Supplementary Material

Appendix S1. Field protocol for swabbing ungulate faecal pellets for DNA. This field protocol is reproduced from Department of Conservation (2012). The laboratory analyses are described in Ramón-Laca et al. (2014).

Overview

Only ungulate pellets of fresh appearance (i.e. moist, soft and usually a black or dark green colour) should be swabbed. Pellets that have lost these colours and have dried out, or are starting to disintegrate, should not be swabbed as it is unlikely that any useful DNA would be recovered. Important notes:

(1) Only one swab sample should be taken from one pellet group and a maximum of one swab sample per quadrat and a maximum of five swab samples per ungulate faecal pellet transect.

(2) A swab sample consists of wiping three different pellets from the same pellet group.

(3) Before handling a sample remember to wear a fresh pair of gloves and use new forceps, swab and tube.

Steps

(1) Remove sterile swab from its protective case.

(2) Submerge CLEAN swab into preservation buffer* ONCE, before swabbing.

(3) Use forceps to hold selected pellet and gently wipe the entire surface of three different pellets from the same pellet group for each swab sample.

(4) Insert swab head into its 1.5 ml tube and split the handle so only the head is submerged in buffer.

(5) Place gloves, forceps and the swab's protective case in a ziplock bag for disposal when you return to base.

(6) Label the lid of the 1.5 ml tube with the unique number specifying the faecal pellet transect ID and quadrat number using a permanent marker and place in a ziplock bag.

(7) Record the sample that was collected in the field booklet by circling the quadrat number.

(8) When all ungulate transects have been sampled, include a waterproof label and mark the outside of ziplock bag containing the samples with: (a) sampling location identifier, and (b) the day's date on the bag (e.g. ABC123, 15/12/2012) and keep samples out of direct sunlight.

(9) Transport the samples to base for safe storage at room temperature and out of direct sunlight (cardboard box) until forwarded to EcoGene®.

*Preservation buffer is Longmire buffer (Longmire et al. 1997). This is a non-toxic solution (although it should not be ingested) that preserves the DNA at room temperature for long periods of time and meets requirements for air transport. Sampling kits (consisting of disposable gloves, disposable forceps, swab and a 1.5 ml tube containing Longmire buffer) are provided by EcoGene®.

A video showing how to swab faecal samples can be found at EcoGene®'s website: http://www.ecogene.co.nz/

Appendix S2. Imperfect detection model. To incorporate the possibility of imperfect detection of ungulate pellets at a site, we constructed a state–space occupancy model (MacKenzie et al. 2018) in a Bayesian framework. The model allowed for differences in occupancy rates between the three islands, between woody and non-woody sites, and by year. The model was:

$$X_i \sim Bernoulli(\psi_i) \quad (1)$$

$$logit(\psi_i) = \alpha_{Island_i} + \beta_{Island_i} \times Woody_i + \gamma \times Year_i \quad (2)$$

$$Y_{i,j} \sim Bernoulli(pX_i) \quad (3)$$

where X_i is 1 if site i is occupied and 0 otherwise; ψ_i is the occupancy rate for a site like i; $Woody_i$ is 1 if the site i is classified as woody and 0 if non-woody; $Year_i$ is the year of the monitoring (centred on the 2014–2015 field season); $Y_{i,j}$ is 1 if the transect j at site i detected ungulate pellets and 0 otherwise; and p is the probability that an ungulate pellet is detected on a transect given that the site is occupied.

This Bayesian occupancy model was constructed in program R (R Core Team 2019) using the package *R2jags* (Su & Yajima 2015). Uninformative priors were used for all parameters (Appendix S3). Four chains were run through 2000 iterations, with a 1000 iteration burn-in and no thinning. For all analyses, trace plots for each parameter in the models indicated that the Markov chains were well mixed. All parameters had Gelman–Rubin statistic (R; Gelman & Rubin 1992) values of < 1.05, indicating convergence of the chains and reliable samples for posterior inference.

Parameter values of the posterior distribution from the occupancy model are given in Appendix S4. The detection rate for a single transect at an occupied site was 70% (95% CI: 68.3–71.3%). When all four transects at a site were considered, the probability of detecting at least one faecal pellet was 99.2% (95% CI: 99.0–99.93%). Hence, due to the very high overall detection rates, the occupancy rates of ungulates corrected for detection probability are nearly identical to the naïve estimates.

Appendix S3. Prior distributions used in the Bayesian occupancy model.

Parameter	Prior distribution
α_{Region_i}	Uniform(–10, 10)
B_{Region_i}	Uniform(–10, 10)
γ	Uniform(–10, 10)

Appendix S4. Posterior distributions (medians and 95% credible intervals) of parameters from the Bayesian occupancy model accounting for imperfect detection.

Island	Parameter	Median	Lower 95% bound	Upper 95% bound
North	α_{North}	–0.436	–0.965	0.079
South	α_{South}	0.310	0.110	0.499
Stewart	$\alpha_{Stewart}$	0.043	–3.041	5.369
North	β_{North}	2.152	1.551	2.769
South	β_{South}	0.849	0.563	1.135
Stewart	$\beta_{Stewart}$	0.953	–4.491	4.224
Overall	γ	0.173	0.100	0.242
Overall	p	0.699	0.683	0.713

Appendix S5. Interpretation of results from our occupancy model. The link function for our occupancy model is the logit (log odds) function:

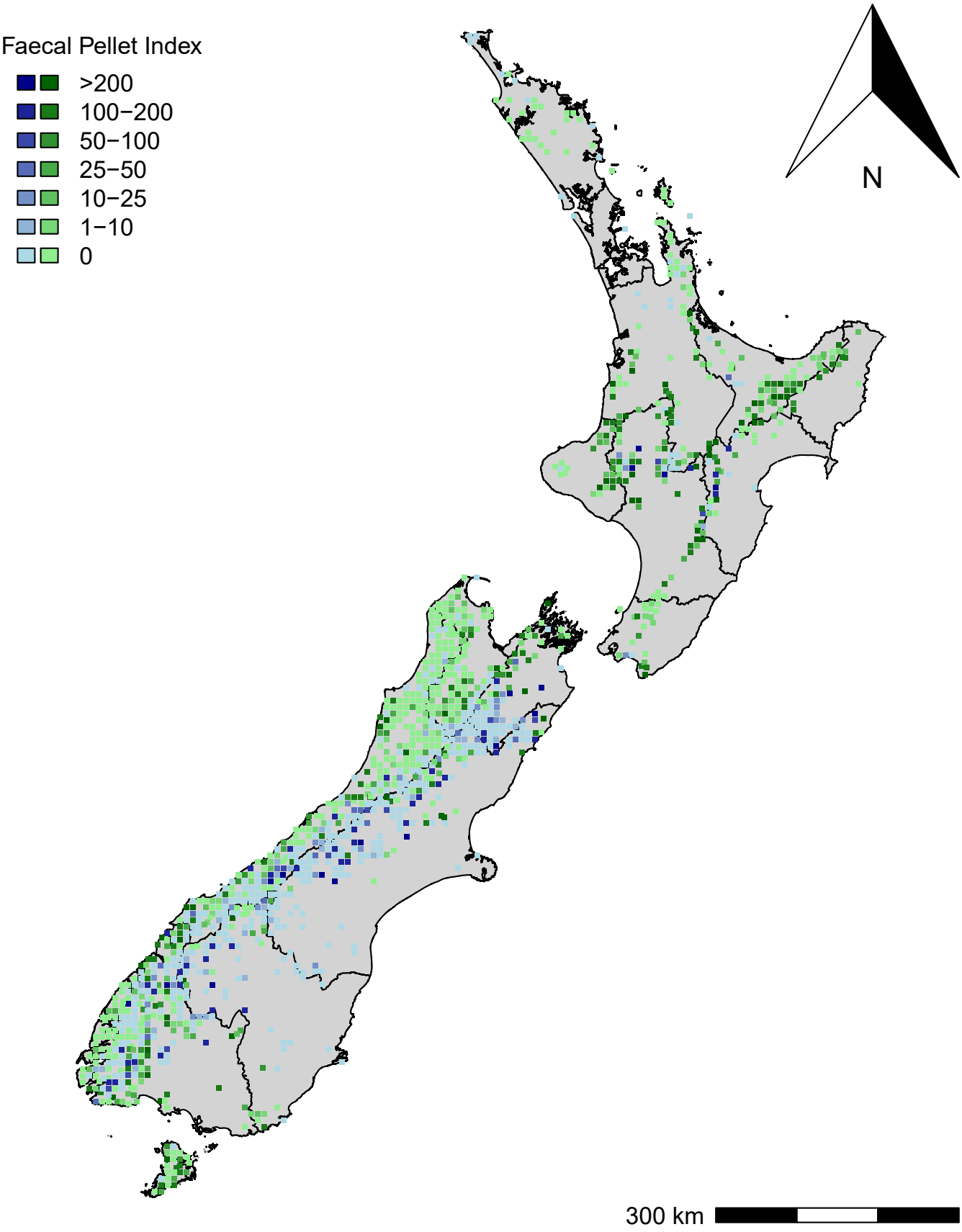
$$logit(p) = ln\left(\frac{p}{1-p}\right) \quad (4)$$

Hence, model estimates are on the logit scale. Obtaining a change in probability using the logit scale requires the initial probability to be known. Also, the logit scale is not intuitive for many people. To enable consistent interpretation of the effects of predictor variables, we express them using the odds (not the odds ratio). Readers must recognise that a change in the odds (e.g. "the annual odds of detecting pellets at a site increase by 34%") does not equate to a consistent change in occupancy probability.

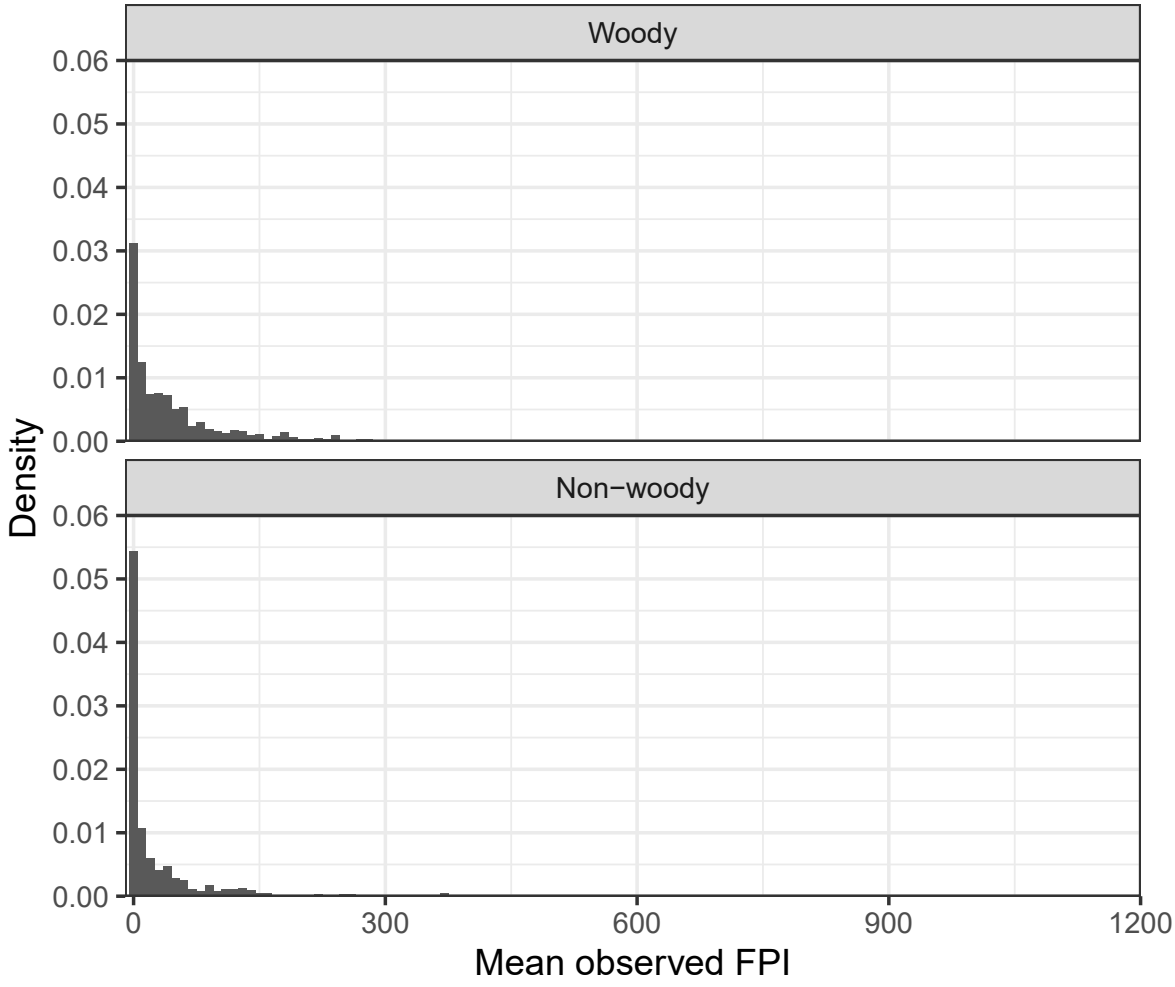
Appendix S6. Prior distributions used in the Bayesian hurdle lognormal models. These occupancy models assumed perfect detection. FPI, Faecal Pellet Index.

Model	Parameter	Prior distribution
Occupancy	α_k, $k \in 1$ *to* 3	Uniform(−10, 10)
Occupancy	$\beta_{m,k}$, $k \in 1$ *to* 3 *and* $m \in 1$ *to* 4	Uniform(−10, 10)
Conditional FPI	γ_k, $k \in 1$ *to* 3	N(0, 20)
Conditional FPI	$\delta_{n,k}$, $k \in 1$ *to* 3 *and* $m \in 1$ *to* 3	N(0, 20)
Conditional FPI	σ	Γ(0.001, 0.001)

Appendix S7. Naïve ungulate occupancy rates and abundance (Faecal Pellet Index) values 2012–2018. Each Faecal Pellet Index (FPI) value shown is the mean of the four transects at that site (Fig. 2). Ungulate pellets were detected at 69.9% of the 1346 sites (Appendix S9). Across all sites, the mean, median and maximum naïve FPI values were 46.8, 10.8 and 1183, respectively (Appendices S8, S9). Blue indicates non-woody sites; green indicates woody sites.



Appendix S8. Histograms of observed Faecal Pellet Index (FPI) values at woody (upper; n = 787) and non-woody (lower; n = 559) sites on New Zealand public conservation land sampled during 2012–2018.



Appendix S9. Mean naïve occupancy rates and Faecal Pellet Index (FPI) values for ungulates on New Zealand's public conservation land during 2012–2018.

Sites	Woody		Non-woody		Total	
	Occupancy	FPI	Occupancy	FPI	Occupancy	FPI
All	0.789 (n = 787)	51.0	0.572 (n = 559)	40.8	0.699 (n = 1346)	46.8
North Island	0.850 (n = 260)	67.5	0.411 (n = 56)	49.6	0.772 (n = 316)	64.3
South Island	0.762 (n = 504)	42.8	0.591 (n = 501)	40.0	0.677 (n = 1005)	41.4
Stewart Island/Rakiura	0.696 (n = 23)	44.3	0.500 (n = 2)	6.0	0.680 (n = 25)	41.2

Appendix S10. By-kill of ungulates in aerial 1080-poisoning operations. The killing of deer and other ungulates during aerial 1080-poisoning operations aimed primarily at brushtail possums is highly variable (from near zero to near 100%; Morriss et al. 2020). The kill rate of deer in these programmes can sometimes be reduced by lowering the bait sowing rate (Morriss et al. 2018) and applying a "deer repellent" to the bait (Morriss 2007). Unfortunately, the records of aerial 1080-poisoning application on PCL during our study period commonly did not include sowing rate or whether deer repellent was applied. We therefore did not attempt to include aerial 1080-poisoning history in our analyses, as was done by Forsyth et al. (2018) for brushtail possums.

References

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