devlin, 1981; Nugent, 1992).

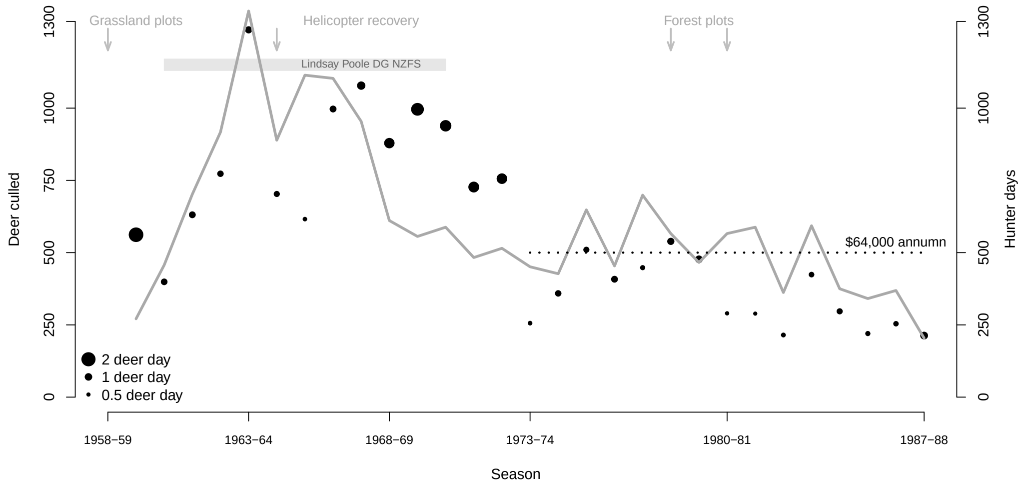


Figure 1: Summary of NZ Forest Service deer culling effort (hunter days year^{-1} —) and kills per hunter day (●) in Kaweka F.P.. Ground-hunters worked between October and May from 1958 to 1988. Data are from Davidson and Fraser (1991), Appendix 1. Years of establishment of alpine grassland monitoring plots, helicopter deer recovery, and forest monitoring plots are indicated. In 1988 deer cullers were paid \$66 day^{-1}, which for 500 culling days amounts to a 2017 value of \$64,000 annumn, and is shown.

	Area km^2
Sika range 1930	84
Sika range 1940	194
Sika range 1950	323
Sika range 1960	709
Sika range 1970	2031
Sika range 2008	8907
Aerial culled 1998-2008	111
Aerial culled 2009-2013	89
Aerial culled 2014-2016	69
KFP	619
KFP mountain beech	139

Table 1: Areas of the range of sika deer from 1930–1970 (Davidson, 1973), 1998 (Banwell, 1999) and 2008 (DOC staff estimates, Map 2). Area of Kaweka Forest Park (KFP) with helicopter deer culling areas from Figure 2.

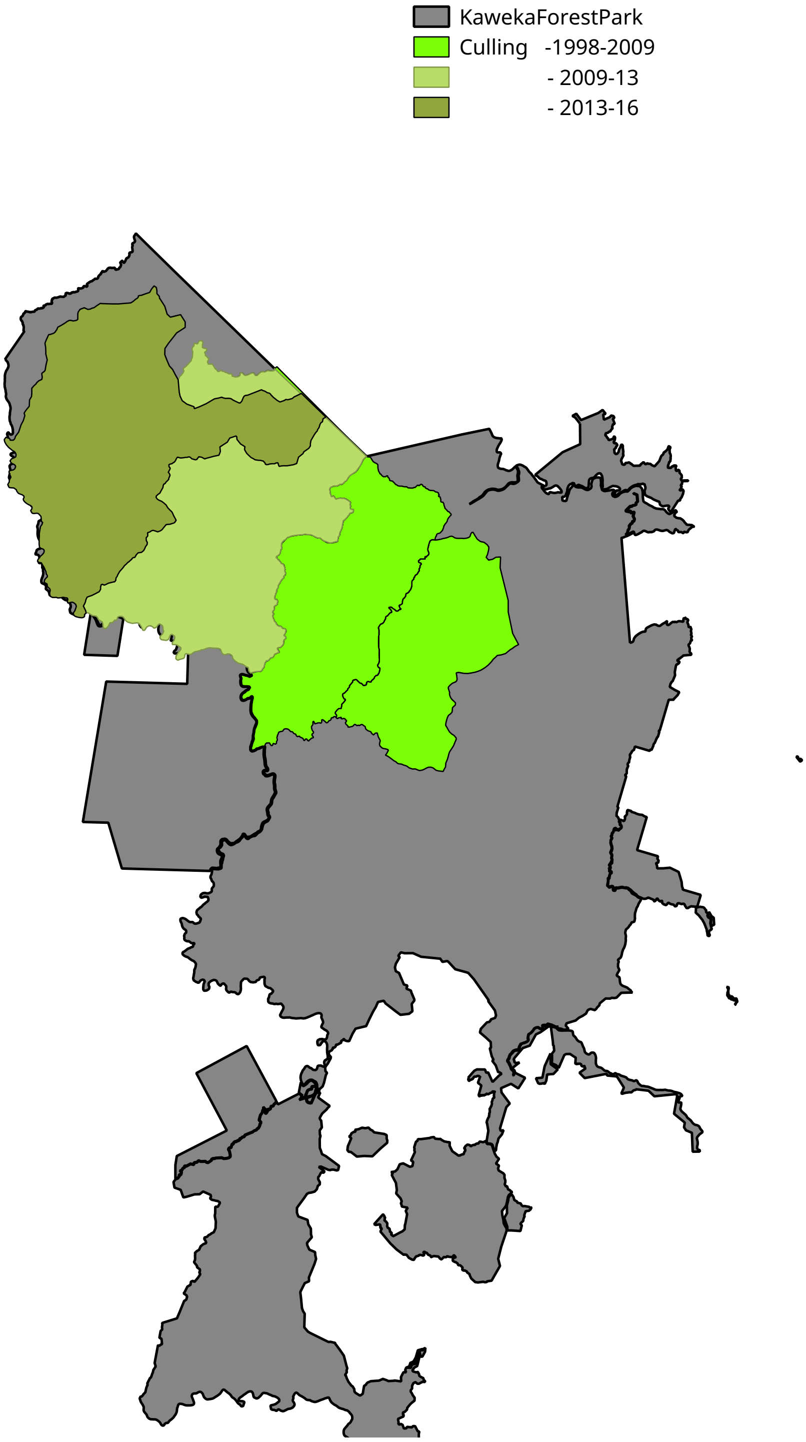


Figure 2: Aerial deer culling areas in Kaweka F.P. 1998–2016.

Season	Hours flown	Cost	Deer shot	Deer shot km^{-2}	Cost ha^{-1} (2015 cpi)
98-99	45	$32,935	382	3.2	$3.92
99-00	73	$53,229	495	4.1	$6.33
00-01	76	$60,587	421	3.8	$7.84
01-02	69	$55,440	343	3.1	$6.96
02-03	56	$44,400	320	2.9	$5.42
03-04	60	$47,853	339	3.1	$5.68
04-05	35	$28,307	245	2.2	$3.30
05-06	56	$44,693	318	2.9	$5.08
06-07	52	$41,747	225	2.0	$4.58
07-08	53	$47,400	224	2.0	$5.08
08-09	44	$51,136	288	2.6	$5.30
09-10	43	$54,229	187	2.1	$6.80
10-11	27	$36,518	128	1.4	$4.48
11-12	36	$48,240	138	1.6	$5.66
12-13	37	$50,512	206	2.3	$5.84
13-14	41	$46,728	110	1.6	$6.99
14-15	22	$22,166	58	0.8	$3.27
15-16	23	$22,883	104	1.5	$3.35
Total	849	$789,004	4531		

Table 2: Helicopter hire costs and hours flown for aerial hunting for the KMB project 1998-2016. Excludes ferry time, GST, staff and overhead costs. Culling costs ha are adjusted for the 2015 consumer price index.

2.2 Deer faecal pellet monitoring

Several faecal pellet counting techniques have been used in Kaweka F.P. to index deer densities. From 1974 until 2000 the presence of deer faecal pellets was recorded within milli-acre (114 cm radius) sub-plots along randomly selected transect lines running from water courses to ridge tops (see Map 3 appended). This method has also been used in Tararua, Ruahine and Kaimanawa F.P.s. In 1959-60, ten milli-acre sub-plots within cruciform plots (method described by Holloway and Wendelken, 1957) were used to index faecal pellet presence in the Tutaekuri catchment (n=66 plots, 25% pellet occurrence Cunningham, 1974; Table 3). During Cunningham's 1960 survey, faecal pellet presence was also recorded in 6" rings in alpine vegetation following Wraight (1960); Cunningham (1974). Cunningham's 1960 survey was repeated in 1965 (Wallis, 1967). In the summer of 1974-75, 142 permanently marked transect lines were established on random start points in watercourses in Kaweka F.P. Faecal pellet presence was recorded in milli-acre plots at 20 m intervals, (hereafter NZ Forest Service plot lines, $\approx$370 pellet groups ha, Fleury, 1980). A subset of these lines were measured in 1981-82 (no raw data for 1981-82, 30% occurrence), 1995 and 1998-2000. From 1997 to 2005, at fifteen subjectively located exclosure plot sites, the presence of pellets was recorded in 160 milli-acre plots along cruciform lines and faecal pellet groups were counted in 160 2.2 m radius sub-plots spaced at 10 m intervals.

From 2006 until 2018, a modified version of Forsyth et al.'s 2007 deer faecal pellet index (FPI) protocol was used annually to index deer densities. The FPI is calculated by counting numbers of individual intact pellets based on the definition of Baddeley (1985, described in detail in Forsyth, 2005). In Kaweka F.P. groups of pellets were counted, using more conservative definitions than described by Baddeley (1985) and Forsyth (2005). Fifty randomly located and permanently marked lines were established initially, each with thirty 1 m radius plots (3.14 m^2 at 5 m intervals). Lines were later measured at permanently marked seedling count plots measured in 2012-13 (Section 2.3). From 2008 to 2017, stratified random sampling was used, with 30 plots measured in arbitrarily selected areas of similar size. Although individual FPI sub-plots were not permanently marked, lines were, and deer may have avoided these sites following measurement. Nugent et al. (1997) warned that red deer avoid permanently marked sub-plots, resulting in faecal pellet densities 2–3 times lower than unmarked sub-plots. In Kaweka F.P., the number of faecal pellet groups (not individual pellets) with at least one pellet in each sub-plot was counted. As deer culling was shifted to western Kaweka F.P., additional lines were established. Details of Kaweka F.P. sampling strategies and methodological variance from Forsyth et al.'s 2005 protocol were not reported. While Forsyth et al.'s (2005; 2007) FPI method is more efficient than preceding methods counting faecal pellets, Allen et al. (2003) and Forsyth et al. (2011) warn managers to carefully consider the rapid adoption of new methods when long-term data is available because comparisons among differing protocols may not be wise.

As pellet count surveys are repeated over several decades, the potential for method creep increases. Definitions of what constituted a valid faecal pellet presence or faecal pellet group changed over time and between surveys in both Kaweka and Kaimanawa F.P.s, with no attempt to calibrate methods between surveys. All surveys required no loss of material from pellets, but the amount of cracking, deformation and decay allowed varied. From 1960–1974 definitions described by Bell (1973) and Apthorp (1983)'s were used, which required an unbroken cuticle and no descernable decay to be intact (allowing for drying cracks, Fleury, 2017). From 1974 until 1982, Baddeley's (1985) definition was used, which allowed pellet decay, cracking and deformation. After 1995, more conservative definitions of intact pellets tended to be used – shifting towards Apthorp's (1983) definitions. Pellets with large cracks, pits (>1 mm), deformation and cuticle deterioration tended to be excluded. Field staff also recall methodological changes between 2006 and 2017 (Mayo, 2017; Lee, 2017), which means that inconsistencies in the application of FPI from 2006–2017 may be just as large as variation with earlier protocols. In 2018, an attempt at collecting comparitive data was made by counting pellet groups using a conservative interpretation of Forsyth's 2005 definition of intact cuticles (no significant pitting and no cuticle deterioration), as well as the interpretation used by DOC's Tier 1 teams which allows for deep pitting, cracking and cuticle (shiny membrane) deterioration.

The number of pellets required to constitue a group declined over surveys, so there was potential for field operators to count what would have been called a single pellet group in early surveys as two or more pellet groups in recent surveys. However, the occurrence of multiple pellet groups in a plot was infrequent enough to reduce the chance of this occurring – 62% of FPI plots contained only one pellet group.

Regardless of changes in definitions of pellet validity, if the average time from defecation of a pellet group until it no longer meets validity criteria is known, the rate of detection of valid pellets by individual operators is known, and the number of defecations of faecal pellets per day is known, deer density can be calculated (Riney, 1957; Bell, 1973; Baddeley, 1985; Fraser, 1998). Unfortunately, wild deer defecation rates are highly variable depending on animal species, sex, age, season and diet (Neff, 1968; Dzieciolowski, 1976; Mitchell et al., 1985; Rogers, 1987; Mayle, 1996; Mayle and Staines, 1998; Mayle et al., 1999). In the absence of reliable data, deer defecation rates in Kaweka F.P. have been guessed at 30 pellet groups per day. This high defecation rate was assumed due to the sika deer browsing large amounts of poor-quality woody vegetation. From personal field observations sika deer seem to produce smaller pellet groups than other deer species. This speculative assumption is high in comparison to previous studies assumptions (e.g. 8 defecations per day for captive muntjac *Muntiacus reevesi*, Chapman, 2004; 17–23 for roe deer Mitchell et al., 1985; 12.5 for red deer Nugent et al., 1987; 25 for sika Nugent et al., 1997, 14 for moose, *Alces alces*, Rönnegård et al., 2008; 20–23, Mayle et al., 1999; 22–52 for whitetail, *Odocoileus virginianus* Rogers, 1987). Red deer may have lower defecation rates than sika deer and were dominant in Kaweka F.P. and southern Kaimanawa F.P. up until the 1980s, when sika deer became more common (Davidson, 1973, 1979; Davidson and Fraser, 1991). Overseas studies show that deer pellet decay rates are also highly variable. Pellets can decay within a month or last over a year depending on deer diet, pellet group size and number, weather, habitat and definitions of pellet validity (Van Etten and Bennett Jr, 1965; Aulak and Babińska-Werka, 1990; Hemami et al., 2005; Swanson et al., 2008). Pellet decay and disappearance rates may also be non-linear, with most pellets in an area decaying within weeks, while some may take months to decay (Hemami and Dolman, 2005; Brodie, 2006; Skarin, 2008; Davis and Coulson, 2016; Jung and Kukka, 2016). Cleared plot techniques have been used to overcome unknown rates of decay (Neff, 1968), but deer may avoid permanently marked cleared plots (Nugent et al., 1997), and cleared plot techniques have not been used in Kaweka F.P.. In New Zealand, most faecal pellet surveys use a definition of pellet group validity described by (Baddeley, 1985), where pellets are intact if no recognisable or significant amount of material is lost, regardless of whether the pellet is cracked or the cuticle intact, has fungal growth, is partly broken, or deformed by trampling or other causes. Using this criteria pellets groups usually remain valid for 3–6 months. Three surveys in Kaimanawa F.P. (Atkinson, 1981; Apthorp, 1983; Whiteford, 1983) and recent surveys in Kaweka F.P. used more strict criteria (Mayo, 2017), so that most pellet groups were invalid within a month of defecation. Holes or flaking of the outer coating, broken cuticles (membranous outer coating), and major cracks were not allowed. Pellets had to be visible without disturbing litter. Up until the introduction of the FPI protocol in 2006, a pellet group was defined as six or more intact pellets from one defecation. The FPI protocol used from 2007 allowed single pellets to be counted as a group, so that a pellet group might remain intact for over a year. The assumptions made in deer density analyses are summarised in Table 3.

Deer densities were calculated with equation 1, where D = (Deer km^{-2}, pellet group density (PGD) = Mean deer faecal pellet groups km^{-2} (Smith, 2012), pellet decay rate (P.Dec) = days from defecation until no longer meeting valid criteria and defecation rate (P.Def) = valid pellet groups per day per deer.

$$\frac{PGD}{P.Dec \times P.Def} = D \tag{1}$$

Error in deer density estimates were calculated by increasing estimates of faecal pellet densities by .1, increasing decay rate estimates (halving the time until a pellet is no longer valid) and lowering defecation rate estimates to 20 per deer per day (Table 3).

2.3 Seedling count monitoring

In the summer of 2005-06, tree basal area was estimated at 230 sites systematically located on a grid in an area mapped as mountain beech in Kaweka F.P. (Map 4). One hundred and eighty nine sites were actually in mountain beech forest and thirty of those (16%) were classed as low basal area using the prism-angle gauge method (Grosenbaugh, 1952). On those mountain beech plots with a basal area ($<$44 m^2 ha^{-1}), mountain beech seedlings ($\leqslant$135 cm high) in a 10 m $\times$ 10 m plot were counted and their heights recorded. On twenty plots with large numbers of seedlings ($>$100), a sub sample of 4–15 2.5 m $\times$ 2.5 m sub-plots were measured. Saplings were counted at twelve plots where they were present. Between November 2012 and January 2013 the survey was repeated using the same seedling counting protocols, with 207 randomly selected sites in mountain beech forest assesed for low basal area. Sampling was extended into southern Kaweka F.P. in the 2012-13 survey, but sampling intensity appeared to be reduced in western Kaweka F.P. particularly around Ngawapurua, but the reason for this is not recorded (see Map 4). Seventy eight plots (37%) were recorded as low basal area. All seedlings were measured in the second survey, with no sub-sampling undertaken. Saplings were counted at 35 plots where they were present. Duncan et al. (2006) used the 2005-6 data (with tagged seedling data, section 2.4) to model the number of years required for canopy replacement, and provides method details. From February to May 2018 plots identified in the 2012-13 survey as low basal area were re-measured using the same protocols. Five low basal area plots were omitted because there were in streams or on steep bluffs.

2.4 Paired fenced 10 m × 10 m plots

One hundred and twenty 10 m × 10 m seedling monitoring plots were subjectively established between 1997 and 2003 in Kaweka F.P. mountain beech forest (1997-98 season n=48; 1998-99 season n=51; 2001-02 and 2002-03 n=21, described by Taylor, 2003). At twenty sites (where paired plots were 100 m or more apart), fences were established to exclude one or two plots, paired with unfenced plots. Establishment criteria varied, but plots were mostly subjectively placed in conspicuous canopy gaps with a range of seedling densities (3–>100). The heights of mountain beech seedlings (5–160 cm high) were measured in plots, although the protocols used required either all seedlings or all seedlings in some sub-plots to be tagged. In some plots in some years all seedlings were measured, but this was inconsistent. At many other plots where it was deemed too time consuming to measure all seedlings, seedlings were measured from a subset of 2.5 m × 2.5 m sub-plots (commonly but not always in a checkerboard pattern). Individual seedlings were numbered with an aluminium tag wired to its stem and its pull-up height measured (cm) to the end of the previous seasons growth (where light coloured new-seasons growth replaced darker growth). As plots were established they were generally re-measured annually up until 2001. Seedling plots were established within a 20 m × 20 m overstorey plot using the protocol described by Hurst and Allen (2007). Data was entered into a series of error prone xcel spreadsheets in an idiosyncratic format, and appear to have been lost or made inaccessible on the DOC computer network (Allan, 2008; McNutt, 2017). From May to October 2017, a field audit was undertaken as part of a re-measure of a selection of paired plots. Fortunately, data from 1998–2001 used by Husheer and Robertson (2005) is still available, and was used by Duncan et al. (2006). From February to May 2018 paired plots were re-measured at eighteen sites where data checking and 2017 field audit showed all seedlings had been tagged by 2000 (Husheer, 2018).

2.5 Data Analysis

Faecal pellet and culling data were provided in xcel spreadsheets, which were checked and converted to text files (comma separated value). Because measurements were counts, data distributions followed a Poisson or quasi-binomial error distribution. Making analysis options even more complicated is the fact that the relationships in FPI among time and space were of most interest. So not only does the lack of independence need to be allowed for, but parameters of most interest need to be modelled spatially and temporally. A series of statistical models were used for exploration and testing. Firstly, least squares linear models were used, then general linear models, and ultimately hierarchical models were used with fixed effects of culling, time and space and mixed effects of time and line identity. Model coefficients were extracted for presentation in Figure 5 (Clark and Bjørnstad, 2004; Gelman and

Hill, 2007) using lmer functions in R (Bates and Maechler, 2010; Pinheiro and Bates, 2009). Because pellet counts were log transformed with residuals near normally distributed, Generalised Linear Mixed Models (GLMM) were not used. When spatial data were included in a model, tests for auto-correlation were undertaken (Moran, 1950). When useful, a spatial correlation matrix was constructed and included in generalised least square models (Pinheiro et al., 2017). A New Zealand digital elevation model (DEM) was downloaded from the land resource information systems portal (www.lris.scinfo.org.nz) and used for spatial prediction. Climate, geology and vegetation landcover layers were also explored but proved less useful that location data (Lris, 2010).

Tagged seedling data were used to calculate seedling relative growths (Swanborough and Westoby, 1996; Equation 2). Relative growth rates of individual seedlings (hereafter seedling growth) is a commonly used index of plant growth that allows for height bias in growth rates of seedlings. Seedling mortality, recruitment and total counts were summarised for each paired plot and compared between fenced and unfenced plots.

$$\frac{log_e \, \text{seedling height}_{2017} - log_e \, \text{seedling height}_{2001}}{16 \text{ years}} \tag{2}$$

3 Results

3.1 Deer culling 1958–1988 and 1998–2016

Historical records for ground based deer cullers from 1960 until 1988 showed a mean of one deer shot per hunter day (min 0.5 deer shot per day in 1982 and max 2 in 1960), or <1 deer km^2. There are no records of DOC funded deer culling or commercial hunting between 1988 and 1997. Aerial deer culling effort and deer kills per flying hour in the KMB project reduced from 1998 until cessation in 2015 (Figure 3). Although culling areas and timing altered, there was a consistent decline in culling effort and the numbers of deer shot per km^2 (Figure 4). Funding remained consistent up until 2004 when both the culling budget and culling hours nearly halved (Table 2). Deer culling was most effective from September to January, while in winter months fewer than five deer per flying hour were shot (5.5 September–February vs 3.6 June–August, t=3.039, df = 26.4, P = 0.005). Cull rates and animal counts are commonly used to index ungulate abundance (e.g. Brennan et al., 1993; Nesslage and Porter, 2001; Matsuda et al., 2002; Potvin and Breton, 2005; Storm et al., 2011; Forsyth et al., 2014). The potential to use helicopter culling results in KFP as an index of deer abundance has been confounded by changes in methods, areas and personal. Some crews appeared more efficient and improved with experience. After 2009, culling excluded stags, flying hours declined further, and included some carcass recovery for TB necropsy.

Before 2000, DOC managers attempted to improve data from recreational hunting. Recorded recreational hunter permit issues (2461), returns (409, 16.7%) and recorded deer kills peaked in 1999 for Kaweka FP. For that year hunters declared 334 sika deer shot and 22 red deer (366 total deer shot) for 1579 recreational hunter days in Kaweka F.P. (0.6 deer km^{-2} and 4.3 hunter days per deer shot). Although recreational hunters were less efficient than deer cullers, their greater numbers meant that overall recreation hunters shot more deer ($\approx$double). If hunters who did not return permits were as successful as those who did return permits, >2,000 deer would have been shot in Kaweka FP in 1999, which may be the upper credible limit. Nugent and Fraser (1993) showed that recreational hunters shot $\approx$54,000 deer year^{-1} in New Zealand in the early 1990s. At that time there were $\approx$250,000 deer in forested deer range inNew Zealand (4 deer km^{21}.) Since 2000, there has been a general decline in hunting permit data returns from hunters. Record compilation appears to have ceased in 2007 with no records available for Kaweka F.P. after that time. Permits that have been returned to DOC with useful data have shown that recreational hunters removed less than one deer km^{-2} annumn^{-1}. Helicopter air-transport operators have confirmed that most recreational hunters are unsuccessful with five to ten hunter days spent per deer kill.

Data from the Sika Foundation is generally consistent with 1999 DOC permit records, with low rates of hunter success in comparison to deer culler kill rates. Organised recreational hunter groups undertook hunts throughout Kaweka and Kaimanawa

F.P.s in March, June, October and November 2017 (Sika Foundation, 2017). In the March to October hunts, Sika Foundation hunters shot 37 deer in 195 hunter days, or a mean of 6 days per deer. In the November organised hunt, hunters shot 14 deer in 126 hunter days, or a mean of 9 days per deer. Most hunters did not shoot any deer in organised hunts.
The DOC hut booking system in Kaweka F.P. shows that huts and helicopter accessed camps in the general area covered by Kaweka mountain beech forest were booked for 2474 hunter days in 2017. This 310 km^2 area is generally accessed only by hunters using helicopter air transport operators, with few hunters walking to remote hunting areas (west of Kaweka Recreational Hunting Area – Kiwi Saddle, the main Kaweka range and the Makino River). Extrapolation of these results suggests that there are over eight hunter days spent per km^2 in Kaweka and Kaimanawa F.P.s combined (1323 km^2), and under 1000 deer shot. These speculative figures were calculated by dividing the known number of hunter days (2474) by hunter success (5.6 days to shoot a deer). This rate of 440 deer in the 310 km^2 of western Kaweka F.P. is then extrapolated to 1323 km^2 of Kaweka and Kaimanawa F.P. for 932 deer shot.

Faecal pellet data collected since 2009 in Kaweka and Kaimanawa F.P.s suggests that there are $>$15 deer km^{-2} in these parks and a total population of $>$20,000 deer (Section 3.3 and Figure 8). DOC aerial, commercial and recreational hunters shot $>$13 deer km^{-2} between October 1998 and June 2001 in the aerial culling area of Kaweka F.P., with many deer still remaining (Husheer and Robertson, 2005). It is possible that deer density is $>$20 km^2 in large areas of Kaimanawa and Kaweka F.P.s. Recreational hunters probably annually harvest $<$1.5 deer km^{-} annumn^{-1}, or $\approx <$10% of the total deer population in Kaweka and Kaimanawa F.P.s. Without reliable data on deer densities and recreational hunter success, these results are speculative.

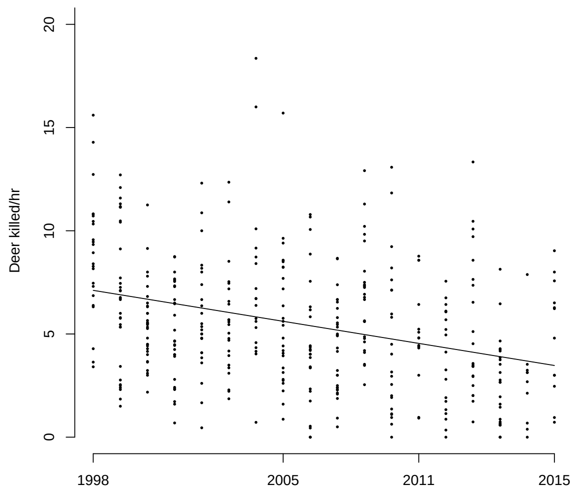


Figure 3: Numbers of deer culled in 411 aerial deer culls between October 1998 and November 2015 in Kaweka F.P.. A least squares regression line is fitted (P<0.001, R^2 = 0.097, year coefficient = -0.202)

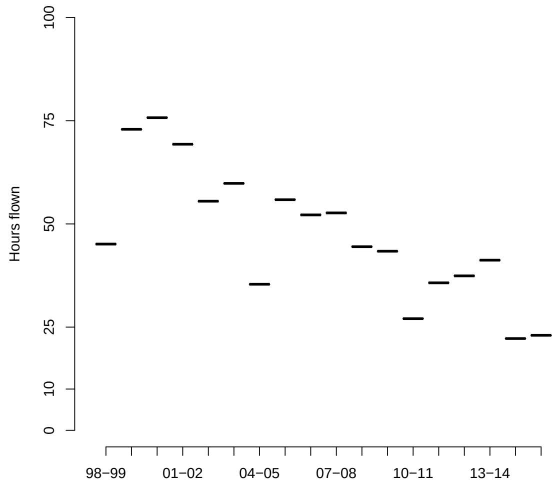


Figure 4: Hours flown in 411 aerial deer culls between October 1998 and November 2015

3.2 Deer faecal pellet monitoring

Deer faecal pellet groups per line (mean Faecal Pellet Index, FPI) remained between 10 and 25 between 2006 and 2018 with variation among years up to 63%, and typically 27% (Figure 5). The large difference in 2018 between different pellet definitions highlight the erratic potential of data. A least squares regression showed no evidence from FPI of any change over time, and a t-test showed higher FPI in lines in culling areas compared to lines without aerial deer culling in 2017 (21.6 vs. 16.2; s.d = 11.9, t = 4.01, df = 109.1, $P < 0.001$) or with all years combined (21.7 vs. 14.1; s.d = 12.8, t = 10.48, df = 1104.6, $P < 0.001$). Attempts to explain variation among years with a spatial model showed no interpret-able pattern. These tests on FPI data violated fundamental assumptions of most statistical analysis. Lines were repeatedly measured, and some plots were close enough to one another that they had similar characteristics, particularly with regard to culling effects. Data were probably not independent through space and time, and residuals from count data were not normally (gaussian) distributed. Because of slow rates of pellet decay, FPI results lagged effects and changes in culling by up to two years.

Deer faecal pellet group counts were converted to pellet groups density ha^{-1}, and compared over time (Figure 6). There was no significant difference in faecal pellet densities between areas aerial culled and areas with recreational hunting alone for pooled 1998 to 2017 data ($\bar{x}$ = 263 vs. $\bar{x}$ = 307, t=1.22, df = 127.8, P = 0.222). Culling areas are illustrated in Figure 2 and the area listed in Table 1. The lack of comparability in cruciform pellet surveys using the method described by Taylor (2003, 1997–2004), and the FPI method of Forsyth (2005, 2007–2017) is apparent. This appears to be an issue of changes in criteria of pallet validity rather than counting methods, because there is a strong relationship between pellet group density and pellet occurrence in 1 m radius plots from FPI surveys (Figure 7).

Power analysis (with significance level = 0.05 and power = 0.8) showed that twelve FPI lines are required to detect a 50% decline in FPI (from 18.6 in 2017) or four lines for an increase of 100%. Detection of an increase mean FPI of 10% requires 257 lines. The 150 lines re-measured in 2017 could detect a change in FPI between two surveys of 2.8 (15%), using a paired t-test.

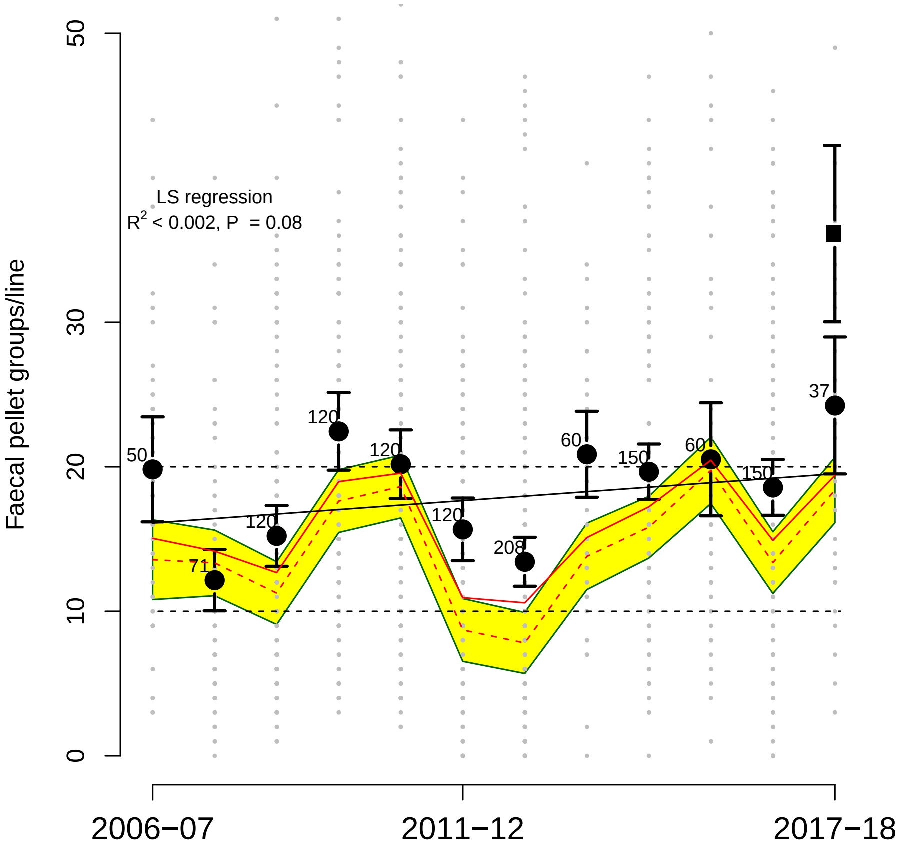


Figure 5: Deer pellet group occurrence on lines of thirty sub-plots measured using a modified version of Forsyth et al.'s 2005 faecal pellet index (FPI) protocol between 2006 and 2017. Means with 95% error limits (•) and measurements based from 2018 on DOC's (2016) definitions (■) are displayed. The number of lines for each survey year (n = 50–208) are shown. A line of best fit (—) using least squares regression is displayed (non-significant slope P=0.08). Fixed effects coefficients from a mixed effects model for lines with (—) and without (- - -) culling are displayed within a region of confidence (2 × SE of fixed effect coefficient). Dashed lines are arbitrary limits of 10 and 20 used by Mayo (2016) to differentiate between low, "acceptable" and high deer densities.

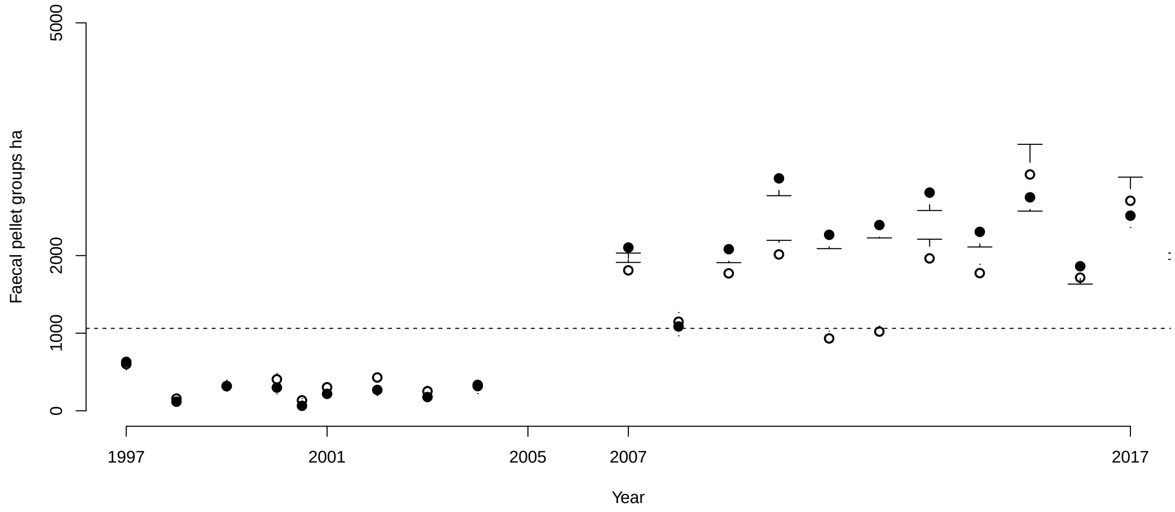


Figure 6: Mean deer faecal pellet group densities from fifteen deer exclosure sites in Kaweka forest park measured annually in summer seasons from 1997-98 to 2004-05 (map Appendix 1), and on FPI lines measured in summer seasons from 2007-08 to 2016-17. Areas with aerial culling (•) and areas with recreational hunting alone (○) are differentiated. Error bars are standard error of means

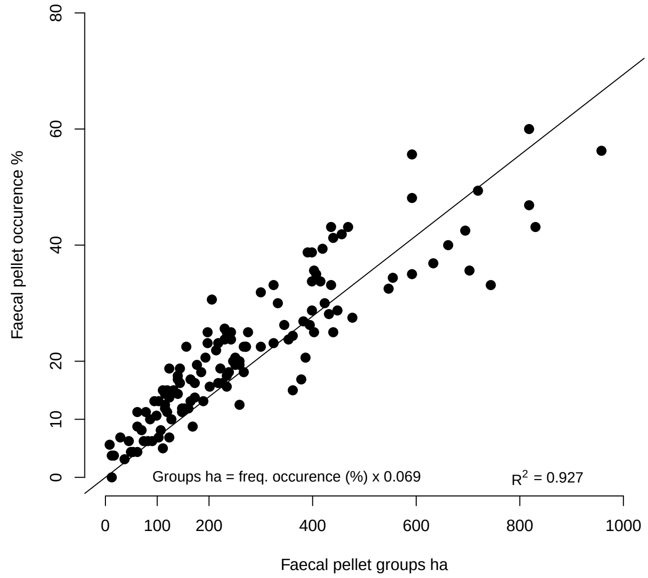


Figure 7: The relationship between deer faecal pellet group counts and pellet frequency of occurrence from FPI lines measured in summer seasons from 2007-08 to 2016-17. A least squares regression line is fitted with an intercept of zero. Results from that regression are displayed (P <0.001)

3.3 Estimates of deer density

Despite the cautions of previous authors against using pellet counting techniques for estimating densities of deer populations which are under 30 km^{-2} (e.g. Fuller, 1991; Marques et al., 2001; Laing et al., 2003; Forsyth et al., 2007; Soofi et al., 2017), an attempt was made to compare absolute population densities using different pellet counting protocols by allowing for pellet decay and deer defecation rates (Table 3). These estimates of deer densities in Kaweka and Kaimanawa F.P.s derived from faecal pellet data suggest that deer numbers may have remained between 5 and 20 deer km^{-2} over the past four decades (Table 3, Figure 8). When the potential for uncertainties in defecation and decay rates was included in estimates, a two to four-fold level of potential error became apparent. In contrast to Kaweka and Kaimanawa, in the South Island's Arawhata Valley deer densities appear to have declined in the decade following the first pellet survey in 1969. Venison recovery began in the Arawhata Valley in the mid 1960s when a helicopter crew could recover >3000 deer in a month (up to 20 deer recovered for each flying hour, Wolf, 2015). Cessna 185 aircraft were able to land on gravel riverbeds and alluvial flats to efficiently transport carcasses to road transport locations, allowing helicopter crews to spend most of their flying time hunting and recovering carcasses. In contrast, more time was spent transporting deer carcasses in Kaweka F.P. than in hunting and recovery at that time. The Arawhata catchment exceeds 1000 km^2 of deer habitat, and in some years between 1965 and 1975 >10,000 deer were shot (>10 deer km^{-2}) during commercial deer recovery operations (Adams, 2017). In contrast, venison recovery in the Kawekas in the mid 1960s achieved $\approx$10 deer per hour flown to road-ends(Cox, 2016). By 1970, kill rates in the Arawhata had declined to <5 deer flying hour and by 1974 <2.5 deer flying hour (typically 200 deer recovered per month for a single operator). The Arawhata deer population appears to have remained <5 deer km^{-2} since the mid 70s (Figure 9).

Survey	N lines	Days until decay (P.Dec)
Kaweka F.P.		
1960 Cunningham	66	365
1965 Wallis	66	365
1974 Fleury	142	182
1981-82 Jenkins	56	182
1995 NZFS lines	22	365
1998-2000 NZFS lines	56	182
1997–2005 KMB exclosure sites	130	365
2007–2016 Herries	1079	365
2017 Mayo	150	365
Kaimanawa F.P.		
1978 Fleury		182
1980 Apthorp		19
1981 Atkinson		19
1981-82 Cleland		19
1982 Whiteford	124	19
1985 RHA		365
1986 RHA		356
1988 Brabyn		365
2004 Husheer	83	365

Table 3: Summary of assumptions made on deer faecal pellet decay rates (P.Dec) for estimation of deer density from faecal pellet data (Equation 1)

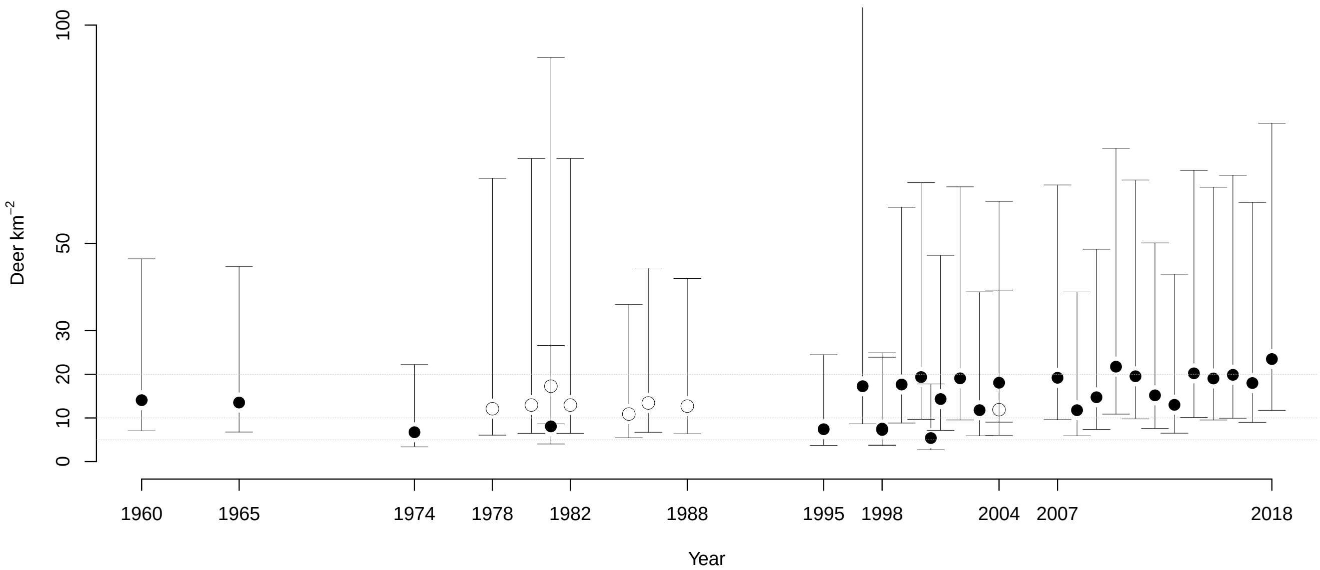


Figure 8: Deer densities predicted from faecal pellet surveys in Kaweka (•) and Kaimanawa (○) F.P.s using assumptions in Table 3 and Equation 1. Upper error bars are estimated by halving the number of days a pellet groups remain intact and lowering defecation rates to 20 per day in calculations. Lower error bars are half predicted densities. Estimates of statistical (sampling) error are not included in error bar calculations.

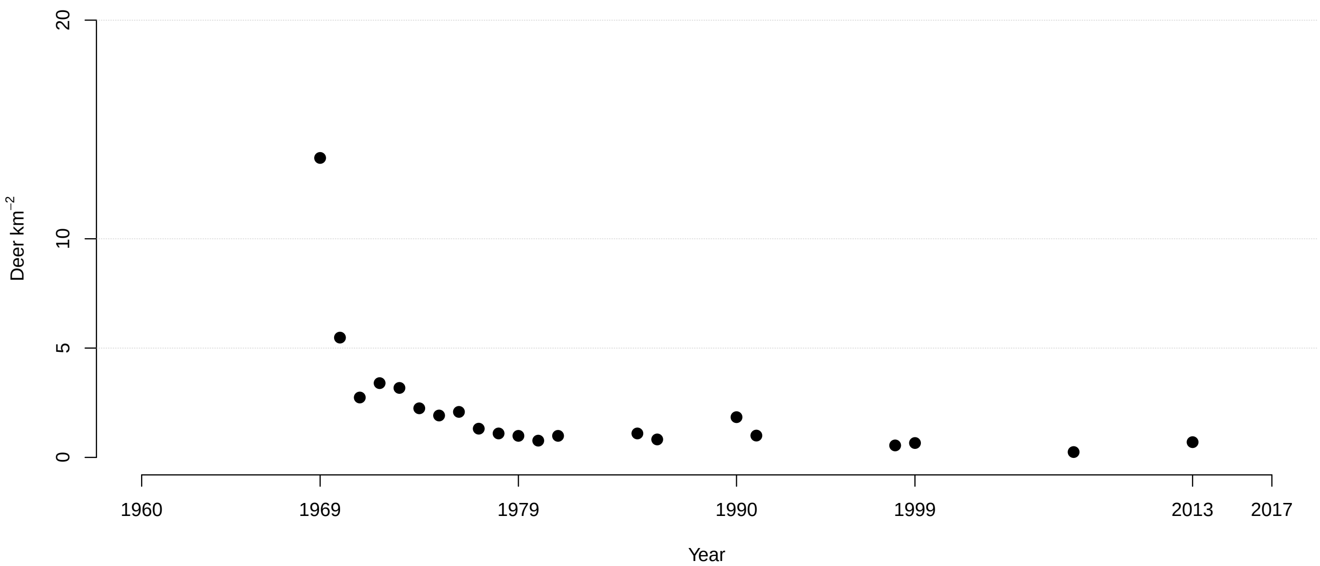


Figure 9: Deer densities predicted from faecal pellet surveys from nine presence-absence lines in the central Arawhata Valley, South Westland. Lines run from the valley floor to alpine grasslands and had milli-acre plots spaced at 25 m intervals (Husheer, 2013). Five pellet group decay rates studies between 1971 and 1976 showed pellets disappeared in one year (Challies, 1977), and defecation rates were assumed to be 25 per day. Lines were measured by NZ Forest Service, DOC and NZ Forest Surveys (2013).

3.4 Seedling count monitoring

In the 2005 seedling count survey of Kaweka F.P., 30 of 189 sites were classed as low basal area mountain beech forest by field staff and had seedlings counted (16%). In 2012 this increased to 78 of 207 sites (38% low basal area, $\tilde{\chi}^2$ = 12.944, df=1, P<0.001), suggesting that there had been an increase in low basal area sites in Kaweka F.P.. Changes in sampling design, inclusion of steep sites and other evolutions of methods between surveys could also explain some of this variation. At these low basal plots, there was a mean of 47.2 seedlings counted in 2005, which declined to 13.1 by 2012 (t=2.041, df = 30.801, P = 0.049). Seedling counts declined further in a February to May 2018 remeasure of 2012 low-basal plots (Husheer, 2018). Mean seedling height increased from 32.6 cm in 2005 to 42.9 cm in 2012 (t=2.498, df = 55.147, P = 0.016). Statistical power analysis of 2012 data showed that re-measurement of 30 seedling count plots could detect a doubling in seedling counts (i.e. from a mean of 13 to 26 seedlings per 10 m × 10 m plot). Twenty plots could detect an increase to 30 seedlings per plot.

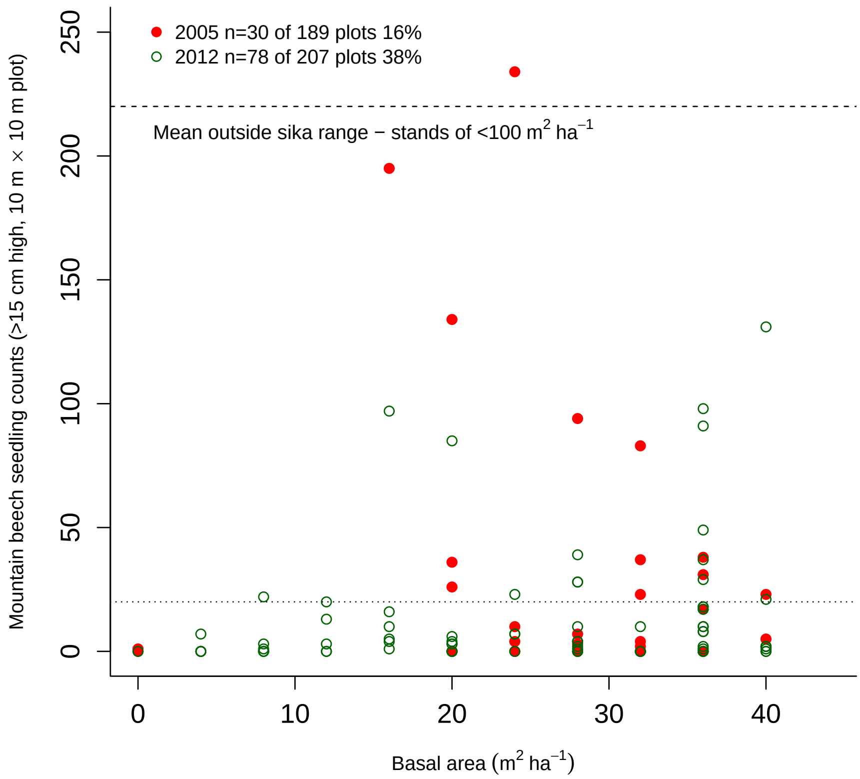


Figure 10: Numbers of mountain beech seedlings counted in low basal area plots in Kaweka F.P. in 2005 and 2012

3.5 Tagged seedling monitoring

A randomised block anova (with deer exclosure site as a blocking variable) showed significantly higher mountain beech seedling relative growth rates in fenced plots compared to seedlings in unfenced plots ($F = 9.672$, d.f. $= 8,77$, $P < 0.001$). Tagged seedlings re-measured in 2017 grew a mean of 1.9 cm a year outside fenced plots (se = ± 0.5), but in fenced plots grew 8.5 cm (± 0.9) a year ($P < 0.001$). At most sites measured in 2017, very few seedlings survived outside fenced plots (Figures 11 and 12, but see Husheer, 2018).

Figure 11: Tira Lodge Paired exclosure plot in May 2017, established 1998. Several hundred mountain beech seedlings inside fence, few outside.

Figure 12: Thorough searching required to find seedlings in unfenced Otutu paired exclosure plot in October 2017.

4 Discussion

4.1 Deer culling 1958–2016

Ground-based deer culling in Kaweka F.P. from 1958–1987 was unsuccessful at restoring mountain beech forest regeneration or increasing palatable tree diversity (Cunningham, 1974; Fleury, 1979; Wardle, 1979; Allen and Allan, 1997). Despite 200–1300 deer being shot annually up until 1987, deer populations remained at high densities (probably >10 deer km^{-2}). Commercial deer culling occurred from 1965 to the late 1980s, with Hughes 300 aircraft being used throughout and frequently recovering >10 deer per flying hour (Wilson, 2010; Cox, 2016). Continued high success rates of government and commercial hunters up until the late 1980s suggest that deer populations were not reduced to low levels by hunters. This contrasts with South Island commercial hunters, who by the late 1970s were recovering under five deer an hour (Challies, 1977; Nugent et al., 1987; Parkes, 2006). Despite the lower number of deer recovered, high carcass weights and fewer restrictions make South Island commercial recovery economic (Parkes et al., 1996). Although commercial helicopter hunters could probably currently recover 1–5 deer hour^{-1} in Kaweka and Kaimanawa F.P.s, carcass weights are low, legal access is poor and returns uneconomic (Wilson, 2017).

A trial of aerial deer culling in an 11,000 ha area of Kaweka F.P. between 1998 and 2001 ($\approx$1 culling hour year^{-1} km^{-2}) was successful, and showed that canopy regeneration could be restored in Kaweka F.P. mountain beech through intensive DOC aerial deer culling at a cost of $\approx$\$10 ha year^{-1} (Husheer and Robertson, 2005). Following the trial, it was shown that the intensity of culling should be sustained where it already existed (Duncan et al., 2006), and that culling should be applied throughout both Kaweka and Kaimanawa F.P.s (Husheer et al., 2003). Instead, both the extent and intensity of deer culling declined, and ceased in 2015 (Herries, 2013; Mayo, 2016). Where sika deer are on DOC land, they remain at high densities (>5 deer km^{-2}) despite decades of unmanaged recreational hunting.

Results do not support the hypothesis that reduced aerial culling and reliance on recreational hunters has reduced sika deer densities to levels where forest regeneration is restored. Instead, evidence from 2018 shows poor mountain beech seedling growth, survival and density in Kaweka F.P. (Husheer, 2018). Successful nature conservation in Kaweka F.P. requires increased – not decreased – aerial deer culling. Pest control is more likely to be successful if it is intensive, sustained and controls all pests affecting forest regeneration (Norton, 2009; Ramsey et al., 2018). Possum control operations using 1080 can result in deer kills, and deer culling costs may be reduced if culling occurs in conjunction with possum control. OSPRI plan an aerial 1080 operation in Kaweka F.P. in 2019 using deer repellent (OSPRI Kaweka fact sheet). Numbers of deer killed in an aerial 1080 possum control operation may vary depending on the type of bait used, deer species and condition, and vegetation condition. Deer populations have been reduced by >90 % using large carrot baits with high poison concentration, to ≈50% using a pollard bait, and <10% using deer repellent (where pig or cattle blood is sprayed over baits; Forsyth, 2002; Morriss, 2007; Graf, 2015). The numbers of deer killed in operations using deer repellent baits is uncertain (Forsyth et al., 2013), although there may be an increase in risk to native bird populations (Morriss et al., 2016). Deer populations may act as a reservoir of bovine TB (*Mycobacterium bovis*, Nugent et al., 2015) for over a decade and can re-infect possum populations with TB so there may be benefits for TB eradication of sustained culling sika deer populations (Nugent, 2016).

4.2 Plants and deer impacts

Kaweka F.P. mountain beech forest remains in a poor state with evidence of deterioration over past decades (Sections 3.4 and 3.5). Deer have prevented seedling regeneration, so that the density and survival of seedlings has declined. Duncan et al. (2006) showed that deer density would need to be maintained at low levels (possibly <1 deer km^2) for several decades to restore mountain beech forest cover in Kaweka F.P. (Figure 13). The main demographic parameter for monitoring regeneration was seedling growth in paired exclosure plots. Seedling growth measurements in paired plots from 2001–2017 show that sika deer continue to suppress mountain beech regeneration. In the absence of successful culling, most of Kaweka F.P. mountain beech forest will be converted to shrub-lands in the next century. With increases in high wind and high snowfall storms, this deterioration may occur in a few decades.

Other forest types are likely to be affected by sika deer browsing. In western Kaimanawa mixed beech–kāmahi forest a paired exclosure plot study showed that kāmahi (*Weinmannia racemosa*) seedling regeneration is prevented by deer browsing (Cieraad et al., 2015; Figure 14). In that study, naturally occurring woody seedlings were monitored between 2005 and 2013 in paired fenced–unfenced–artificial gap–intact plots to determine the growth responses to the removal of herbivory along artificial canopy gap gradients. The study showed that along with kāmahi, miro *Prumnopitys ferruginea*, red beech *Fuscospora fusca*, *Coprosma lucida* and *C. tenuifolia* were prevented from regenerating at randomly selected monitored sites. Similarly, deer browsing in Kaweka F.P. is widely suppressing broadleaf (*Griselinia littoralis*), māhoe *Melicytus ramiflorus* and three-finger *Pseudopanax arboreus* regeneration. Browsing by deer in the unproductive alpine zone appears to have prevented recovery of vegetation above the treeline (Figure 15 Mark, 1989; Coomes et al., 2003; Mark and McLennan, 2005; Tanentzap et al., 2009; Cruz et al., 2016). Large areas of regenerating mānuka-kānuka scrub in south-east Kaweka F.P. are unlikely to be restored to tall mountain, red and black beech forest in the absence of successful culling.

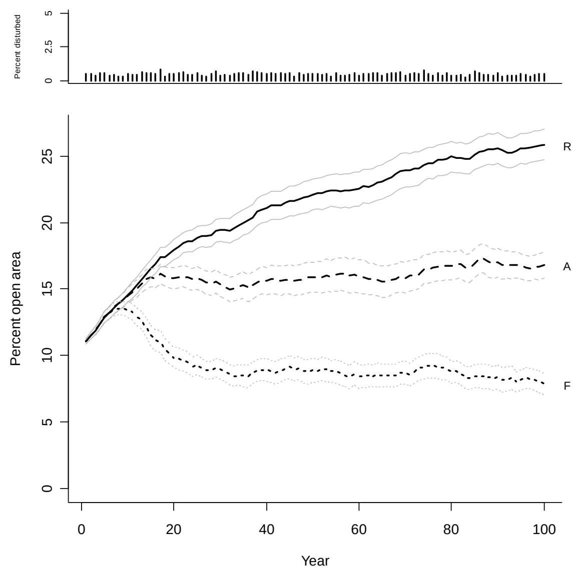


Figure 13: Figure 13 from Duncan et al. (2006), showing a radomised simulation model of forest disturbed annually ($\bar{x}$ $\approx$0.5% forest disturbance annumn^{-1}, upper graph), and the amount low basal forest forest with fencing (F), aerial culling (A), recreational hunting (R, lower graph). Confidence intervals are 95% of the mean.

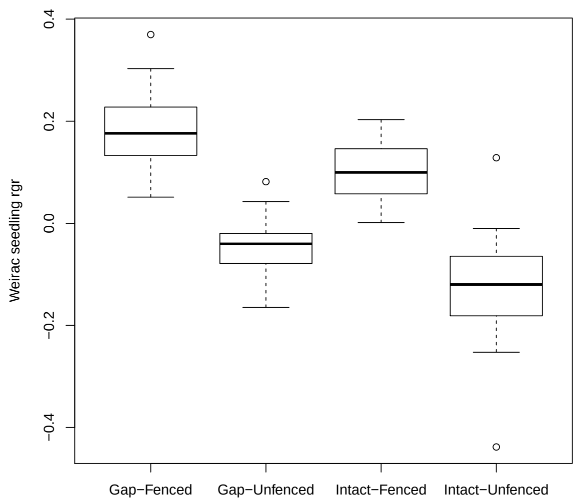


Figure 14: Kāmahi seedling relative growth rates from paired exclosure plots, western Kaimanawa F.P., measured by NZ Forest Surveys 2014

Figure 15: Spion Kop grassland plot in 2017 (G35, lower picture), which is representative of other alpine plots visited in Kaweka F.P. in 2017. The plot was established in 1960 above the natural tree-line and re-measured in 1981 (middle) following the method of Wraight (1960). Unpermitted sheep grazing occurred up until 1966 (Logan, 1968). In the plot, palatable alpine grasses and herbs have declined and bare ground increased. Slow-growing unpalatable alpine shrubs have increased. In the background beech seedlings appear to have established in the 1960s with red deer present, and have grown into small trees. Since 1980, unpalatable shrub species have colonised.

4.3 Faecal pellet monitoring

Intuitively more deer will leave more faecal pellets on the ground. Repeated studies have shown that other factors upset that simple and direct relationship between deer density and pellet counts, to the extent the faecal pellet monitoring is too unreliable for guidance of decision making (e.g. Dzieciolowski, 1976; Mayle and Staines, 1998; Smart et al., 2004; Brodie, 2006). However, a New Zealand study suggested that a deer incresed pellet density by 140 ha^{-1} in 20 deer enclosures (Forsyth et al., 2005). But this relationship is variable, even in the same season (68–227 pellets ha^{-1}).

Faecal pellets can decay faster in dry and warm sites, and disappearance rates increase in windy sites with high litter-fall. Poorer habitat may result in poorer and lower dietary intake resulting in lower total pellet defecation. For these reasons the FPI may be just as good an index of micro-climate at individual lines, or seasonal changes in weather in Kaweka F.P., as it is at indexing deer density. Operator bias may also vary more than the 10% used in the present study for the calculation of upper limits of the deer densities (Jenkins and Manly, 2008). Faecal Pellet Index (FPI) results are difficult to interpret, and do not appear to be linearly related to deer density. If the relationship between FPI and deer density were consistent among years, FPI shows biologically impossible increases between 2009 and 2010 and again between 2013 and 2015 in the deer population. FPI has also shown inconsistent results in Kaimanawa Forest Park (Forsyth et al., 2013). Because FPI appears to be an inadequate technique at estimating deer density in Kaweka F.P., FPI results are likely to be misleading. This may potentially be dangerous if managers take them at face value. Although FPI showed that deer had increased in density, and densities were higher in aerial culled areas, this may not be the reality (Legg and Nagy, 2006). Forsyth et al. (2007) cautions against comparisons in pellet frequency of occurrence surveys with FPI as has been undertaken here, because as deer abundance increases plots will become saturated once occurrence reaches high levels (e.g. >50%). Comparisons between pellet group counts and presence were closely linear in Kaweka F.P. suggesting that saturation was not as important an issue as variability in decay rates among years. The erratic results are more likely to be due to changes between seasons and sites in pellet decay, defecation rates and operator definitions of what an intact pellet group is. Without definitive information on decay and defecation rates faecal pellet monitoring will remain imprecise. Changes among observers may also be an issue. Pellet counting techniques have also proven ineffective for hares, with hare decay rates varying from 7–>36 months in a Nelson Lakes study (Flux, 1967). FPI may be able to detect a doubling or halving of deer densities at best. Power analysis shows that 10–20 lines are required to detect a doubling in FPI for each treatment area (culling – no culling). Using more lines than this will increase statistical precision and may provide a false sense of confidence in results.

Despite these uncertainties, faecal pellet monitoring from 1960–2017 indicates that deer densities have remained between 5–20 deer km^{-2} in Kaweka and Kaimanawa F.P.s for the past six decades despite commercial, government-funded and recreational deer hunting. Because of poor reporting and data storage of faecal pellet data

FPI results should be treated cautiously (Section 5.2). Nevertheless rates of harvest in KFP suggest that deer populations were >16 deer km^{-2} in 2000 (Husheer and Robertson, 2005).

In summary, there are several reasons why faecal pellet techniques should not be relied upon for measurements of change in deer density in Kaweka F.P.:

1. FPI results obtained from Kaweka F.P. to date are erratic and confusing, senstive to methodological interpretation, and suggest that faecal pellet group counts are unlikely to be related to deer density. Future results are also likely to be unreliable, even if they appear more sensible. Previous authors have claimed that faecal pellet counts can be used as an index of deer density (Husheer and Robertson, 2005; Forsyth et al., 2011), but for an index of density to be useful it needs to be closely related to density with high confidence.

2. Deer culling may take several years to reduce deer densities, and reductions may be at rates as low as 1 deer km^2 year^{-1}. Depending on definitions, valid pellets may remain intact for one or more years so FPI results will lag changes in deer density making analysis complex and potential confusing.

3. Forsyth et al. (2007) were unable to detect differences in deer density with FPI of much less than 100%, and then only at much higher densities than in Kaweka F.P. ($\approx$50 vs. $\approx$200 deer km^{-2}; but see Forsyth et al., 2011). FPI is unlikely to be able to detect differences required by Kaweka F.P. managers (i.e $\approx$10 vs. $\approx$5 deer km^{-2}, Figure 16).

4. Kaweka F.P. managers require estimates of changes in deer densities with and without culling of <50%. Forsyth et al. (2007) concluded that while faecal pellet counts and deer density were linearly related, that deer densities could not be predicted from faecal pellet counts. Forsyth et al. (2007) also cautioned against comparisons among years without specific knowledge of actual deer densities. In that case FPI should not be recommended to Kaweka F.P. managers who need to know absolute densities in order to judge the relative success of aerial culling. Other techniques should be considered instead. See Section 5.1.

5. Repeated measurements of pellet group densities spanning decades must allow for creep in the application of definitions of what an intact pellet is and how much effort is placed in searching for pellets. Inevitably, this will vary over time rendering faecal pellet monitoring less useful than concurrent comparisons among sites (Van Etten and Bennett Jr, 1965; Caughley et al., 1976; Jenkins and Manly, 2008).

6. Identification, disappearance, defecation and decay rates of deer vary depending on factors such as the species, sex and age of animals, habitat type, season and diet. Juveniles produce smaller faster-decaying pellets (Hanya et al., 2017),

and sika deer pellets tend to be smaller than red deer. Decay is also likely to vary with habitat and diet (Skarin, 2008; Jung and Kukka, 2016). Rain, temperature and humidity (both soil and air) affect the decay rates of pellet groups, which have varied in Kaweka and Kaimanawa from under 20 days to over one year. Variation among seasons in decay rates can lead to particularly miss-leading results (Aulak and Babińska-Werka, 1990; Bayliss and Giles, 1985). Pellet count results need to be converted into deer densities to be most meaningful. Depending on the defecation rate used and the decay rate of pellets, which will vary at fine- and course-scales, different density estimates will be obtained. This renders comparisons of densities among regions to high bias from arbitrary selection of decay and defecation rates — seriously limiting the application of FPI for management.

7. Forsyth et al.'s 2005's appears to be an efficient method of counting pellet densities in comparison to past protocols, with low standard deviations and high confidence in mean values. This can give a false sense that equal confidence can be applied to relative deer density estimates. Even when the relationship between pellet counts and deer density is known, it is likely to be highly variable within and between years and sites in Kaweka and Kaimanawa F.P.

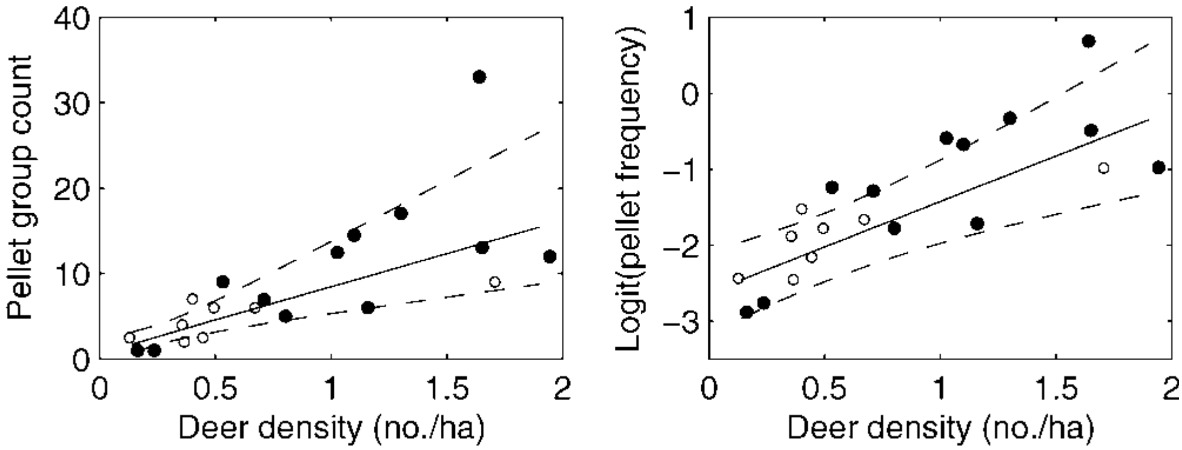


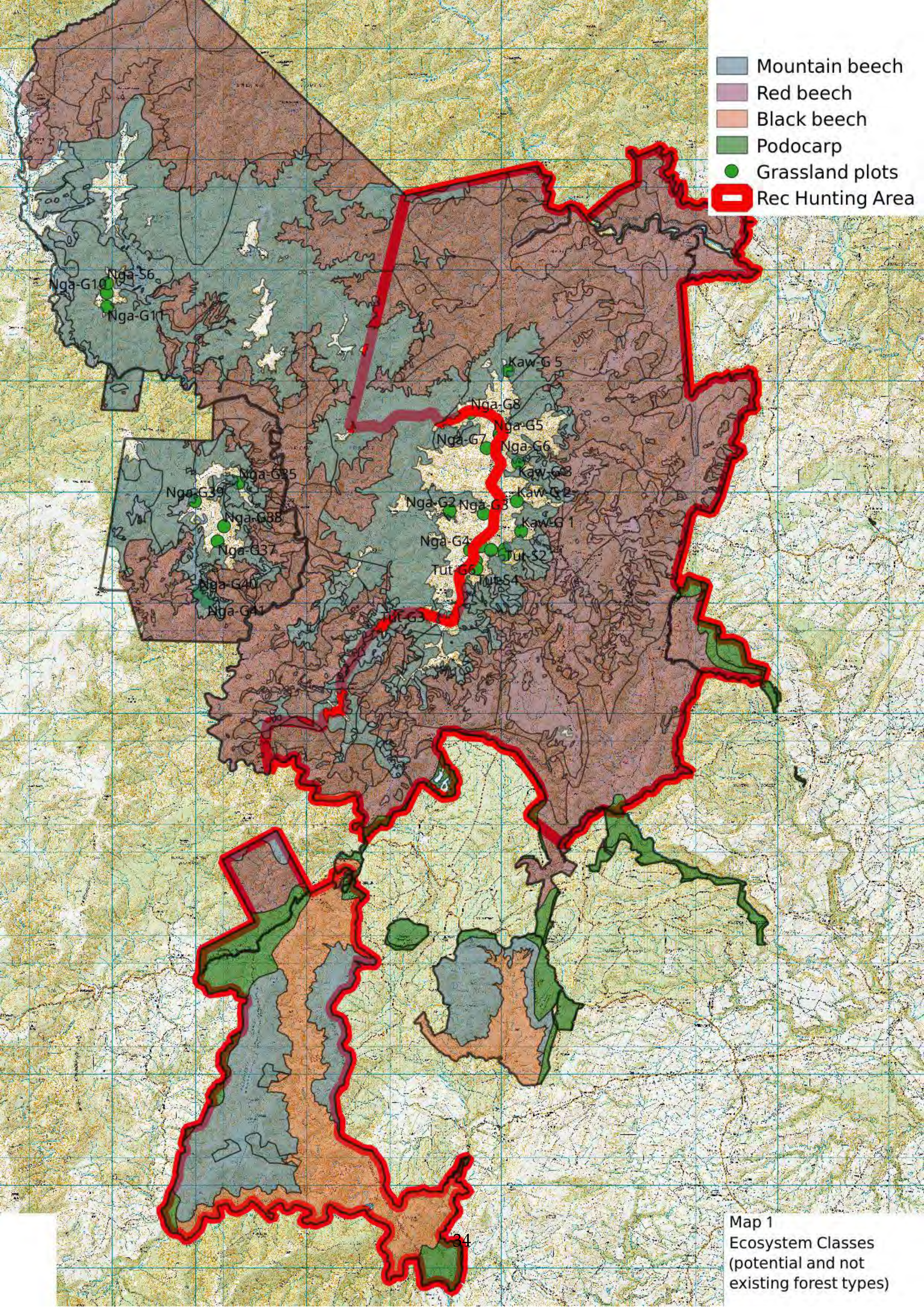
Figure 16: Copy of Figure 2 from Forsyth (2007), with fitted relationships between deer density ha^{-1} and FPI (left) and pellet frequency of occurrence (right). For North Island sites (○) mean FPI was 3–10 (vs.sometimes >20 in Kaweka F.P.), for estimated deer densities between 13 and 170 deer km^{-2}. The graph illustrates FPI is probably able to reliably and repeatedly differentiate between populations of 10 and 100 deer km^{-2}, whereas Kaweka F.P. managers need to be able to differentiate reduction is deer densities from 20 to 10 deer km^{-2}. Only one site in Forsyth's study (a 76 ha South Island enclosure with a density of 164 deer km^{-2}) had a higher FPI than the 2017 Kaweka FPI of 18.6.

4.4 Carbon storage and soils

New Zealands total greenhouse gas emissions have grown by $>1\%$ per year in the past decade, offset in part by an increase in carbon stocks in indigenous forests on conservation land (Bellingham et al., 2014). Between a first measurement in 2002–2007 and a second in 2009-2013 of MFE's LUCAS plot system there was a net increase in carbon pf 0.56 tonnes ha year^{-1} across public conservation land. These stocks are $\approx$ 111 ($\pm$4) tonnes ha^{-1} in above-ground biomass, and increasing by $>$1 year^{-1}, mostly at sites reverting from shrubland to forest (Beets et al., 2012, 2014). Although the effects of introduced ungulates on New Zealand carbon stocks are likely to be small (Peltzer et al., 2010; Tanentzap and Coomes, 2012, Figure 17), there may be localised reductions in carbon storage if forest regeneration is suppressed (Holdaway et al., 2012). Long-term effects on forest succession, diversity and carbon storage may be massive on a regional or national scale (Burrows et al., 2008). Mānuka-kānuka forest regenerating into beech forest can reduce atmospheric carbon, if not prevented through browsing by deer of beech seedlings. Following beech forest collapse, there is likely to be a decline in Kaweka forests up to 100 tonnes ha^{-1}. Tall mountain beech forest is currently being replaced by slow-growing small-leaved shrubs of much lower biomass. Carbon prices are projected to exceed \$20 tonne in the next decade. If regeneration of Kaweka and Kaimanawa forests is not restored there is a risk that a carbon liability in excess of \$1,000 ha may be incurred (i.e. tens of millions of dollars of carbon value lost). Although deer culling is expensive ($>$\$10 ha year), it is less than the current value of stored carbon. Managers should focus efforts on managing deer and their effects on forest regeneration in the period that follows major canopy disturbance such as is currently occurring in Kaweka F.P. (Bellingham et al., 2016).

If Kaweka F.P. forests continue to decline there are likely to be implications for erosion and hydrological processes. Global warming is forecast to result in more severe storms. In conjunction with reduction in tall forest cover, gully and channel erosion on moderate slopes and landslides on unstable slopes will become more common (Glade, 2003). Deforestation may lead to increased flood flows and sedimentation in the Ngaruroro, Mohaka and Tutaekuri catchments (Ellison et al., 2017; Zhang et al., 2017).

Unpublished data from paired exclosure plots shows that the presence of deer and goats compacts soils by $\approx$10% (Tanentzap and Coomes, 2012). Soil compaction reduces the air content of soils affecting root growth and nutrient availability, reduces plant cover and water storage, and can increase the potential for erosion and high flood flows (Nguyen et al., 1998; Russell et al., 2001; Drewry, 2006). As litter input into soils reduces in quality with high deer densities, nutrient input may also be affected. Unpublished data suggests that deer browsing can reduce phosphorus input into soils at some sites (Figure 18). As deer browsing converts tall forest into shorter stature forest and shrub-lands in Kaweka F.P., affects on flood-flows and soil nutrient loss become more likely



Map 1
Ecosystem Classes
(potential and not
existing forest types)

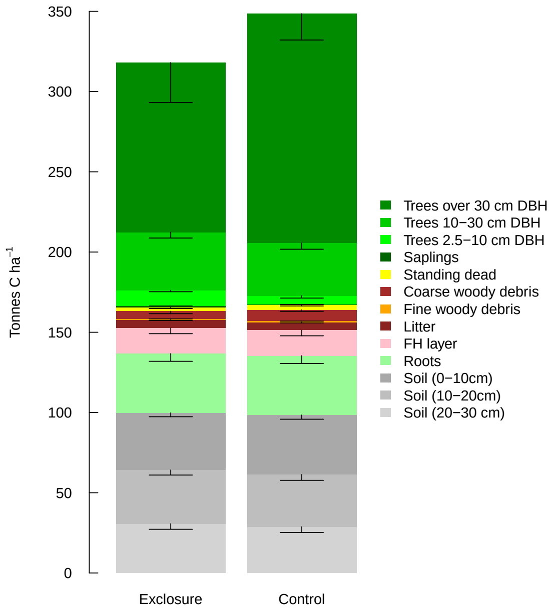


Figure 17: Carbon from 32 paired exclosure plots measured by NZ Forest Surveys 2009

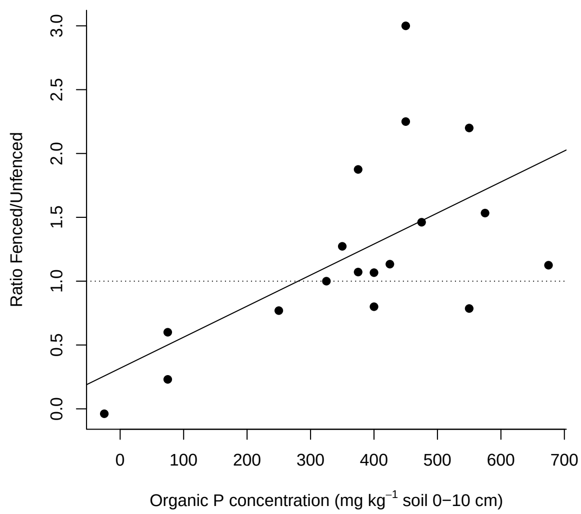


Figure 18: Soil organic Phosphorous from 18 paired exclosure plots measured by NZ Forest Surveys 2008

4.5 Management of deer in Kaweka F.P.

Because the KMB project does not appear to have reduced deer densities and restored mountain beech canopy regeneration in the past decade, current decision makers have a wide range of options available without being encumbered by previous decision making. Table 4 summarises options. The optimal choice for managers will be a compromise between availability of funding, public acceptability and operational risk. Recreational hunting is important in Kaweka F.P. and so maintaining sika deer at high density is important to a large number of park users (Nugent and Fraser, 1993). Recreational hunters can oppose conservation management if it is likely to result in less successful hunting (Fraser, 1989). The majority of deer (over three-quarters) are shot by a minority of hunters (under one-quarter) who have success rates of approximately one deer per hunter day (Nugent, 1992). The typical kill rate of sika deer by hunters on conservation land is one deer per five to ten hunter days, so most hunters (possibly >80%) have very low success rate (harvest <20% of deer). This is similar to the success of hunters in the 1980s in Blue Mountains (15 hunter days deer^{-1}; Nugent et al., 1988), Oxford (9 hunter days deer^{-1}; Nugent and Henderson, 1990), Kaimanawa (6 hunter days deer^{-1}; Fraser and Sweetapple, 1992) and Pureora Recreational Hunting Areas (5 hunter days deer^{-1}; Fraser, 1996) . Most deer in Kaweka and Kaimanawa F.P.s are likely to be shot by a small group of highly successful hunters (perhaps only a few hundred hunters). If deer numbers are lowered to levels satisfactory for forest regeneration the average hunter will experience poor hunting. These less succesful hunters would then require several weeks of hunting to shoot a deer, and likely to loose interest in hunting in Kaweka F.P. It is unlikely that reasonable average hunter satisfaction can be achieved when intensive culling is undertaken (i.e. enough to assure mountain beech forest regeneration).

The most cost-effective control options for culling are likely to be politically and operationally risky. Targeting deer with poison or even removal of deer repellent from baits may pose an unacceptable public relations risk to DOC. Aggregated application of 1080 pellets can increase possum kill rates, and reduce costs and native bird deaths (Nugent et al., 2012; Nugent and Morriss, 2013; Morriss et al., 2016), and if high concentrations of 1080 are used in large baits, rates of deer kills could be high. A combination of long-term ground and aerial culling may prove to be an acceptable option. That option would likely cost in the region of \$200,000–\$300,000 per annumn including auditing and monitoring. If cullers are responsible for nearly all deer kills, a minimum population can be calculated, which is an additional benefit (Section 5.1). Culling intensity sufficient to lower deer densities enough to assure forest conservation is likely to cost in the region of ten dollars a hectare a year. Past aerial culling has used DOC staff and expensive gas turbine powered helicopters (costing ≈\$1000 an hour to run), so there is potential for efficiency gains without compromising safely. A Robinson R22 costs as little as \$500 an hour to run on hunting and a more stable Hughes 300 \$600 (Hire Rates). There is a significant jump in cost with the fast and productive turbine powered helicopters where running costs can exceed $1,000 an hour. If contracts for aerial and ground culling are tendered, auditing of work would need to be taken seriously. Ground observers checking flight paths and verifying kills would be a consideration as part of key performance indicators of a culling contract.

	Cost	Operational risk	Conservation outcome	Animal welfare	Public acceptability	
No expenditure	Low	Low	Poor	Poor	Poor	Conservation management no longer subsidised by recreational funding
Foster Rec hunting	Med	Low	Poor	Med	Good	Current management – >$100,000 expenditure on hunter facilities and liaison for <1000 deer annumn
Aerial deer culling <$10 ha year	Med	Low	Poor	Good	Good	Ineffective in past decade
Ospri possum control with deer repellent	High	Med	Poor	Poor	Poor	Uncertainty on effectiveness of repellent in deterring sika deer in KFP mtn beech. Few deer poisoned in Kaimanawa Forest Park
Ospri possum control without deer repellent	Low	Med	Med	Poor	Poor	May reduce deer density by >90% depending on bait. Variable effectiveness on deer even with pre-feed and large baits
Aerial deer culling >$10 ha year	High	Low	Good	Good	Med	Proven in first years of KMB project. Continued success not assured
Ground-based deer culling	High	High	Med	Good	Med	Can be very effective with a team of pro deer cullers. High risk of poor hunter quality. H&S risk
Foliage 1080	High	High	Good	Poor	Poor	Potentially effective at sustaining deer densities to low levels
Aerial 1080 deer baits	Med	Low	Good	Poor	Poor	Potentially effective

Table 4: Matrix of management options for deer culling in Kaweka Forest Park. Operational risk includes operations failing to be fulfilled to expectations. Conservation outcome refers to natural forest regeneration including mountain beech regeneration. Aerial and ground-based deer culling can be an effective index of deer density (catch per unit effort – Brennan et al., 1993; Forsyth et al., 2014). Deer repellent covered 1080 bait sown in Kaimanawa F.P. killed ≈10% of sika deer (Ospri, 2017). Limited trials of foliage baiting have been undertaken in KFP and other areas (Batcheler and Challies, 1988; Veltman and Parkes, 2004)

5 Monitoring requirements

5.1 Deer impact monitoring

The objectives of the KMB project "to provide a monitoring programme to assess mountain beech regeneration, vegetation composition and structural change including palatable and unpalatable shrub species" have not been met. Because vegetation monitoring has been neglected in the past decade, it has become necessary to re-measure existing plots to provide contemporary data to justify the restoration of deer culling in Kaweka F.P. Seedling count monitoring in 2005-6 was undertaken to allow development of a predictive model on mountain beech regeneration, and is not a reliable long-term technique for monitoring changes in mountain beech canopies or seedling regeneration.

Mountain beech 10 m × 10 m seedling plots In Kaweka F.P., there are thirty-three pairs of 10 m × 10 m seedling exclosure plots (n=66 plots) established between 1998 and 2000 at eighteen sites. At some of these sites fenced plots are far enough apart that they might be considered independent replicates, and so it might be possible to reliably measure over twenty pairs. To provide useful data on small-tree recruitment within fenced plots a minimum of fifteen paired plots should be re-measured. Data is available for all plots up until 2001, but measurements from following seasons (up until 2004) appears to be lost. Another fifty-six 10 m × 10 m tagged seedling plots without fenced pairs were established between 1998 and 2004, with most of the data from those measures having also been lost. In each 10 m × 10 m plot an assortment of mountain beech seedlings were tagged and measured. Seedling and sapling sub-plots were measured upon plot establishment following the methods of Hurst and Allen (2007). All seedling plots had 20 m × 20 m overstorey plots measured at the time of establishment following Hurst and Allen (2007). This means that 10 m × 10 m plot measurement would fulfill the KMB project objective of monitoring mountain beech canopy replacement and the state of palatable and unpalatable species. Plots should be re-measured following the recommendations of McNutt (2017) and Allan (2008). Thereafter a decision should be made on abandonment and fence removal. If deer culling is implemented again, the information from these paired plots will not be relevant due to the two decade lag from their establishment.

To provide a representative comparison, a selection of at least twenty of the 10 m × 10 m seedling count plots measured in 2012-13 at low basal areas sites should also be re-measured. Palatable seedlings and saplings should be measured also. While on site, FPI lines could cost-effectively be re-measured, although given past results that data are unlikely to be useful.

Alpine grassland plots Deer have an impact on alpine grassland vegetation, as well as grass and scrub-lands where forest is currently establishing. Vegetation above the natural tree-line is very slow growing and appears vulnerable to deer browsing. A selection of the alpine grassland plots established in 1960 in Kaweka F.P. have been recently visited and show decline or little change above the treeline (Figure 15). Below the treeline there has been rapid scrub growth since last measurement in 1980 (mānuka, neinei, toatoa). There are 28 grassland plots located above the natural treeline (⩽6 degrees mean annual temp), and these should be a priority for measurement.

Deer abundance monitoring Cost-effective methods for estimating the deer population in Kaweka F.P. might be considered by those designing a long-term monitoring system:

1. FPI has been an uninformative method for estimation of deer densities, and has cost hundreds of thousands of dollars to implement in Kaweka F.P. in the past decade. Results are difficult to interpret and appear unreliable. Power analysis showed that only 10–20 lines are required for FPI to detect a deer population doubling. This is a level where statistical imprecision is less than the likely inherent error in estimation of deer abundance from faecal pellet counting (at least two fold). Therefore FPI should only be undertaken when a vegetation plot is measured, as the incidental cost of measurement while on site is low.

2. Camera trapping has been used as a monitoring tool, but its potential is unclear for estimating deer densities (Foster and Harmsen, 2012).

3. (Tanentzap et al., 2009) used the method of McCullough et al. (1990) to estimate deer density. The method requires an accurate estimate of population harvest and a representative sample of aged jaw bones (counting dental cementum layers) (Fraser and Sweetapple, 1993). It assumes low rates of immigration or emigration, age structure stability and no change in the age specific vulnerability of deer to hunting (Gove et al., 2002). Age-specific fecundity data would also provide the ability to calculate the potential for population increase, and to confirm that the population is demographically stable. A representative sample of jawbones and data on fecundity should be collected during culling operations. Recreational hunters may also be interested in deer weights and indices of condition.

4. Catch per unit effort (CPUE) is routinely used in the United States (Roseberry and Woolf, 1991) and Japan to monitor deer abundance (Matsuda et al., 2002; Uno et al., 2006, 2009; Kaji et al., 2010), and may be a more accurate index of deer abundance than FPI. Because recreational hunter success is highly variable (one deer shot each 1–20 hunter days depending on hunter quality) and permit return rates low and probably biased (Fraser and Sweetapple, 1992), recreational hunter kill return data should not be relied upon for CPUE. Instead, ground and aerial deer culling data could be compiled and used as an index of deer abundance. Ground deer culler data is available from 1958. Hughes 300 aircraft

have been used since 1965 and operator interviews have revealed a consistent 5–10 deer recovered per hour up until 2001. Managers could set arbitrary objective thresholds (e.g <1 deer helicopter hour and $<$ one deer per professional deer culler day), and monitor the response of tagged seedlings to that index of deer density. CPUE indicies could then be compared to McCullough et al.'s 1990 method to gauge the historical usefulness of aerial and ground deer culler success data. Other techniques such as aerial surveys (Linchant et al., 2015; Haroldson et al., 2003), DNA analysis of pellets (Goode et al., 2014; Ramón-Laca et al., 2014; Yamashiro et al., 2017), trail-cameras (Foster and Harmsen, 2012; Jacobson et al., 1997; Dougherty and Bowman, 2012) and FPI might also be compared.

5.2 KMB data management and reporting

Data collection, auditing, entry, storage and management Several million dollars have been spent on vegetation and deer faecal pellet monitoring in the KMB project since 1998, with a surprisingly low proportion of that data currently ready for statistical analysis. Considerable amounts of data collected from 1998 to 2006 can not be found. With the exception of permanent 20 m $\times$ 20 m forest plots measured on random lines from 1980 until 2000 and seedling count survey data from 2005-06, a search of the NVS data bank and DOC repositories in 2017 found no vegetation plot data in digital form. During the course of producing this review much lost data has been re-found. There were no records on NVS (DOCs long-term vegetation plot data repository) of the 120 10 m $\times$ 10 m seedling and understorey (and associated 20 m $\times$ 20 m overstorey) plots measured between 1998 and 2004. There were no records of the 2012-13 seedling count survey on NVS. The 2012-13 seedling count survey data held by local DOC offices had conspicuous errors which have been addressed. Error rates would need to be massive to affect interpretation of results, given the large reduction in seedling counts from 2005-06 to 2012-13 and 2018. Likewise raw data from faecal pellet surveys prior to 2005 appears to be lost, along with some of the associated pellet decay rate data. Most of the raw data from faecal pellet surveys by NZ Forest Service appears to have been lost during the 1987 transition to DOC. Faecal pellet data collected since 2006 is available in raw data. This is in a series of error-prone xcel worksheets. Dozens of additional hours were required during the preparation of this report in error checking.

Despite Excel being the most widely used software for storing data in DOC, it is usually a terrible choice for data base management and analysis. It is typically used because it is familiar and easy to use. Unfortunately, short-term ease of use is offset by long-term problems. The inability to directly see entered data (e.g cell references, formulae and text appearing as numeric) induces errors. Poor version control, poor file sharing (e.g R will not read some entries into Excel workbooks), inability to act relationally, and the ability to format data for analysis, appearance and printing make excel spreadsheets a terrible choice for data storage. All modern database and statistical analysis packages can easily read data stored in comma delimited format (.csv). In this format, columns of data are simply separated by commas. For the KMB a dedicated database should be used to store meta data, and raw data in separate comma delimited format, which can be read by databases (e.g. Access, MySQL, sqlite), statistical analysis packages (e.g R, SYSTAT and SPSS) and spreadsheets. Normalised databases eliminate redundant data (for example, storing the same data in more than one table or comma delimited file) and data dependencies are simple (only related data in a table). This reduces the amount of space required and most importantly ensures that data is logically stored.

Data should not have to be edited during analysis. When errors are found the authoritative data set should be edited by the person responsible for managing that data. To ensure compatibility of data all FPI data should use the same data storage template. Microsoft products should never be used for data analysis (McCullough and Heiser, 2008; Yalta, 2008). Future data collected should be promptly entered into digital databases suitable for purpose. A suitable database, would be normalised, relational, have national consistency and have integrated error checking. Data should be readily available for statistical analysis, and publicly available. Part of the development of a long-term monitoring plan for Kaweka F.P. should include a data management and quality assurance plan.

6 References

Adams, B. 2017. Personal communication, Brian "Tug" Adams. Haast 2017. – Personal interview by Sean Husheer. 21

Allan, C. 2008. Kaweka Mountain Beech Project programme review and monitoring proposal 2008–2013. – Tech. rep., Department of Conservation, Hawkes Bay District Office. 12, 39

Allen, R. and Allan, C. 1997. Mountain beech forest dynamics in the Kaweka Range and the influence of browsing animals. – Science for Conservation 44: 20pp. , 1, 26

Allen, R., Bellingham, P. and Wiser, S. 2003. Developing a forest biodiversity monitoring approach for New Zealand. – New Zealand Journal of Ecology 27(2): 207–220. , 9

Apthorp, B. 1983. Forest and animals of the north and southwestern Kaimanawas. – Tech. rep., New Zealand Forest Service. 1, 9, 10

Atkinson, K. 1981. Animal survey of the northeastern Kaimanawa range. – Tech. rep., New Zealand Forest Service, Napier. 10

Aulak, W. and Babińska-Werka, J. 1990. Estimation of roe deer density based on the abundance and rate of disappearance of their faeces from the forest. – Acta Theriologica 35(1-2): 111–120. 10, 32

Baddeley, C. 1985. Assessments of wild animal abundance. – Tech. rep., Forest Research Institute Bulletin 106. pp 146. 9, 10

Banwell, D. B. 1999. The Sika. – Halycon Press. 6,

Barnett, S., Brown, R. and Spearpoint, G. 2012. Shelter from the Storm: The Story of New Zealand's Backcountry Huts. – Craig Potton Publishing. 1

Batcheler, C. and Challies, C. 1988. Loss of compound 1080 (sodium monofluoroacetate) from carbopol gel smeared onto foliage to poison deer. – New Zealand Journal of Forestry Science 18(1): 109–115. 38

Bates, D. and Maechler, M. 2010. lme4: Linear mixed-effects models using S4 classes. – R package version 0.999375-33. 13

Bayliss, P. and Giles, J. 1985. Factors affecting the visibility of kangaroos counted during aerial surveys. – The Journal of Wildlife Management pp. 686–692. 32

Beets, P. N., Kimberley, M. O., Oliver, G. R., Pearce, S. H., Graham, J. D. and Brandon, A. 2012. Allometric equations for estimating carbon stocks in natural forest in New Zealand. – Forests 3(3): 818–839. 33

Beets, P. N., Kimberley, M. O., Paul, T. S., Oliver, G. R., Pearce, S. H. and Buswell, J. M. 2014. The inventory of carbon stocks in New Zealands post-1989 natural forest for reporting under the Kyoto protocol. – Forests 5(9): 2230–2252. 33

Bell, D. 1973. The mechanics and analysis of faecal pellet counts for deer census in New Zealand. – Tech. rep., New Zealand Forest Service Protection Forestry Report 124: 158. 9, 10

Bellingham, P. and Allan, C. 2003. Forest regeneration and the influences of white-tailed deer (*Odocoileus virginianus*) in cool temperate New Zealand rain forests. – Forest Ecology and Management 175(1-3): 71–86. 1, 2

Bellingham, P., Richardson, S., Gormley, A., Husheer, S. W. and Monks, A. 2014. Department of Conservation biodiversity indicators: 2014 assessment. Landcare Research Contract Report: LC1957. – Tech. rep., Landcare Research. 33

Bellingham, P. J., Richardson, S. J., Mason, N. W., Veltman, C. J., Allen, R. B., Allen, W. J., Barker, R. J., Forsyth, D. M., Nicol, S. J. and Ramsey, D. S. 2016. Introduced deer at low densities do not inhibit the regeneration of a dominant tree. – Forest Ecology and Management 364: 70–76. 1, 33

Brennan, M., Moller, H. and Parkes, J. P. 1993. Indices of density of feral goats in a grassland/forest habitat, Marlborough, New Zealand. – New Zealand Journal of Ecology 17(2): 103–106. 14, 38

Brodie, J. F. 2006. An experimentally determined persistence-rate correction factor for scat-based abundance indices. – Wildlife Society Bulletin 34(4): 1216–1219. 10, 30

Burrows, L., Peltzer, D., Bellingham, P. and Allen, R. 2008. Effects of the control of introduced wild animal herbivores on carbon stocks.. – Tech. rep., Landcare Research Contract Report LC0708/087, prepared for the Department of Conservation, Wellington. 33

Caughley, G., Sinclair, R. and Scott-Kemmis, D. 1976. Experiments in aerial survey. – The Journal of Wildlife Management pp. 290–300. 31

Challies, C. N. 1977. Effects of commercial hunting on red deer densities in the Arawata Valley, South Westland, 1972–76. – New Zealand Journal of Forest Science 7(3): 63–73. 23, 26

Chapman, N. G. 2004. Faecal pellets of Reeves muntjac, *Muntiacus reevesi*: defecation rate, decomposition period, size and weight. – European Journal of Wildlife Research 50(3): 141–145. 10

Cieraad, E., Easdale, T. and Richardson, S. 2015. Effects of deer on kāmahi regeneration in Kaimanawa Forest Park 2008–2013. – Tech. rep., Landcare Research. 27

Clark, J. and Bjørnstad, O. 2004. Population time series: process variability, observation errors, missing values, lags, and hidden states. – Ecology 85(11): 3140–3150. 12

Coomes, D., Allen, R., Forsyth, D. and Lee, W. 2003. Factors preventing the recovery of New Zealand forests following control of invasive deer. – Conservation Biology 17(2): 450–459. 27

Cox, N. 2016. Personal communication, Neville Cox. Hastings Airfield 2016. – Personal interview by Sean Husheer. 4, 21, 26

Cruz, J., Thomson, C., Parkes, J. P., Gruner, I. and Forsyth, D. M. 2016. Long-term impacts of an introduced ungulate in native grasslands: Himalayan tahr (*Hemitragus jemlahicus*) in New Zealands Southern Alps. – Biological Invasions 19(1): 339–349. 27

Cunningham, A. 1974. Headwaters of Tutaekuri Catchment – study of an erosion problem in Hawkes Bay. – Tech. rep., Forest Research Institute, Technical Paper No. 62. 8, 26

— 1979. A century of change in the forests of the Ruahine Range, North Island, New Zealand: 1870–1970. – New Zealand Journal of Ecology pp. 11–21. 1

Davidson, M. and Fraser, K. 1991. Official hunting patterns, and trends in the proportions of sika (*Cervus nippon*) and red deer (*C. elaphus scoticus*) in the Kaweka Range, New Zealand, 1958–1988. – New Zealand journal of Ecology 15: 31–40. , 6, 10

Davidson, M. M. 1973. Characteristics, liberation and dispersal of sika deer (*Cervus nippon*) in New Zealand. – New Zealand Journal of Forestry Science 3(153–180). 4, 6, 10,

— 1979. Movement of marked sika (*Cervus nippon*) and red deer (*Cervus elaphus*) in central North Island, New Zealand. – New Zealand Journal of Forestry Science 9: 77–88. 10

Davis, N. E. and Coulson, G. 2016. Habitat-specific and season-specific faecal pellet decay rates for five mammalian herbivores in south-eastern Australia. – Australian Mammalogy 38(1): 105–116. 10

DOC 2016. Field protocols for DOC tier 1 inventory, monitoring and LUCAS plots, version 11.. – Tech. rep., Department of Conservation, Wellington. 18

Dougherty, S. Q. and Bowman, J. L. 2012. Estimating sika deer abundance using camera surveys. – Population Ecology 54(2): 357–365. , 41

Drewry, J. 2006. Natural recovery of soil physical properties from treading damage of pastoral soils in New Zealand and Australia: a review. – Agriculture, Ecosystems and Environment 114(2): 159–169. 33

Duncan, R., Ruscoe, W., Richardson, S. and Allen, R. 2006. Consequences of deer control for Kaweka mountain beech forest dynamics. – Tech. rep., Landcare Research, Lincoln, New Zealand. , 1, 2, 11, 12, 26, 27, 28

Dzieciolowski, R. 1976. Roe deer census by pellet-group counts.. – Acta theriologica 21: 351–358. 10, 30

Elder, N. L. 1948. The vegetation of the Kaimanawas. – Wellington Botanical Society Bulletin 19: 1–4. 1

— 1956. North Island protection forests. – New Zealand Journal of Forestry 7: 96–103. , 1

— 1959. Vegetation of the Kaweka range. – Tech. rep., Forest Research Institute, New Zealand Forest Service. 1

— 1962. Vegetation of the Kaimanawa Ranges. – Transactions of the Royal Society of New Zealand (Botany) 2: 1–37. 1

Ellison, D., Morris, C. E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., Van Noordwijk, M., Creed, I. F., Pokorny, J. et al. 2017. Trees, forests and water: Cool insights for a hot world. – Global Environmental Change 43: 51–61. 33

Fleury, W. 1979. Animal survey of the northern Kaimanawas. – Tech. rep., New Zealand Forest Service. 1, 26

— 1980. Report on the 1974–75 survey of the forest and animals of the upper Ngaruroro catchment, the upper Tutaekuri catchment and the upper Mohaka catchment. – Tech. rep., New Zealand Forest Service. , 8

Fleury, W. 2017. Personal communication, Bill Fleury 2017. – Personal email to Sean Husheer. 4, 9

Flux, J. E. C. 1967. High altitude ecology: hare numbers and diet in an alpine basin in New Zealand. – Proceedings of the New Zealand Ecological Society 14: 27–34. 30

Forsyth, D. 2002. Identifying a deer repellent for carrot possum baits. – Tech. rep., Landcare Research, Lincoln, New Zealand. 27

Forsyth, D., Barker, R., Morriss, G. and Scroggie, M. 2007. Modeling the relationship between fecal pellet indices and deer density. – The Journal of Wildlife Management 71(3): 964–970. 9, 20, 30, 31

Forsyth, D., MacKenzie, D. and Wright, E. 2014. Monitoring ungulates in steep non-forest habitat: a comparison of faecal pellet and helicopter counts. – New Zealand Journal of Zoology 41(4): 248–262. 14, 38

Forsyth, D., Richardson, S. and Menchenton, K. 2005. Foliar fibre predicts diet selection by invasive red deer *Cervus elaphus scoticus* in a temperate New Zealand forest. – Functional Ecology 19(3): 495–504. 9, 18, 30, 32

Forsyth, D., Thomson, C., Hartley, L., MacKenzie, D., Price, R., Wright, E., Mortimer, J., Nugent, G., Wilson, L. and Livingstone, P. 2011. Long-term changes in the relative abundances of introduced deer in New Zealand estimated from faecal pellet frequencies. – New Zealand Journal of Zoology 38(3): 237–249. 9, 31

Forsyth, D. M. 2005. Protocol for estimating changes in the relative abundance of deer in New Zealand forests using the Faecal Pellet Index (FPI). – Tech. rep., Landcare Research. 9, 17

Forsyth, D. M., Ramsey, D. S., Veltman, C. J., Allen, R. B., Allen, W. J., Barker, R. J., Jacobson, C. L., Nicol, S. J., Richardson, S. J. and Todd, C. R. 2013. When deer must die: large uncertainty surrounds changes in deer abundance achieved by helicopter-and ground-based hunting in New Zealand forests. – Wildlife Research 40(6): 447–458. 27, 30

Foster, R. J. and Harmsen, B. J. 2012. A critique of density estimation from camera-trap data. – The Journal of Wildlife Management 76(2): 224–236. 40, 41

Fraser, K. 1998. Assessment of wild mammal populations.. – Tech. rep., Landcare Research Contract Report LC9798/79 102 p. 10

Fraser, K. W. 1996. The effect of recreational hunters on deer populations in Pureora Conservation Park. – Science for Conservation 31. 36

Fraser, K. W. and Sweetapple, P. J. 1992. Hunters and hunting patterns in part of the Kaimanawa Recreational Hunting Area. – New Zealand Journal of Zoology 19(3-4): 91–98. 36, 40

— 1993. Assessing the age and condition of deer from jawbones.. – Tech. rep., Manaaki Whenua - Landcare Research New Zealand. 32 p. 40

Fraser, W. 1989. Recreational hunting areas: A thorn in the Department of Conservation's side?. – Management of New Zealands Natural Estate. New Zealand Ecological Society occasional publication 1: 108–111. 36

Fuller, T. K. 1991. Do pellet counts index white-tailed deer numbers and population change?. – The Journal of Wildlife Management 55(3): 393–396. 20

Gelman, A. and Hill, J. 2007. Data Analysis using Regression and Multilevel/Hierarchical Models. – Cambridge University Press, Cambridge. 12

Gill, R. 1992. A review of damage by mammals in north temperate forests: 1. Deer. – Forestry 65(2): 145–169. 1

Glade, T. 2003. Landslide occurrence as a response to land use change: a review of evidence from New Zealand. – Catena 51(3): 297–314. 33

Goode, M. J., Beaver, J. T., Muller, L. I., Clark, J. D., Manen, F. T. v., Harper, C. A. and Basinger, P. S. 2014. Capturerecapture of white-tailed deer using DNA from fecal pellet groups. – Wildlife Biology 20(5): 270–278. , 41

Gove, N. E., Skalski, J. R., Zager, P. and Townsend, R. L. 2002. Statistical models for population reconstruction using age-at-harvest data. – The Journal of wildlife management pp. 310–320. 40

Graf, C. 2015. 1080 Poison deer repellent not effective. – Press Release. 27

Grosenbaugh, L. R. 1952. Plotless timber estimates–new, fast, easy. – Journal of Forestry, 50(1): 32–37. 11

Hanya, G., Naito, S., Namioka, E., Ueda, Y., Sato, Y., Pastrana, J. A., He, T., Yan, X., Saito, M., Costa, R. F. P. et al. 2017. Morphometric and genetic determination of age class and sex for fecal pellets of sika deer (*Cervus nippon*). – Mammal Study 42(4): 239–246. 31

Haroldson, B. S., Wiggers, E. P., Beringer, J., Hansen, L. P. and McAninch, J. B. 2003. Evaluation of Aerial Thermal Imaging for Detecting White-Tailed Deer in a Deciduous Forest Environment. – Wildlife Society Bulletin 31(4): 1188–1197. , 41

Harris, L. 2002. The Deer Menace: A History of Government Pest Control Operations, 1930-1987. – LH Harris, Wellington. 4

Hemami, M. R. and Dolman, P. M. 2005. The disappearance of muntjac (*Muntiacus reevesi*) and roe deer (*Capreolus capreolus*) pellet groups in a pine forest of lowland England. – European Journal of Wildlife Research 51(1): 19–24. 10

Hemami, M.-R., Watkinson, A. and Dolman, P. 2005. Population densities and habitat associations of introduced muntjac *Muntiacus reevesi* and native roe deer *Capreolus capreolus* in a lowland pine forest. – Forest Ecology and Management 215(1): 224–238. 10

Herries, D. 2009. Kaweka Mountain Beech project report - 2008/2009 Monitoring Season - DOCDM-405091.doc. – Tech. rep., Department of Conservation, Hawkes Bay District Office. 2

— 2011. Kaweka Mountain Beech project annual report 2010–2011. DOCDM-755502. – Tech. rep., Department of Conservation Hawkes Bay Area Office. 5

— 2013. Kaweka Mountain Beech Project Annual Report 2012–2013. – Tech. rep., Department of Conservation, Hawkes Bay District Office. DOCDM-1453036.doc. , 2, 26

— 2015. Kaweka Hunter Liaison Group Meeting Minutes May 2015. DOC-2822049. – Tech. rep., Department of Conservation. 2

— 2016. Kaweka Mountain Beech Project 18 year summary – Online article. – New Zealand Hunter Magazine . 2, 5

Holdaway, R., Burrows, L., Carswell, F. and Marburg, A. 2012. Potential for invasive mammalian herbivore control to result in measurable carbon gains. – New Zealand Journal of Ecology 36(2). 1, 33

Holloway, J. 1950. Deer and the forests of western Southland. – New Zealand Journal of Forestry 6: 123–137. 1

Holloway, J. and Wendelken, W. 1957. Some unusual problems in sample plot design. – New Zealand Journal of Forestry 7(4): 77–83. 8

Hosking, G. and Hutcheson, J. 1988. Mountain beech (*Nothofagus solandri var. cliffortioides*) decline in the Kaweka Range, North Island, New Zealand. – New Zealand Journal of Botany 26(3): 393–400.

Hurst, J. and Allen, R. 2007. A permanent plot method for monitoring indigenous forests–field protocols.. – Landcare Research Manaaki Whenua, Lincoln. NZ. 12, 39

Husheer, S. and Frampton, C. 2005. Fallow deer impacts on Wakatipu beech forest. – New Zealand Journal of Ecology 29(1): 83–94. 1

Husheer, S. and Robertson, A. 2005. High-intensity deer culling increases growth of mountain beech seedlings in New Zealand. – Wildlife Research 32(4): 273–280. , 2, 5, 12, 15, 26, 31

Husheer, S., Robertson, A., Coomes, D. and Frampton, C. 2006a. Herbivory and plant competition reduce mountain beech seedling growth and establishment in New Zealand. – Plant Ecology 183(2): 245–256. , 1

Husheer, S. W. 2003. Impacts of Deer on Kaimanawa Beech Forests. Ph.D. thesis, A Thesis Presented in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy in Ecology. 1

— 2005. Vegetation Monitoring, Tararua Forest Park, New Zealand, 1958–85. – DOC Research & Development Series 212: 1–42. 1, 2

— 2007. Introduced red deer reduce tree regeneration in Pureora Forest, central North Island, New Zealand. – New Zealand Journal of Ecology 31(1): 79–87. 2

— 2013. Measurement of Deer Pellet Lines, Arawhata Valley, South Westland March 2013 Operational report. – Tech. rep., New Zealand Forest Surveys. 23

— 2018. Kaweka Forest Park Mountain Beech 2018. Re-measurement of paired exclosure and 10 m × 10 m seedling plots.. – Tech. rep., New Zealand Forest Surveys. 12, 24, 25, 26

Husheer, S. W., Allen, R. and Robertson, A. 2006b. Suppression of regeneration in New Zealand mountain beech forests is dependent on species of introduced deer. – Biological Invasions 8(4): 823–834. , 1, 4

Husheer, S. W., Coomes, D. and Robertson, A. 2003. Long-term influences of introduced deer on the composition and structure of New Zealand *Nothofagus* forests. – Forest Ecology and Management 181(1-2): 99–117. , 1, 26

Husheer, S. W., Hansen, Q. and Urlich, S. 2005. Effects of red deer on tree regeneration and growth in Aorangi Forest, Wairarapa. – New Zealand Journal of Ecology 29(2): 271–277. 1

Jacobson, H. A., Kroll, J. C., Browning, R. W., Koerth, B. H. and Conway, M. H. 1997. Infrared-triggered cameras for censusing white-tailed deer. – Wildlife Society (USA) . , 41

Jenkins, C. 1982. The animals and vegetation of Kaweka State Forest Park. – Tech. rep., New Zealand Forest Service. , 1

Jenkins, K. J. and Manly, B. 2008. A double-observer method for reducing bias in faecal pellet surveys of forest ungulates. – Journal of Applied Ecology 45(5): 1339–1348. 30, 31

Jung, T. S. and Kukka, P. M. 2016. Influence of habitat type on the decay and disappearance of elk *Cervus canadensis* pellets in boreal forest of northwestern Canada. – Wildlife Biology 22(4): 160–166. 10, 32

Kaji, K., Saitoh, T., Uno, H., Matsuda, H. and Yamamura, K. 2010. Adaptive management of sika deer populations in Hokkaido, Japan: theory and practice. – Population Ecology 52(3): 373–387. 40

Laing, S., Buckland, S., Burn, R., Lambie, D. and Amphlett, A. 2003. Dung and nest surveys: estimating decay rates. – Journal of Applied Ecology 40(6): 1102–1111. 20

Latham, A. D. M., Herries, D. and Latham, M. C. 2015. Seasonal patterns of resource selection by introduced sika deer (*Cervus nippon*) in Kaweka Forest Park Recreational Hunting Area, New Zealand. – New Zealand Journal of Ecology 39(2): 291–302. 5

Latham, A. D. M., Latham, M. C., Herries, D., Barron, M., Cruz, J. and Anderson, D. P. 2017. Assessing the efficacy of aerial culling of introduced wild deer in New Zealand with analytical decomposition of predation risk. – Biological Invasions . 5

Leathwick, J., Hay, J. and Fitzgerald, A. 1983. The influence of browsing by introduced mammals on the decline of North Island kokako. – New Zealand Journal of Ecology 6: 55–70. 1

Lee, A. 2017. Personal communication, Allan Lee. Napier November 2017. – Personal interview by Sean Husheer. 9

Legg, C. and Nagy, L. 2006. Why most conservation monitoring is, but need not be, a waste of time. – Journal of Environmental Management 78(2): 194–199. 30

Linchant, J., Lisein, J., Semeki, J., Lejeune, P. and Vermeulen, C. 2015. Are unmanned aircraft systems (UASs) the future of wildlife monitoring? A review of accomplishments and challenges. – Mammal Review 45(4): 239–252. , 41

Logan, P. 1957. The Japanese deer herd; spread, density and control problems. – Tech. rep., New Zealand Forest Service Report SF 90/1. 1

Logan, P. C. 1968. Inspection of the Kaweka range an Manson block 19–23 February 1968. – Tech. rep., New Zealand Forest Service Report, Palmerston North. 1, 4, 29

Lris 2010. Digital Elevation Model of New Zealand produced from public good funding by the New Zealand Foundation for Research, Science and Technology.. – Tech. rep., data reproduced with the permission of Landcare Research New Zealand Limited. 13

Mark, A. 1989. Responses of indigenous vegetation to contrasting trends in utilization by red deer in two south-western New Zealand national parks. – New Zealand Journal of Ecology 12 (Supplement): 103–114. 27

Mark, A. F. and McLennan, B. 2005. The conservation status of New Zealand's indigenous grasslands. – New Zealand Journal of Botany 43(1): 245–270. 27

Marques, F. F., Buckland, S. T., Goffin, D., Dixon, C. E., Borchers, D. L., Mayle, B. A. and Peace, A. J. 2001. Estimating deer abundance from line transect surveys of dung: sika deer in southern Scotland. – Journal of Applied Ecology 38(2): 349–363. 20

Mason, N., Peltzer, D., Richardson, S., Bellingham, P. and Allen, R. 2010. Stand development moderates effects of ungulate exclusion on foliar traits in the forests of New Zealand. – Journal of Ecology 98(6): 1422–1433. 1

Matsuda, H., Uno, H., Tamada, K., Kaji, K., Saitoh, T., Hirakawa, H., Kurumada, T. and Fujimoto, T. 2002. Harvest-based estimation of population size for sika deer on Hokkaido Island, Japan. – Wildlife Society Bulletin pp. 1160–1171. 14, 40

Mayle, B., Peace, A. and Gill, R. 1999. How many deer? A field guide to estimating deer populations. – Tech. rep., Forestry Commission Fieldbook 18. 10

Mayle, B. and Staines, B. 1998. An overview of methods used for estimating the size of deer populations in Great Britain. – In: C.R.Goldspink, S. . R. (ed.), Management and Welfare of Deer. Manchester Metropolitan University and Universities Federation for Animal Welfare, Manchester, UK., pp. 19–31. 10, 30

Mayle, B. A. 1996. Progress in predictive management of deer populations in British woodlands. – Forest Ecology and Management 88(1): 187 – 198. Ungulates in Temperate Forest Ecosystems. 10

Mayo, K. 2016. Kaweka Mountain Beech Project Annual Report 2015–2016. – Tech. rep., Department of Conservation, Hawkes Bay District Office. DOC-2825102.docx. , 2, 18, 26

Mayo, K. 2017. Personal communication, Kellie Mayo. Napier November 2017. – Personal interview by Sean Husheer. 9, 10

McCullough, B. and Heiser, D. 2008. On the accuracy of statistical procedures in Microsoft Excel 2007. – Computational Statistics & Data Analysis 52(10): 4570–4578. 43

McCullough, D. R., Pine, D. S., Whitmore, D. L., Mansfield, T. M. and Decker, R. H. 1990. Linked sex harvest strategy for big game management with a test case on black-tailed deer. – Wildlife Monographs pp. 3–41. 40, 41

McKelvey, P. J. 1957. Damage in protection forests at Poronui (northern Kaimanawa Range). – Tech. rep., New Zealand Forest Service Report. 1

— 1959. Animal damage in the North Island protection forests. *In*: Browsing animals in protective vegetation. – New Zealand Science Review 17(2): 28–34. 1

McNutt, K. 2017. Advice on re-measurement of tagged seedlings from the Kaweka Mountain Beech Project. DOC-2605233. – Tech. rep., Planning Monitoring and Reporting Team, Department of Conservation. 2, 12, 39

Mitchell, B., Rowe, J. J., Ratcliffe, P. and Hinge, M. 1985. Defecation frequency in Roe deer (*Capreolus capreolus*) in relation to the accumulation rates of faecal deposits. – Journal of Zoology 207(1): 1–7. 10

Moran, P. A. 1950. Notes on continuous stochastic phenomena. – Biometrika 37(1/2): 17–23. 13

Morriss, G. 2007. Epro deer repellent for baits used in possum control: Review of development and use 2001–2007.. – Tech. rep., Landcare Research Contract Report LC0607/147 for the West Coast Regional Council. 20 p. 27

Morriss, G. A., Nugent, G. and Whitford, J. 2016. Dead birds found after aerial poisoning operations targeting small mammal pests in New Zealand 2003–14. – New Zealand Journal of Ecology 40(3): 361–370. 27, 36

Neff, D. J. 1968. The pellet-group count technique for big game trend, census, and distribution: a review. – The Journal of Wildlife Management 32(3): 597–614. 10

Nesslage, G. M. and Porter, W. F. 2001. A geostatistical analysis of deer harvest in the Adirondack Park, 1954–1997. – Wildlife Society Bulletin pp. 787–794. 14

Nguyen, M., Sheath, G., Smith, C. and Cooper, A. 1998. Impact of cattle treading on hill land: 2. Soil physical properties and contaminant runoff. – New Zealand Journal of Agricultural Research 41(2): 279–290. 33

Norton, D. A. 2009. Species invasions and the limits to restoration: learning from the New Zealand experience. – Science 325(5940): 569–571. 26

Nugent, G. 1992. Big-game, small-game, and gamebird hunting in New Zealand: hunting effort, harvest, and expenditure in 1988. – New Zealand Journal of Zoology 19(3-4): 75–90. 5, 36

— 2016. Ghost hosts: Deer, pigs, and TB eradication. – Kararehe Kino Vertebrate Pest Research . 27

Nugent, G. and Fraser, K. 1993. Pests or valued resources? Conflicts in management of deer. – New Zealand Journal of Zoology 20(4): 361–366. 14, 36

Nugent, G., Fraser, K. and Sweetapple, P. 1997. Comparison of red deer and possum diets and impacts in podocarp-hardwood forest, Waihaha Catchment, Pureora Conservation Park. – Science for Conservation 50: 1–20. 9, 10

Nugent, G., Gortazar, C. and Knowles, G. 2015. The epidemiology of *Mycobacterium bovis* in wild deer and feral pigs and their roles in the establishment and spread of bovine tuberculosis in New Zealand wildlife.. – New Zealand veterinary journal 63(sup1): 54–67. 27

Nugent, G. and Henderson, R. 1990. Putting a value on hunting in the Oxford RHA.. – New Zealand Wildlife. NZDA. 12(93): 39–40. 36

Nugent, G. and Morriss, G. A. 2013. Delivery of toxic bait in clusters: a modified technique for aerial poisoning of small mammal pests. – New Zealand Journal of Ecology pp. 246–255. 36

Nugent, G., Parkes, J. and Tustin, K. 1987. Changes in the density and distribution of red deer and wapiti in northern Fiordland. – New Zealand Journal of Ecology 10: 11–21. 10, 26

Nugent, G., Warburton, B., Thomson, C., Cross, M. L. and Coleman, M. C. 2012. Bait aggregation to reduce cost and toxin use in aerial 1080 baiting of small mammal pests in New Zealand. – Pest Management Science 68(10): 1374–1379. 36

Nugent, G. et al. 1988. Successful control of fallow deer by recreational hunters in the Blue Mountains, Otago. – New Zealand Journal of Forestry Science 18(3): 239–252. 36

Ospri 2017. Sika deer repellent trials factsheet. – Tech. rep., Ospri. 38

Parkes, J. 2006. Does commercial harvesting of introduced wild mammals contribute to their management as conservation pests?. – In: Allen, R. and Lee, W. (eds.), Biological Invasions in New Zealand. Springer, pp. 407–420. 26

Parkes, J. P., Nugent, G. and Warburton, B. 1996. Commercial exploitation as a pest control tool for introduced. – Wildlife biology 2(3). 26

Peltzer, D., Allen, R., Lovett, G., Whitehead, D. and Wardle, D. 2010. Effects of biological invasions on forest carbon sequestration. – Global Change Biology 16(2): 732–746. 33

Pinheiro, J. and Bates, D. 2009. Mixed-effects models in S and S-PLUS. – Springer Verlag. 13

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D. and R Core Team 2017. nlme: Linear and Nonlinear Mixed Effects Models. – R package version 3.1-131. 13

Poole, A. L. 1973. No place for animals on eroded high country*and* Protecting Ruahines more important than saving Manapouri. – Soil and Water, June 1973 . 4

— 1983. Catchment control in New Zealand. – Tech. rep., Water and Soil Miscellaneous Publication No. 48. 185 p. Government Printer, Wellington. 4

Poole, A. L. and Adams, N. M. 1963. Trees and Shrubs of New Zealand. – Wellington Government Printer. Reprinted 1964, 1979, 1986, 1990. Manaaki Whenua Press 1994,. 4

Potvin, F. and Breton, L. 2005. Testing 2 aerial survey techniques on deer in fenced enclosuresvisual double-counts and thermal infrared sensing. – Wildlife Society Bulletin 33(1): 317–325. 14

Ramón-Laca, A., Gleeson, D., Yockney, I., Perry, M., Nugent, G. and Forsyth, D. M. 2014. Reliable discrimination of 10 ungulate species using high resolution melting analysis of faecal DNA. – PloS one 9(3): Online. 41

Ramsey, D. S., Forsyth, D. M., Veltman, C. J., Richardson, S. J., Allen, R. B., Allen, W. J., Barker, R. J., Bellingham, P. J., Jacobson, C. L., Nicol, S. J. et al. 2018. A management experiment reveals the difficulty of altering seedling growth and palatable plant biomass by culling invasive deer. – Wildlife Research 44(8): 623–636. 26

Riney, T. 1957. The use of faeces counts in studies of several free-ranging mammals in New Zealand. – New Zealand Journal of Science and Technology, Section B 38: 507–532. 10

Rogers, L. L. 1987. Seasonal changes in defecation rates of free-ranging white-tailed deer. – The Journal of Wildlife Management pp. 330–333. 10

Rönnegård, L., Sand, H., Andrén, H., Månsson, J. and Pehrson, Å. 2008. Evaluation of four methods used to estimate population density of moose *Alces alces*. – Wildlife Biology 14(3): 358–371. 10

Roseberry, J. L. and Woolf, A. 1991. A comparative evaluation of techniques for analyzing white-tailed deer harvest data. – Wildlife monographs pp. 3–59. 40

Russell, J., Betteridge, K., Costall, D. and Mackay, A. 2001. Cattle treading effects on sediment loss and water infiltration. – Journal of Range Management 54(2): 184–190. 1, 33

Schofield, C. 1957. Inspection of control operations in the upper Mohaka River catchment and survey of noxious animals situation of S.F. 90 period 1/4–10/4/57.. – Tech. rep., New Zealand Forest Service Report. FS 90/20/2. 1

Sika Foundation 2017. Summary of Kaimanawa Forest Park organised hunts (March, June, October and November 2017) – prepared by Cam Speedy and John Cook. – Tech. rep., Central North Island Sika Foundation, www.sikafoundation.co.nz/hunts/ retrieved January 2018. 15

Simmons, D. G. and Devlin, P. 1981. The recreational hunter.. – Tech. rep., Department of Horticulture, Landscape and Parks, Lincoln College. 5

Skarin, A. 2008. Decay rate of reindeer pellet-groups. – Rangifer 28(1): 47–52. 10, 32

Smart, J. C., Ward, A. I. and White, P. C. 2004. Monitoring woodland deer populations in the UK: an imprecise science. – Mammal Review 34(1-2): 99–114. 30

Smith, D. 2012. Animal pests: faecal pellet counts. Version 1.0. DOCDM-323171. – In: Greene, T. and McNutt, K. (eds.), Inventory and monitoring toolbox. Department of Conservation, New Zealand. Department of Conservation, Department of Conservation. 11

Soofi, M., Ghoddousi, A., Hamidi, A. K., Ghasemi, B., Egli, L., Voinopol-Sassu, A.-J., Kiabi, B. H., Balkenhol, N., Khorozyan, I. and Waltert, M. 2017. Precision and reliability of indirect population assessments for the Caspian red deer *Cervus elaphus maral*. – Wildlife Biology . 20

Storm, D. J., Samuel, M. D., Van Deelen, T. R., Malcolm, K. D., Rolley, R. E., Frost, N. A., Bates, D. P. and Richards, B. J. 2011. Comparison of visual-based helicopter and fixed-wing forward-looking infrared surveys for counting white-tailed deer *Odocoileus virginianus*. – Wildlife Biology 17(4): 431–440. 14

Swanborough, P. and Westoby, M. 1996. Seedling relative growth rate and its components in relation to seed size: phylogenetically independent contrasts. – Functional Ecology 10(2): 176–184. 13

Swanson, G., Campbell, D. and Armstrong, H. 2008. Estimating deer abundance in woodlands: the combination plot technique.. – Tech. rep., Forestry Commission Bulletin 128. 10

Tanentzap, A., Bazely, D., Koh, S., Timciska, M., Haggith, E., Carleton, T. and Coomes, D. 2011. Seeing the forest for the deer: Do reductions in deer-disturbance lead to forest recovery?. – Biological Conservation 144(1): 376–382. 1

Tanentzap, A., Burrows, L., Lee, W., Nugent, G., Maxwell, J. and Coomes, D. 2009. Landscape-level vegetation recovery from herbivory: progress after four decades of invasive red deer control. – Journal of Applied Ecology 46(5): 1064–1072. , 2, 27, 40

Tanentzap, A. and Coomes, D. 2012. Carbon storage in terrestrial ecosystems: do browsing and grazing herbivores matter?. – Biological Reviews 87: 72–94. 33

Tanentzap, A., Kirby, K. and Goldberg, E. 2012. Slow responses of ecosystems to reductions in deer (Cervidae) populations and strategies for achieving recovery. – Forest Ecology and Management 264: 159–166. 1

Taylor, C. 2003. Manual of practical monitoring techniques for the Kaweka Mountain Beech project (revised from 1999, 2001, 2002, 2003). – Tech. rep., Department of Conservation, Hawkes Bay District Office. 12, 17

Uno, H., Kaji, K., Saitoh, T., Matsuda, H., Hirakawa, H., Yamamura, K. and Tamada, K. 2006. Evaluation of relative density indices for sika deer in eastern Hokkaido, Japan. – Ecological Research 21(5): 624–632. 40

Uno, H., Kaji, K. and Tamada, K. 2009. Sika deer population irruptions and their management on Hokkaido Island, Japan. – In: McCullough, D. R., Takatsuki, S. and Kaji, K. (eds.), Sika Deer: Biology and Management of Native and Introduced Populations. Springer, Tokyo, pp. 405–419. 40

Van Etten, R. C. and Bennett Jr, C. L. 1965. Some sources of error in using pellet-group counts for censusing deer. – The Journal of Wildlife Management 29(4): 723–729. 10, 31

Veltman, C. J. and Parkes, J. P. 2004. The potential of poisoned foliage as bait for controlling feral goats (*Capra hircus*). – Science for Conservation 204: 1–21. 38

Wallis, F. 1967. Report on a resurvey of condition and trend in the vegetation of the upper Tutaekuri catchment. – Tech. rep., New Zealand Forest Service Protection Forestry Report No. 25. Forest Research Institute, Napier. 1, 8

Wardle, D., Bonner, K. and Barker, G. 2002. Linkages between plant litter decomposition, litter quality, and vegetation responses to herbivores. – Functional Ecology 16: 585–595. 1

Wardle, J. A. 1979. Inspection of proposed recreational hunting area, Kaweka State Forest Park. – Tech. rep., New Zealand Forest Service. , 1, 26

Whiteford, C. 1983. 1981/82 Animal survey of the Kaimanawas. – Tech. rep., New Zealand Forest Service, Napier. 10

Wilson, L. 2010. Personal communication, Lin Wilson. Hastings Airfield 2010. – Personal interview by Sean Husheer. 4, 26

Wilson, M. 2017. Personal communication, Mathew Wilson. Hastings Airfield 2017. – Personal interview by Sean Husheer. 26

Wolf, F. 2015. Personal communication, Frank Wolf. Haast 2015. – Personal interview by Sean Husheer. 20

Wraight, M. 1960. The alpine grasslands of the Hokitika River catchment, Westland. – New Zealand Journal of Science 3(2): 306–332. 8, 29

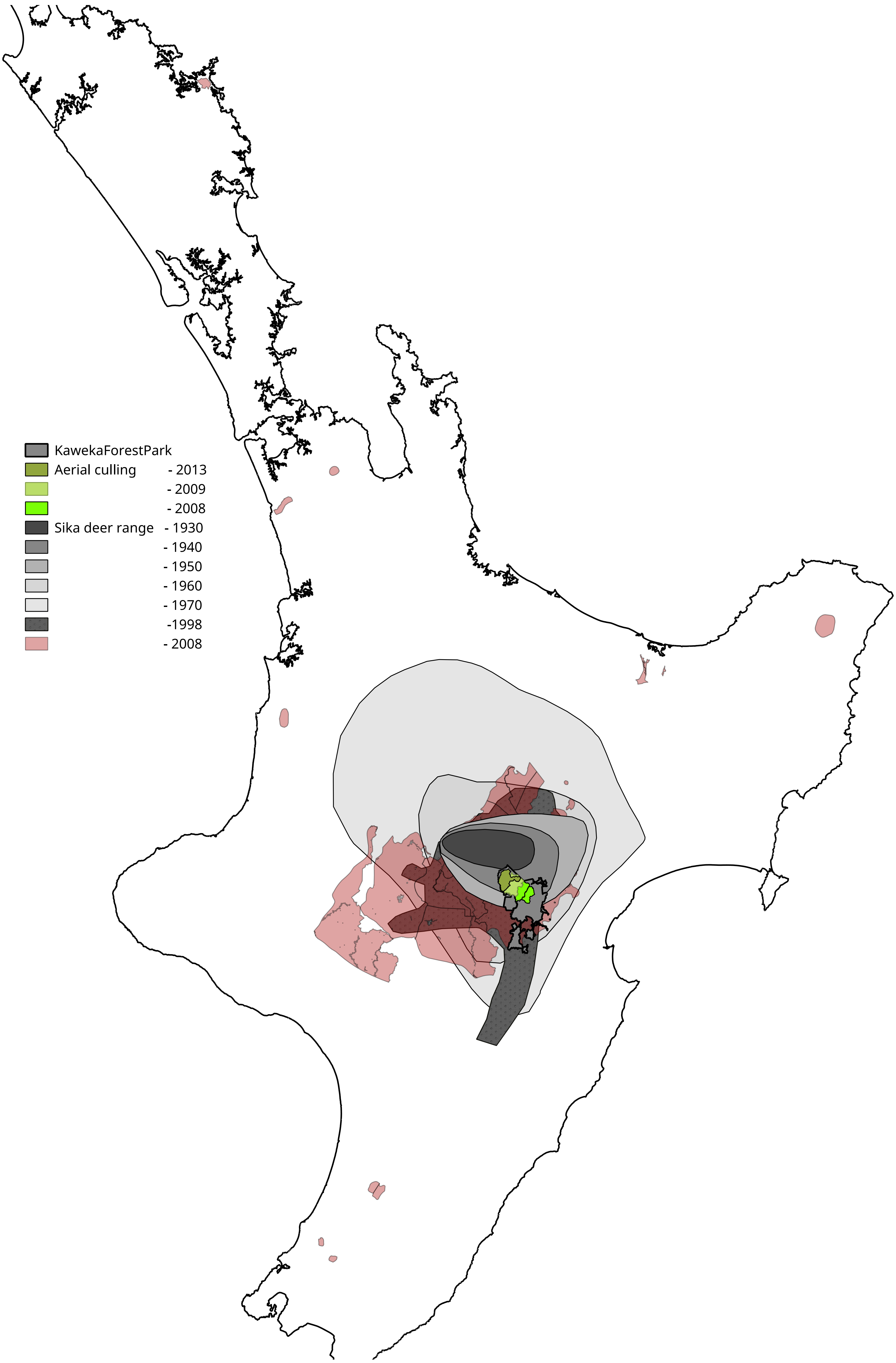
Wright, D., Tanentzap, A., Flores, O., Husheer, S., Duncan, R., Wiser, S. and Coomes, D. 2012. Impacts of culling and exclusion of browsers on vegetation recovery across New Zealand forests. – Biological Conservation 153: 64–71. 1, 2

Yalta, A. 2008. The accuracy of statistical distributions in Microsoft Excel 2007. – Computational Statistics & Data Analysis 52(10): 4579–4586. 43

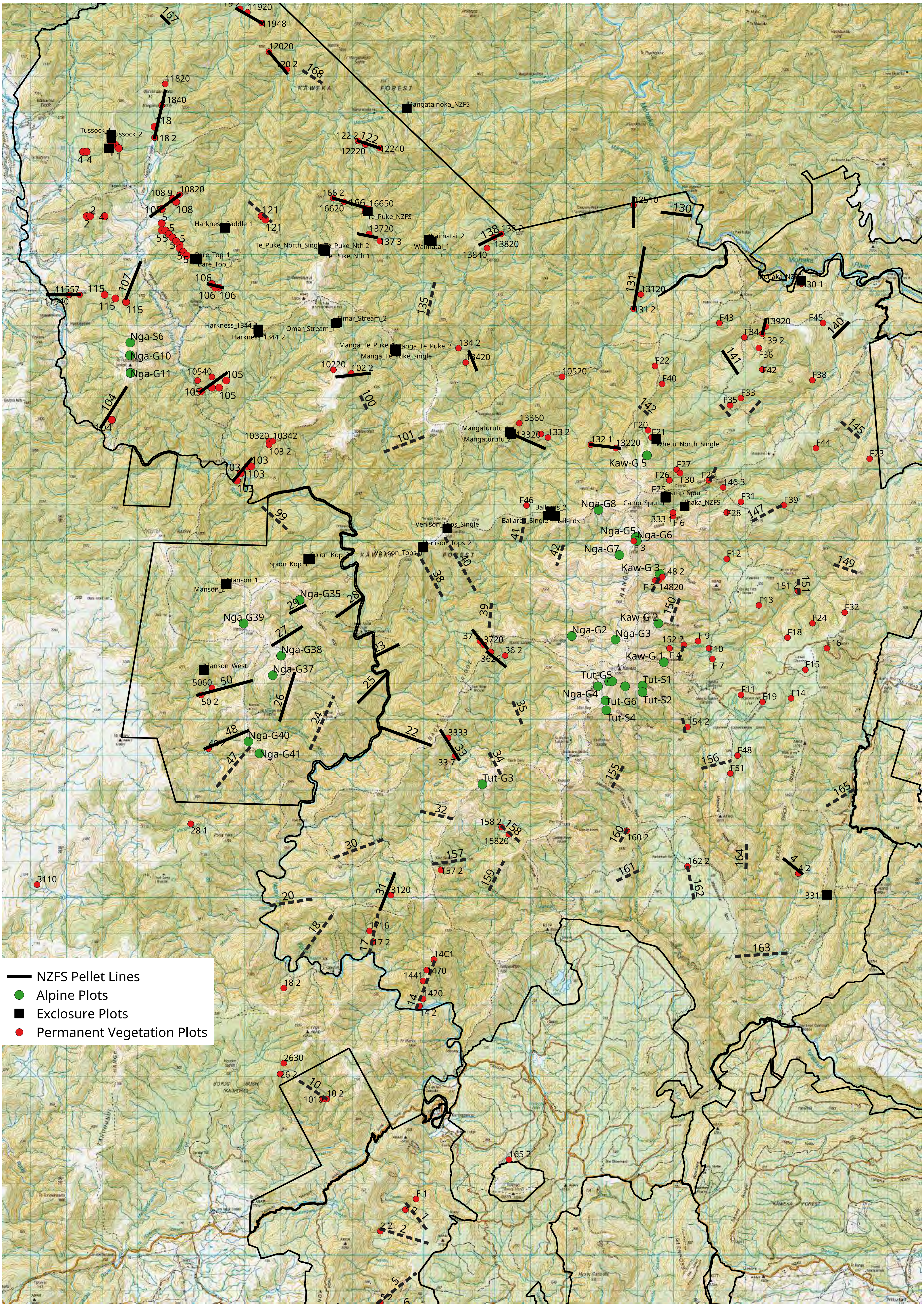
Yamashiro, A., Kaneshiro, Y., Kawaguchi, Y. and Yamashiro, T. 2017. Species, sex, and individual identification of Japanese serow (*Capricornis crispus*) and sika deer (*Cervus nippon*) in sympatric region based on the fecal DNA samples. – Conservation Genetics Resources 9(2): 333–338. , 41

Zhang, M., Liu, N., Harper, R., Li, Q., Liu, K., Wei, X., Ning, D., Hou, Y. and Liu, S. 2017. A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. – Journal of Hydrology 546: 44–59. 33

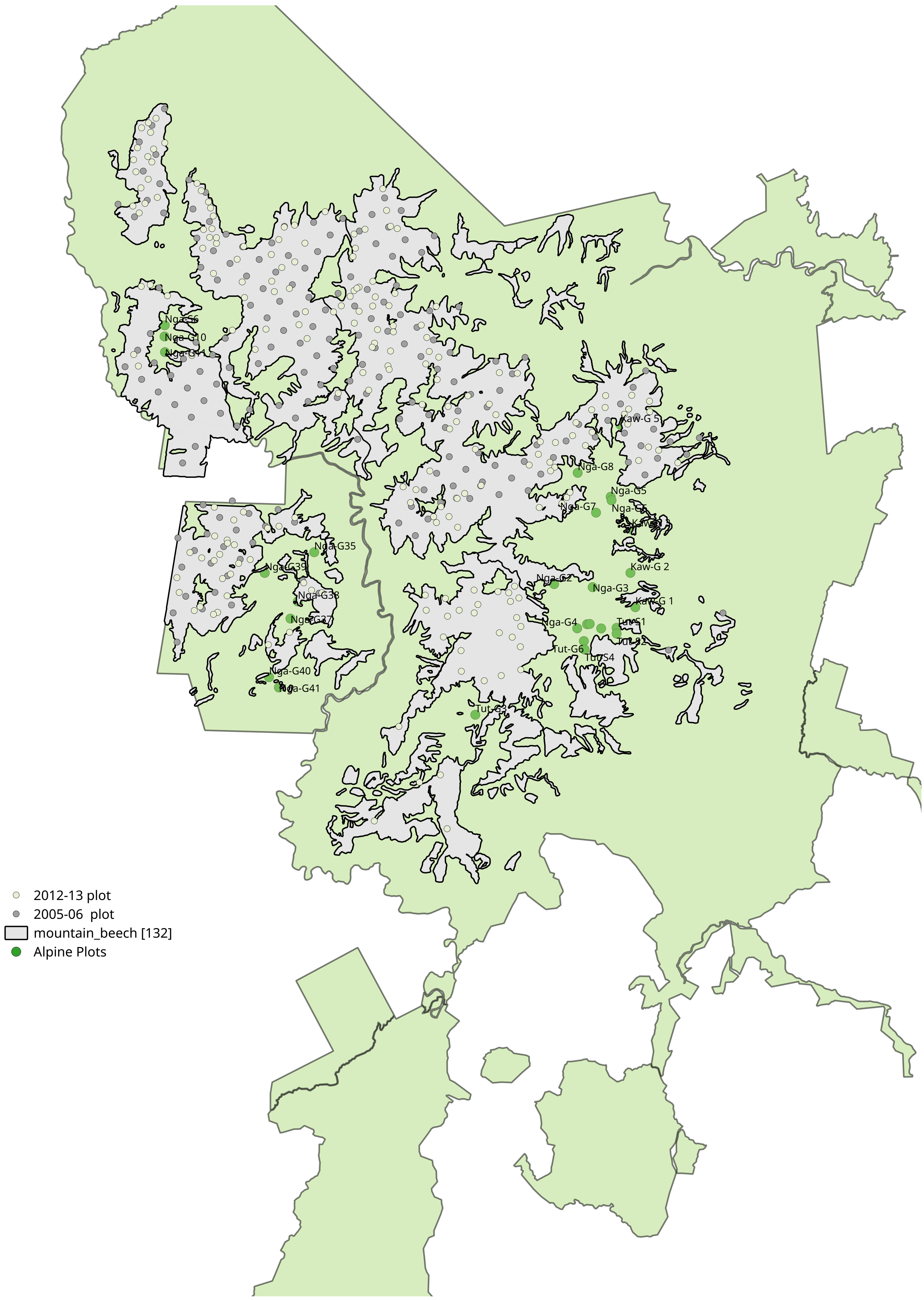
This document was produced with R version 3.4.4 on an i486-Linux system, using R spatial libraries, GRASS, QGIS and LaTeX document preparation.



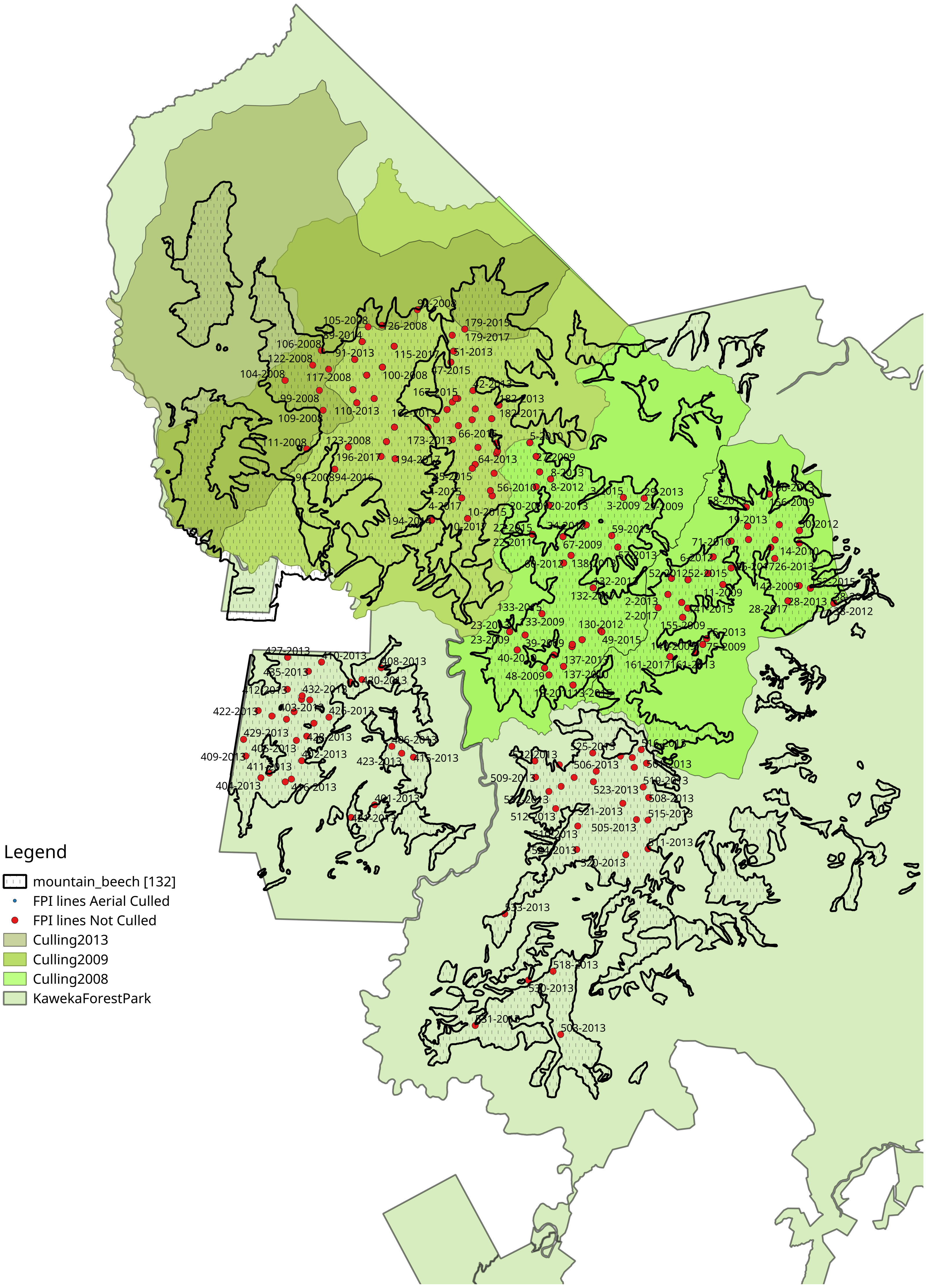
Map 2: Range of sika deer from 1930–1970 (Davidson, 1973), 1998 (Banwell, 1999) and 2008 (DOC staff estimates). Kaweka Forest Park and aerial deer culling areas are also shown. Sika deer have also been liberated in the South Island.



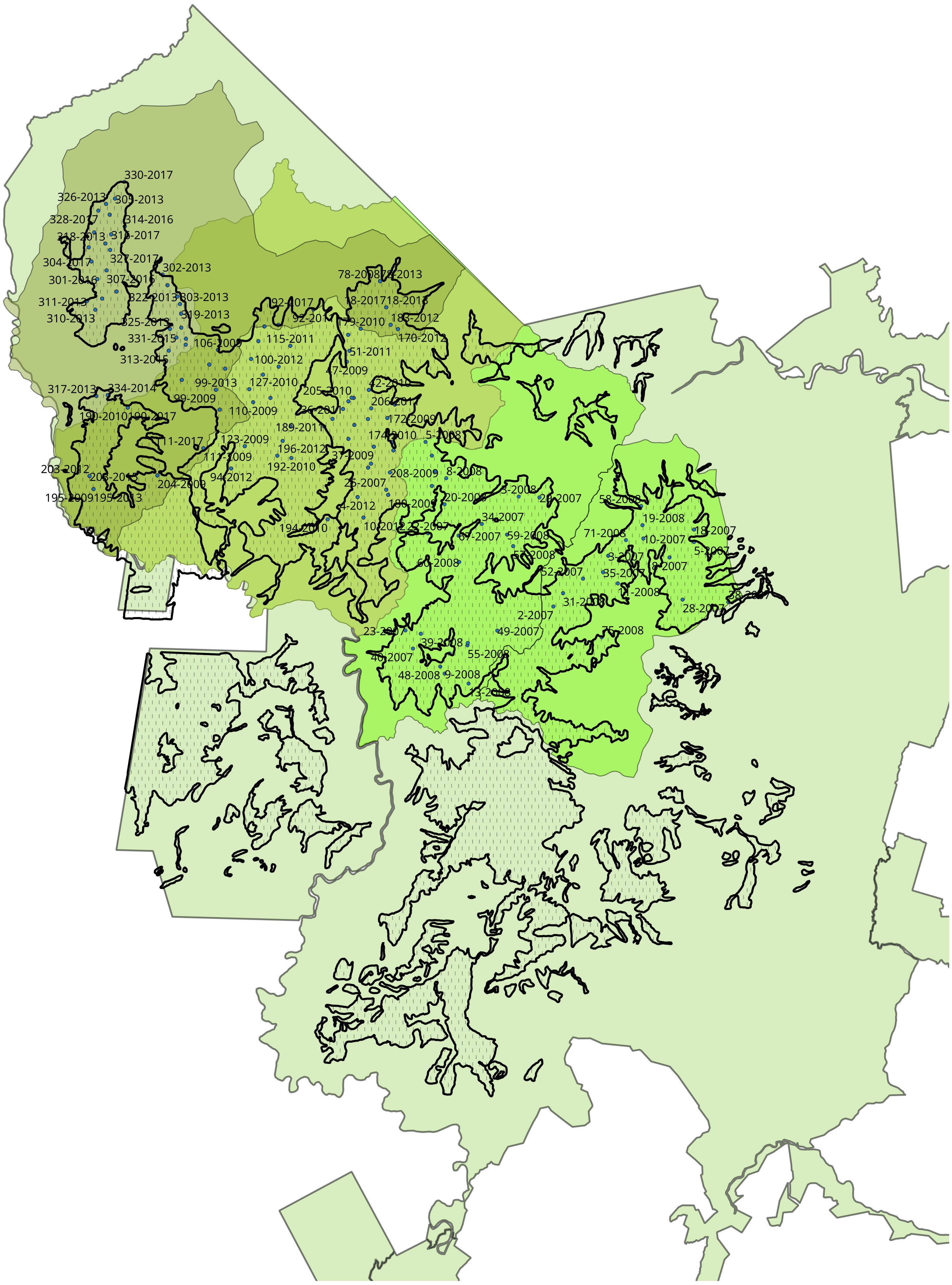
Map 3: Kaweka Forest Park permanently marked lines and permanent plots (print A3). NZ Forest Service 20 × 20 m permanent plots (●). NZ Forest Service permanent lines with (—) and without (- - -) existing permanent plots. Exclosure plots (■) include 20 × 20 m and 10 × 10 m plots. Alpine grassland plots (●) were established above the natural tree line.



Map 4: Kaweka Forest Park mountain beech forest with forest stands assessed in 2005 (•) and 2012 (○) for low basal area. Mountain beech seedling heights were measured in 10 × 10 m plots at low basal area stands (<44 m^2 ha^{-1}). Results displayed in Section 3.4 and Figure 10.



Map 5: FPI lines in areas without culling (some lines were culled in some years and not others). Lines with culling are in Map 6. Results displayed in Section 3.2 and Figure 5.



Map 6: FPI lines in areas with culling