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Sampling design options for forest monitoring in the Bay of Plenty Region and the Kaimai Mamaku Conservation Park

Prepared for: Bay of Plenty Regional Council

March 2021



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Contract Report: LC3925

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Summary

Project and client

- Bay of Plenty Regional Council contracted us to perform power analyses (based on LUCAS permanent plot data) of changes in plant species preferred by ungulates (i.e. deer and goats), and the mean number and size of tree stems, for indigenous forests in the entire Bay of Plenty region, the Kaimai Mamaku Conservation Park, and individual ecosystem types within Bay of Plenty.
- The results from these power analyses and, where necessary, generic power look-up tables, were used to identify the number of survey locations required to detect a desired effect size with acceptable power. Potential survey locations were generated using balanced acceptance sampling for each area of interest and for individual ecosystem types within each area of interest.

Objectives

- To develop a survey design providing acceptable power to detect change in monitoring metrics in the Bay of Plenty region, the Kaimai Mamaku restoration project area, and individual ecosystem types within these areas.

Methods

- We used a simulation-based approach to estimate the sample size required to detect changes of different sizes with acceptable power (80% chance of obtaining a significant result at $p < 0.05$) across a variety of vegetation indices:
 - mean tree diameter (decreases might indicate recruitment of small trees following ungulate control)
 - total tree populations (which are expected to increase in response to ungulate control)
 - the proportional abundance of species preferred by ungulates in the tree, sapling and seedling size classes.
- We used balanced acceptance sampling to locate the supplementary survey plots required to achieve acceptable power to detect change within individual ecosystem types.

Results

- Generic power analyses (not based on plot data) reveal that nine survey locations provide acceptable power to detect change between surveys when the mean plot-level probability of change in the desired or expected direction is ≥ 0.925 , while six locations are required when this probability is ≥ 0.975
- Six survey locations were sufficient to detect only the largest effect examined ($\geq 50\%$ decrease) in mean plot stem diameter across five of the six ecosystem types with enough existing plot data for power analyses. Nine locations were sufficient to detect a decrease of $\geq 25\%$ across five of the six ecosystem types examined.

- Six survey locations were sufficient to detect a $\geq 45\%$ increase in tree populations across four of the six ecosystem types examined. Nine locations were sufficient to detect an increase of $\geq 35\%$ across five of the six ecosystem types examined.
- A sampling intensity of ≤ 10 locations per ecosystem type was insufficient to detect all but the largest changes ($\geq 85\%$ increase) in preferred species abundance in the tree size class across the majority of ecosystems examined.
- This sampling intensity was insufficient to detect any of the effect sizes examined for preferred species abundance in the sapling size class across the majority of ecosystem types.
- However, ≤ 10 locations were sufficient to detect increases of $\geq 50\%$ in the abundance of preferred species in the seedling size class for five of the six ecosystem types examined.
- Proportional abundance of preferred species was significantly lower in the sapling size class than in either the tree or seedling size classes in LUCAS plots within the Bay of Plenty region. Further, preferred species were missing from the sapling size class in 40% of plots. This is the size class most vulnerable to ungulate browsing, so these results add support to previous evidence that the composition of forests in the Bay of Plenty region has been heavily affected by ungulate herbivory.
- Obtaining a sufficient sample size for individual ecosystem types requires a survey design that is stratified by ecosystem type, and is not achieved for the vast majority of ecosystem types under the existing LUCAS/Tier 1 survey design.

Conclusions

- Total tree populations and abundance of preferred species in seedling size classes could provide acceptable power to detect the positive impacts of mammalian herbivore management on individual forest ecosystem types in the Bay of Plenty region with a sample size of ≤ 10 survey locations per ecosystem type.
- It is possible that our analyses have underestimated the potential power of preferred species abundance in the sapling size class to reveal the impacts of management. Our analyses assume that locations with a starting value of zero do not change between surveys. However, it is possible that preferred species may be recruited into the sapling size class in plots where they are currently missing from this size class due to their presence in either (or both) the tree and seedling size classes. This might be especially true under management scenarios where ungulate herbivore pressure is greatly reduced relative to current levels.

Recommendations

- The sampling universe for the Bay of Plenty region and the Kaimai Mamaku restoration project area should be adjusted to incorporate feasibility criteria relating to safety and accessibility.
- Vegetation metrics obtained from 20 m \times 20 m permanent survey plots will be able to detect the impacts of ungulate herbivore control within individual ecosystem types using an appropriately designed region-wide sampling design.

- Given the apparent impacts of ungulates on forest ecosystems, serious consideration should be given to (a) expanding and intensifying ungulate herbivore management in the Bay of Plenty region and (b) including ungulate control as a major component of the Kaimai Mamaku restoration project.
- Discussions involving all relevant stakeholders are required to determine desired outcomes for indigenous forest vegetation in response to mammalian herbivore control efforts.
- Improved methods for monitoring ungulate species population density and predicting population responses to management are required.
- Mechanistic models of preferred plant population dynamics at various ungulate population densities are required for realistic simulations of vegetation metric responses to management. These models should include information on plant demography, and ungulate diet preferences, diet requirements, and movements.

1 Introduction

In a previous study (Mason & Price 2019), changes in tree populations, size distributions and the relative abundance of palatability groups were assessed in forest communities of the Bay of Plenty using the LUCAS plot network for (a) the entire region, (b) individual ecosystem types, and (c) the eastern Bay of Plenty goat control zone. This project builds on that work by identifying the sample sizes needed to detect desired effect sizes, and providing potential locations for survey plots in individual forest ecosystem types across the Bay of Plenty and within the Kaimai Mamaku project area.

2 Background

The 8 km national plot-sampling grid (LUCAS / Tier 1) was originally designed as a system for providing an unbiased estimate of the carbon stored in New Zealand's natural forest and shrubland (Coomes et al. 2002; Payton et al. 2004). The grid size (8 km) was based on the sample size required to estimate the national carbon stock to a certain level of precision (i.e. a 95% probability that carbon stock estimates will be within 5% of the mean (+/- 10 Mg ha⁻¹) (Payton et al. 2004).

Plots were randomly allocated a year to be sampled based on a theoretical 5-year cycle with no geographical stratification (Payton et al. 2004). With revisions of the mapped area of forest and shrubland (e.g. the creation of the LUCAS Land Use Map), new plots have been added to the grid. These were also allocated an ideal year of measurement using random sampling. Repeat measurements (i.e. in both survey periods) were made in over 700 LUCAS plots.

Remnant woody vegetation in the Bay of Plenty region primarily occurs on the steeper, wetter, and higher-altitude areas (Table 1). Most remeasured LUCAS plots in the Bay of Plenty (53/73) are within Public Conservation Land (Figure 1) and primarily occur on podzolised pumice soils (55 plots) or recent soils (eight plots) (nomenclature follows NZ Soil Classification; Hewitt 2003).

Table 1. Mean environmental values for LUCAS plots in the Bay of Plenty region (Mean LUCAS) and for all 100 m × 100 m pixels in the region (Mean BOP).

Variable	Mean LUCAS	Mean BOP
Mean annual temp. (°C)	11.3	11.9
Mean temp. coldest month (°C)	2.0	2.2
Mean annual rainfall (mm)	2046	1863
Elevation (m)	499	379
Slope (°)	22	15

Source: Data are from Leathwick et al. 2003

A regional ecosystem classification has been developed for the Bay of Plenty (Singers 2014) based on a national ecosystem classification system (Singers & Rogers 2014). This classification system amalgamates previous classifications and ecological studies within an abiotic framework and describes potential ecosystem types at a variety of scales. Singers (2014) amalgamated three data sets to form an 'ecosystem unit' layer: the New Zealand Fundamental Soil layer¹, S-map² and the New Zealand Forest Service map series 6³. Distributional information (sourced from the New Zealand Plant Conservation Network⁴ for a range of diagnostic species – hard beech (*Fuscospora truncata*), pōhutukawa (*Metrosideros exselsa*), mangeao (*Litsea calicaris*), kohekohe (*Dysoxylum spectabile*), kauri (*Agathis australis*), tawa (*Beilschmedia tawa*), taraire (*Beilschmedia tarairi*), pūriri (*Vitex lucens*), and pukatea (*Laurelia novae-zelandiae*) – was used to refine ecosystem unit boundary determination. Finally, the impacts of recent (post-Taupō, AD 232) volcanism were used to further refine ecosystem unit boundaries.

Forest areas within the Bay of Plenty fall primarily into the following 'Zonal' ecosystems (*sensu* Singers & Rogers 2014): Warm Temperate Forest (WF), Mild Forest (MF), Cool Forest and Scrub (CLF), and Cold Forest and Scrub (CDF). Singers (2014) provides a detailed description of all ecosystem types identified using the classification framework. Below we present information for the six types containing enough LUCAS plots for analyses of forest health indicators in the Bay of Plenty region (Table 2).

¹ <https://soils.landcareresearch.co.nz/soil-data/fundamental-soil-layers/>

² <https://smap.landcareresearch.co.nz/>

³ <https://koordinates.com/layer/300-nz-fsms6-north-island/>

⁴ <http://www.nzpcn.org.nz/>

Table 2. Description of the most common forest ecosystem types in the Bay of Plenty region

Ecosystem	Description
CLF9: Red beech, podocarp forest	<p>This type occurs in the main axial ranges from the Ahimanawa in the south to the Raukūmara in the north. Typically it occurs above (in altitude) MF8 (kāmahī broadleaved podocarp forest) and below pure beech forest. Depending on altitude and landform it has a variable abundance of podocarp trees, and locally, such as on steep ridge lines, is dominated by red beech. Throughout its range red beech is always present, though in some locations silver beech also occurs.</p> <p>This ecosystem type is equivalent to NZFS MS 6 forest class I 'Rimu General Hardwoods Beeches' and especially NZFS MS 2 types I1, I2 & I4 and K3 (Nicholls 1966b, 1969a 1969b), which were primarily used to map its distribution.</p>
MF7-1: Tawa, mangeao, podocarp forest MF7-2: Rātā, tawa, kāmahī, podocarp forest	<p>This type was arguably the most common forest ecosystem unit within the region, despite being displaced from large areas of suitable habitat as a result of Māori fires. It occurs within central and inland areas and merges into WF13 (tawa, kohekohe, rewarewa, hīnau, podocarp forest) at lower altitude and MF8 (kāmahī broadleaved podocarp forest) at higher altitude, often forming the lower and upper distributional limits.</p> <p>It has partial correspondence with NZFS MS6 rimu – tawa class, although this class is broader and required subdivision to map. It occurs in areas with a mild climate and low soil moisture deficit (<70 mm).</p> <p>Two variants were recognised, which were mapped: MF7-1 (tawa, mangeao, podocarp forest) and MF7-2 (rata, tawa, kāmahī, podocarp forest). These two variants were mapped because they occur in geographically distinct parts of the region and have slightly different species compositions.</p>
MF8: Kāmahī broadleaved podocarp forest	<p>This type primarily occurs in the southern Ikawhenua and Whirinaki Ranges, with smaller examples elsewhere. It usually occupies a zone above the altitudinal limit of tawa at approximately 700 m a.s.l. or in areas where it was extirpated by the Taupō 232 AD eruption and has not recolonised fully (McKelvey 1973).</p> <p>MF8 is equivalent to types within the broader forest class M 'rimu, mataī, general hardwoods' (e.g. M1; Nicholls 1969a).</p>
MF22: Tawa, rimu, northern rātā, beech forest	<p>This ecosystem unit occurs predominantly in the eastern Bay of Plenty steep hill-country within the mild climatic zone (Singers & Rogers 2014). It is partially equivalent to the NZFM MS6 (Nicholls 1976) forest classes H 'rimu-tawa-beeches' and the logged variant class O 'tawa-beeches'. It usually merges into WF14-1 in the warm climatic zone. These two types were separated using the distribution of kohekohe as a surrogate for the warm/mild temperature boundary.</p>
WF13: Tawa, kohekohe, rewarewa, hīnau, podocarp forest	<p>This type occurs in lowland and climatically warm areas, often on moderate to steep hill slopes, which experience limited frost. It is partially equivalent to the NZFM MS6 (Nicholls 1976) forest class D 'rimu-tawa'.</p>

Source: adapted from Singers 2014. Refer to the original for citations listed within the table.

There are concerns in the Bay of Plenty about the impact of invasive mammalian herbivores – particularly ungulates (mainly goats and deer), but also marsupials (dama wallabies and brushtail possums) – on indigenous forest health. This relates to the richness and abundance of plant species preferred by mammalian herbivores relative to those that are avoided (Forsyth et al. 2002). In a previous report (Mason & Price 2019) we obtained strong evidence for a decline in abundance of the species preferred by ungulate herbivores in the Bay of Plenty, with this decline apparently being disproportionately severe relative to national-scale trends (Figure 1). This was attributed to the high abundance of ungulates in the Bay of Plenty, although it was impossible to rule out the impacts of high possum abundance (Figure 2).

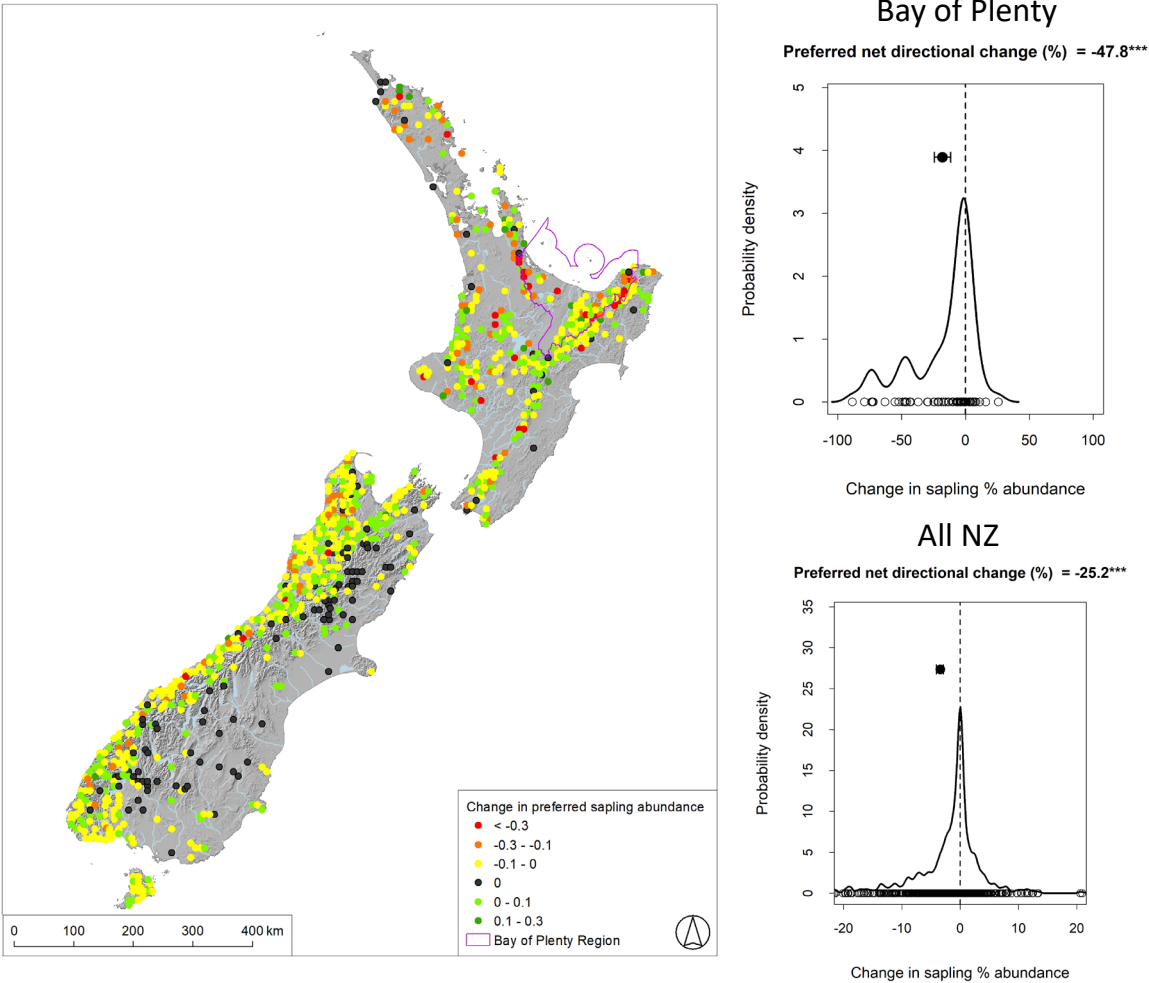


Figure 1. Map of changes in the proportional abundance of species in the preferred ungulate palatability group within the sapling (*sensu* Hurst & Allen 2007) size class in LUCAS survey plots (A), and the probability distribution and significance test results for plot-level changes in the Bay of Plenty region (B) and all of New Zealand (C). Source: adapted from Mason & Price 2019.

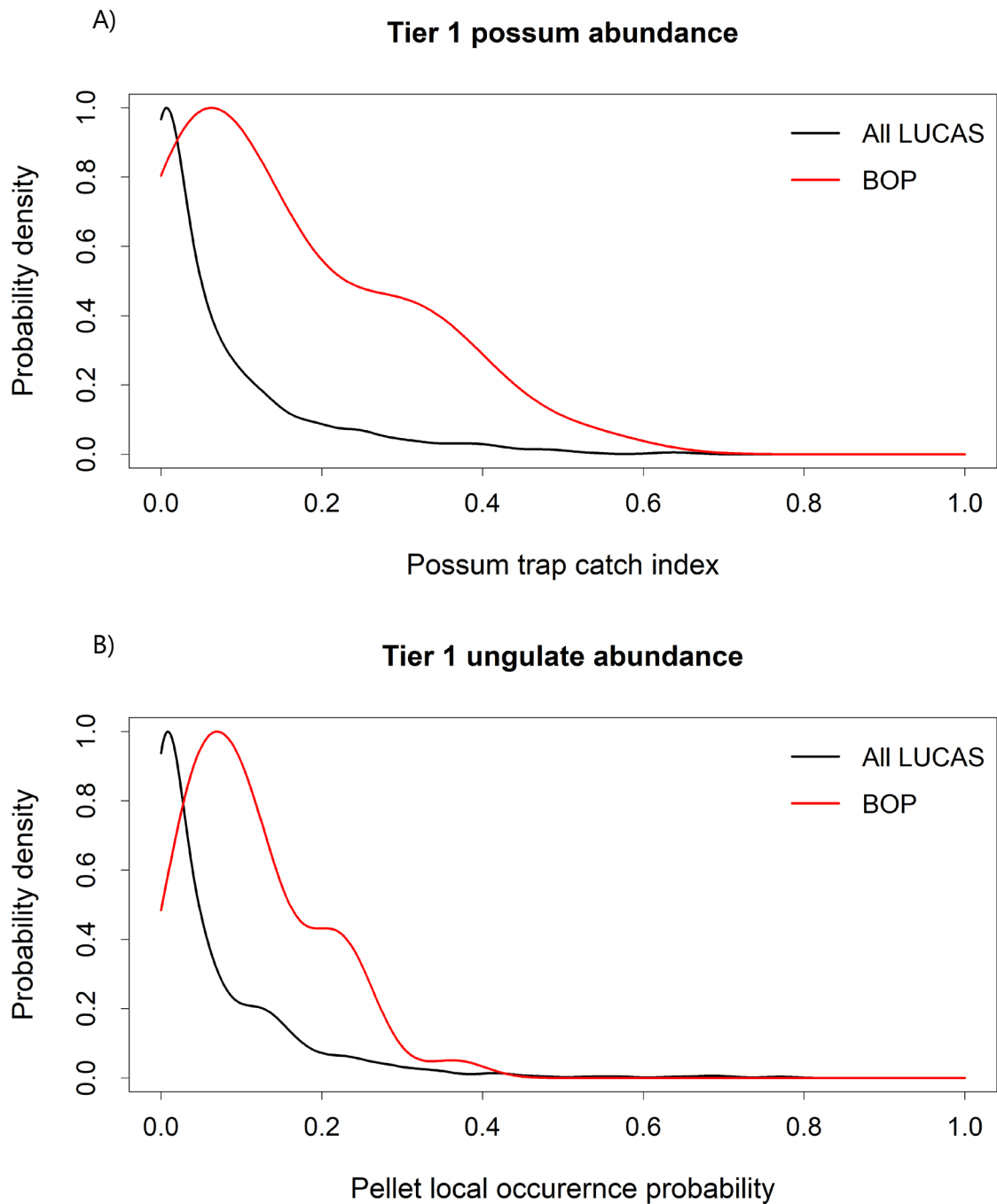


Figure 2. Tier 1 abundance estimates for possums (A) and ungulates (B) at LUCAS indigenous forest and shrubland survey locations in the Bay of Plenty (BOP) and across New Zealand (All LUCAS). In both cases, the peak of the probability distribution curve for the Bay of Plenty (the red curve) occurs at higher values than (i.e. to the right of) that for the whole of New Zealand. This shows that possum and ungulate relative abundance in the Bay of Plenty is, on average, higher than for the rest of New Zealand.

Source: see Mason & Bellingham 2018 for details of Tier 1 data collection and analyses.

Within the Bay of Plenty an area of particular concern regarding ungulate impacts has been the eastern Bay of Plenty, where a control programme targeting goats is currently in operation (Mason & Price 2019). The past impacts of ungulates on vegetation in this area are evident in the large declines of saplings from 'preferred' species between the first two LUCAS survey periods (Figure 3). This figure also reveals that the Kaimai Mamaku area (on the north-western boundary of the Bay of Plenty region) has experienced severe declines in saplings of preferred species. Consequently, arresting and reversing ungulate impacts on vegetation in the Kaimai Mamaku area is a major focus of an upcoming multi-year conservation management project⁵.

Permanent forest survey plots are currently the main tool for monitoring vegetation change in response to mammalian herbivory in New Zealand (Ramsey et al. 2019). Currently the Kaimai Mamaku project area contains 14 such plots (Figure 4). There are concerns that this level of replication will be insufficient to detect all but the largest, most consistent changes in relevant metrics across the project area, changes that may not be feasible under the constraints of management practices and the capacity for biodiversity metrics to respond to management.

Another concern regarding biodiversity monitoring in the Bay of Plenty is that some ecosystem types are poorly represented, or not represented at all, in existing monitoring networks. This hinders the ability of biodiversity managers to detect impacts on these ecosystems, which may lead to considerable biodiversity loss going unnoticed. Similarly, there is concern that lack of provision to detect change in individual ecosystem types in designing the monitoring network for the Kaimai Mamaku project area may limit our ability to detect the positive impacts of conservation management on biodiversity.

In this study we first perform generic power analyses based on artificial data generated with as few assumptions as possible to determine the number of survey plots required to detect the responses of relevant biodiversity metrics of varying levels of consistency. For the purposes of this study we define consistency of response as the proportion of plots experiencing either positive or negative changes in biodiversity metrics between survey periods. The results of these analyses are summarised in a look-up table determining the sample size required for acceptable power at differing levels of consistency (see Table 3).

Where data at sufficient survey locations are available (≥ 6) for individual ecosystem types, we apply a simulation approach that uses available data from repeatedly measured plots to assess the mean change in metric values required to achieve a given level of consistency. The consistency of response is recorded and used to find the required sample size in the look-up table produced by the generic power analyses. This combination of generic and data-based approaches and a focus on the direction rather than the magnitude of changes was chosen for several reasons.

- We lack data for power analyses in most ecosystem types, particularly within the Kaimai Mamaku region. In these situations we have to use generic look-up tables incorporating as few assumptions as possible to determine sample size.

⁵ <https://www.beehive.govt.nz/release/jobs-nature-boosts-efforts-restore-kaimai-mamaku>

- However, power analyses informed by observed data are still important, since they indicate the likely mean effect size of ungulate management required to produce a given consistency of response, and also allow us to assess the sample size required to reliably detect a given effect size.
- Without knowing the intended management regime, it is impossible to know what changes in herbivore abundance to expect, so we need to assess power for multiple effect sizes.
- Even if we could predict changes in herbivore abundance, we do not have a strong evidence base for predicting the size and consistency of resulting changes in biodiversity metrics.
- We cannot assume that changes in metrics of a given magnitude are proportional to biodiversity impacts under different contexts (e.g. different ecosystem types or stand development stages). Consequently, significance tests based on the direction rather than the magnitude of change are more appropriate given our current knowledge (or, rather, lack of knowledge) of how our biodiversity metrics behave in different contexts.

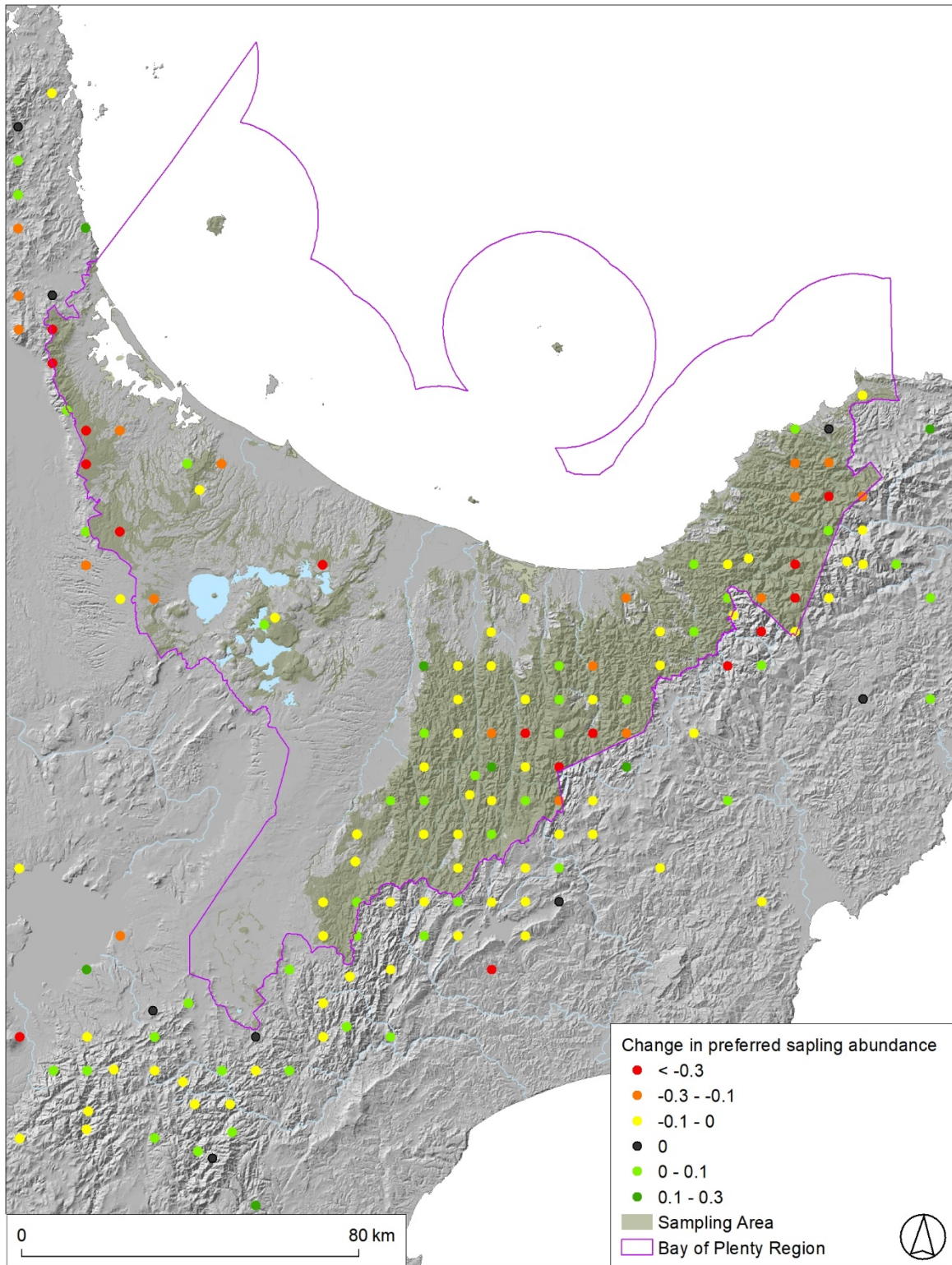


Figure 3. Changes in the proportional abundance of species in the preferred ungulate palatability group within the sapling (*sensu* Hurst & Allen 2007) size class in LUCAS survey plots within the Bay of Plenty region.
 Source: adapted from Mason & Price 2019.

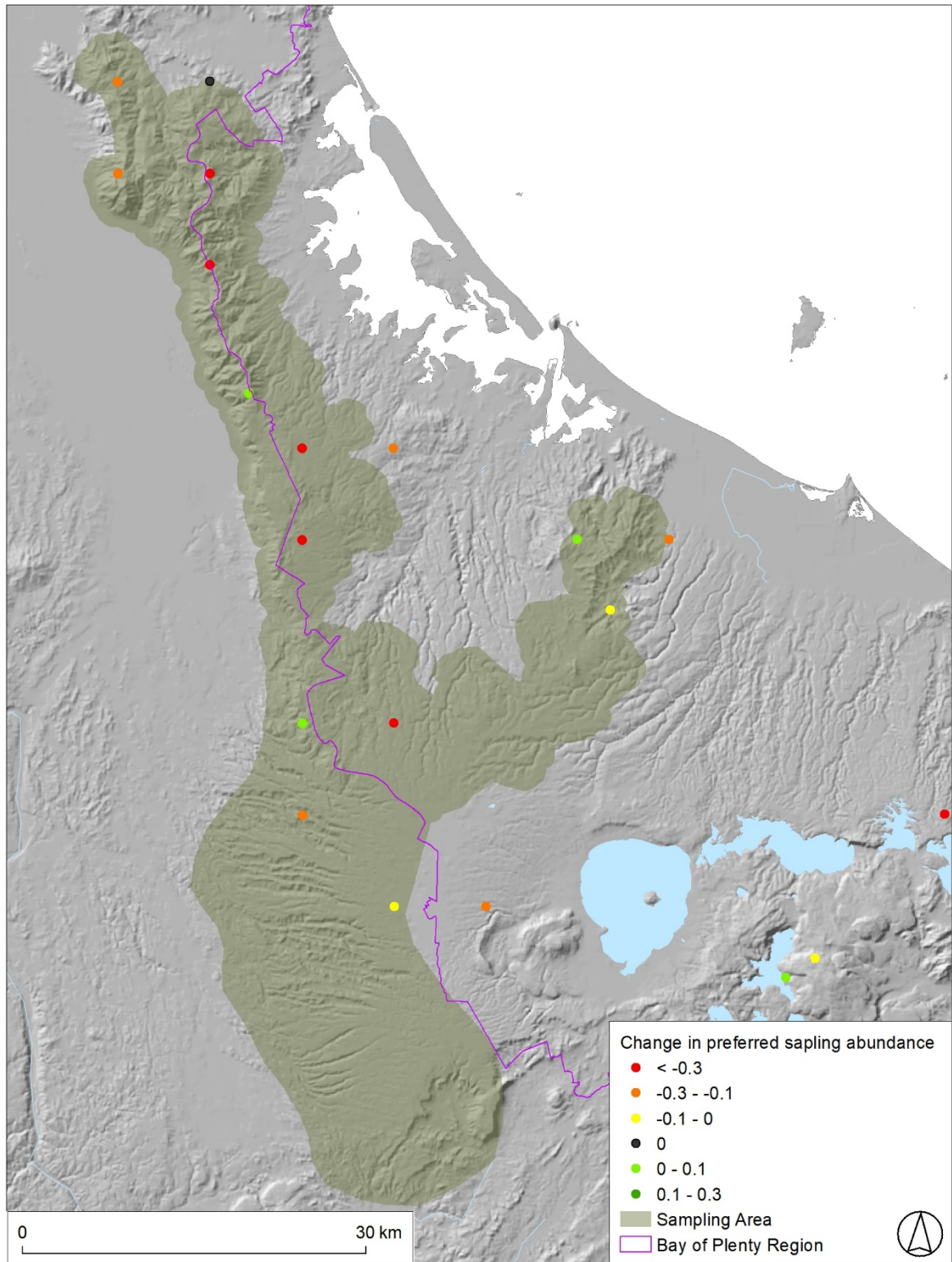


Figure 4. Changes in the proportional abundance of species in the preferred ungulate palatability group within the sapling (*sensu* Hurst & Allen 2007) size class in LUCAS survey plots in the Kaimai Mamaku project area. The project area straddles the boundary between the Waikato and Bay of Plenty regions.

Source: adapted from Mason & Price 2019.

3 Objectives

- 1 Define the sample size required to detect differing levels of consistency in biodiversity metric change with an acceptable level of power.
- 2 Define the mean proportional change in metric values required to achieve a given level of consistency in individual ecosystem types.
- 3 Identify potential survey plot locations to supplement existing plots in providing power to detect changes in individual ecosystem types at differing levels of consistency.

4 Methods

4.1 Data used and plot-level indicators

We used vascular plant species lists, stem diameter at breast height (DBH, 1.35 m) measurements, and seedling and sapling counts from LUCAS plots in the region, with measurements from both the 2002–2007 and 2009–2014 survey periods. Only live stems recorded within the main 20 × 20 m plot with a valid National Vegetation Survey (NVS) databank species code were included. Only plots within the region with live tree stems recorded in both survey periods ($n = 73$) were analysed, since this study is focused on changes at locations where forest land cover occurred throughout the study period, rather than areas where land cover changed from forest to other cover types or *vice versa*.

Methods for plot measurements followed standard LUCAS protocols (Payton et al. 2004). LUCAS plots in the Bay of Plenty were assigned to forest types following the ecosystem classification system of Singers 2014. Individual species were assigned to ungulate palatability classes ('Avoided', 'Preferred', 'Not selected' or 'Unclassified') using classifications available from the NVS.

We calculated mean tree diameter, total number of tree stems and proportional abundance of the preferred palatability class (i.e. abundance of preferred species expressed as a proportion of total abundance across all species within the relevant size class). Abundance of preferred species was estimated as counts of either tree stems, saplings or seedlings.

4.2 Data analysis

4.2.1 Tests for significant changes within plots between surveys

We extended the statistical significance testing method of Mason and Bellingham (2018), which is based on a non-parametric test statistic (T_{dir}) recording the net direction of paired differences (expressed as a proportion of the total number of pairs, in this report equal to the number of remeasured plots):

$$Tdir = \frac{N(t_2 > t_1) - N(t_2 < t_1)}{Nplots} \quad (1)$$

where $N(t_2 > t_1)$ is the number of plots where the measurement in sample 2 is greater than in sample 1; $N(t_1 > t_2)$ is the number of plots where the measurement in sample 1 is greater than in sample 2; and $Nplots$ is the total number of plots.

The advantage of this test is that, by only documenting the direction of shift between survey periods (but within plots), it provides equal power to detect increases or decreases even in data sets where values are constrained by fixed upper and/or lower values. For proportional abundance values, the lower bound is generally zero, and many such data sets exhibit extremely right-skewed distributions (many small values, few large values).

Test statistics incorporating both the magnitude and direction of shift within pairs have lower power to detect decreases than increases for right-skewed data sets with a fixed lower bound (Mason & Bellingham 2018). We used randomisation tests to test whether observed values of $Tdir$ differed significantly from those expected by chance. These tests randomly allocate data between surveys, but within plots, thus retaining the repeated measures structure of the data (see Mason & Bellingham 2018 for details). Mason and Price (2019) showed that interpretation of the results of these tests is aided by presentation of actual values for the difference between survey periods for each plot (e.g. the open circles in Figure 1B and 1C) and the probability distribution function for these differences (generated using kernel density estimators; e.g. the solid lines in Figure 1B and 1C).

4.2.2 Simulation approach

In this report we adapt the simulation approach used by Mason and Price (2019) to estimate the power of the LUCAS sampling design in the eastern Bay of Plenty goat control zone to detect an increase in abundance of species in the 'Preferred' palatability group. This was based on the non-parametric significance test outlined in 4.2.1. This approach simulates positive or negative changes of a fixed size in proportional abundance, based on different target values for $Tdir$. For instance, with a $Tdir$ target value of 0.4, the probability of each plot experiencing an increase or decrease in proportional abundance may be calculated as:

$$P_{pos} = 0.5 + \frac{Tdir}{2} = 0.5 + 0.2 = 0.7 \quad (2)$$

$$P_{neg} = 1 - P_{pos} = 0.3 \quad (3)$$

where P_{pos} is the probability of a plot experiencing a positive change (i.e. an increase) and P_{neg} is that of a negative change.

In the present study we first performed a large number (10,000) significance tests for various combinations of target P_{pos} value and sample size. For each combination, the proportion of tests producing a significant result was recorded. These results were used as a look-up table to identify the sample size needed to detect a given effect consistency (as measured by P_{pos}) with the desired power (power = 0.8 and alpha = 0.05). The R source

code for the analyses is provided in file `PowerPairedContinuousGenericLookUp.r` and results are presented in file `PairedPowerContinuousGeneric.csv`.

Next, we applied a novel simulation method to generate new data for effect sizes expressed as the mean ratio of indicator values in survey 1 to indicator values in survey 2. This uses the difference between the observed and the target ratio to transpose the entire distribution of the survey 2 data set while retaining the variance structure of the observed data:

$$t'_{2i} = t_{2i} + t_{1i} [Target\ t_2 : t_1 - Observed\ t_2 : t_1] \quad (4)$$

where: t'_{2i} is the simulated value for plot i in survey 2; t_{1i} and t_{2i} are the observed values for survey 1 and survey 2 respectively; $Target\ t_2 : t_1$ is the target ratio of the mean of survey 2 values to the mean of survey 1 values (equivalent to $1 + target\ effect\ size$); and $Observed\ t_2 : t_1$ is the observed ratio of the mean of survey 2 values to the mean of survey 1 values.

The next step is to estimate the mean plot-level probability of obtaining a positive (where $Target\ t_2 : t_1 > 1$) or negative (where $Target\ t_2 : t_1 < 1$) change in index values between surveys. To do this we used kernel density estimators to fit a probability density function to paired differences between t'_{2i} and t_{1i} values. We then simply calculated the probability density >0 or <0 , depending on whether or not the probability of a positive or negative change was required. This approach was chosen to avoid simulated paired differences close to 0 having a disproportionately large effect on probability estimates. This simulation approach is illustrated for proportional abundance of 'preferred' species in the sapling size class (Figure 5) and mean tree stem DBH (Figure 6).

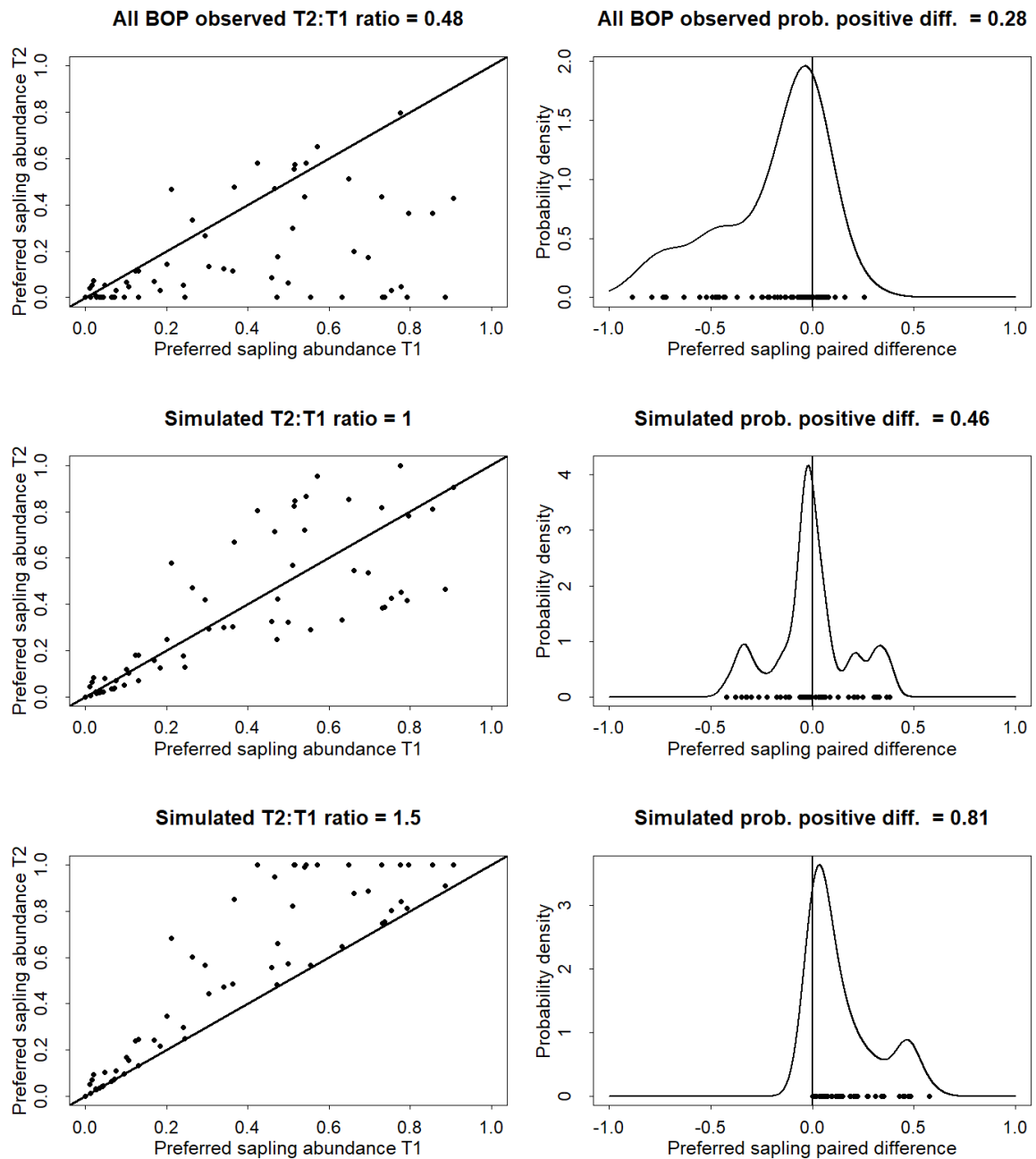


Figure 5. Example of simulation method as applied to the proportional abundance of preferred species in the sapling size class for all LUCAS plots in the Bay of Plenty region. In this example there is considerable variation in plot-level changes in preferred species abundance in the sapling size class. Consequently, a large mean plot-level increase of 50% (T2:T1 ratio of 1.5) is required to produce a simulated mean plot-level probability of achieving a positive change of >0.8

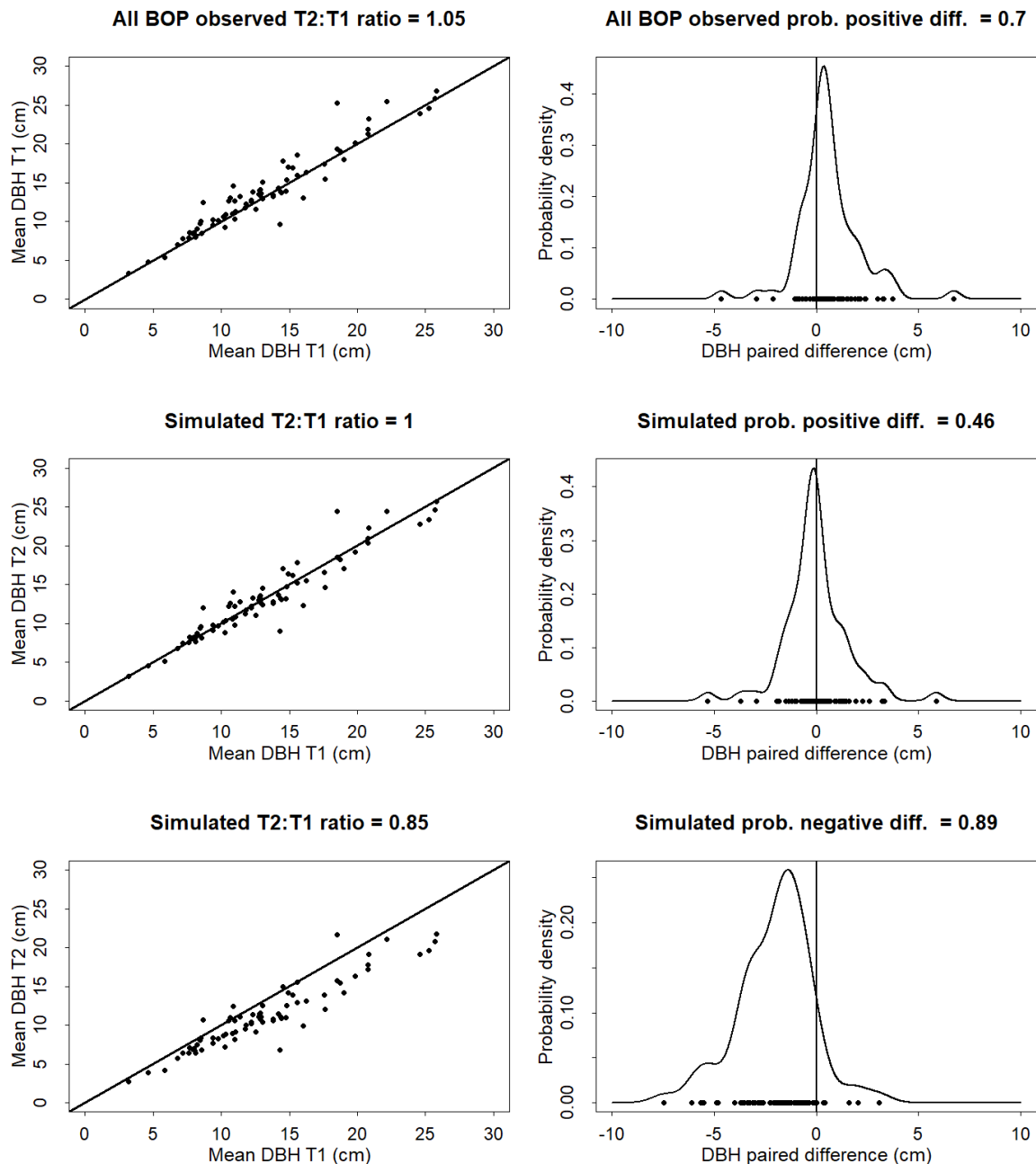


Figure 6. Example of simulation method as applied to mean DBH of tree stems for all LUCAS plots in the Bay of Plenty region. In this example the narrow spread of change values for plot-level mean DBH indicates that a decrease of 15% (T1:T2 ratio of 0.85) yields a plot-level probability of achieving a negative change of 0.89.

An advantage of this simulation approach is that it makes minimal assumptions about the shape of the probability density distribution, for either observed or simulated paired differences, while still incorporating variation in pairwise differences in power analyses. For instance, in Figure 5 there is considerable variation in plot-level changes in preferred species abundance in the sapling size class. Consequently, a large mean plot-level increase of 50% (T2:T1 ratio of 1.5) is required to produce a simulated mean plot-level probability of achieving a positive change of >0.8. By contrast, the narrow spread of change values for

plot-level mean DBH in Figure 6 means that a mean decrease of 15% (T1:T2 ratio of 0.85), yields a mean plot-level probability of achieving a negative change of 0.89.

To aid interpretation of results, we include the standardised effect size (SES), which is calculated as:

$$SES = \frac{\text{Target } t_2 : t_1 - 1}{sd_{[t_2 : t_1 - 1]}}$$

where $sd_{[t_2 : t_1 - 1]}$ is the standard deviation of observed plot-level effect size across the entire Bay of Plenty region. This SES provides a convenient method for expressing targeted effect sizes relative to the variation in observed effect sizes for each metric.

One disadvantage of our approach is that simulations are not based on predicted responses to likely management scenarios (c.f. simulations for bird and possum abundance in Mason & Bellingham 2018). Modelling management effects on indicator values was beyond the project brief and would require further research before being applied to power analyses for vegetation indicators. The estimated mean plot-level probability of obtaining a positive or negative paired difference between surveys was then used to obtain the required number of plots to achieve an 80% chance of obtaining a significant result ($\alpha = 0.05$). The R source code for simulations is provided in file `SampleSizeContinuousGeneric.R`. Separate analyses were done for the entire Bay of Plenty region, the Kaimai Mamaku Conservation Park, and individual ecosystem types with sufficient LUCAS plots across the Bay of Plenty.

4.2.3 Identifying potential survey locations

We applied balanced acceptance sampling (Van Dam-Bates et al. 2018) to locate potential survey sites for the entire Bay of Plenty region, the Kaimai Mamaku project area, and individual potential ecosystems in each region. This approach is designed to provide a spatially balanced sample of an area of interest for any given sample size. It functions by generating an infinite number of potential sampling points based on an arbitrary starting value, known as the seed.

The Department of Conservation (DOC) has used balanced acceptance sampling to generate a master sample of survey locations for their Tier 2 monitoring programme. In our analyses we use the same seed that was used to generate the master sample to ensure our survey design is compatible with the master sample. Balanced acceptance sampling is suitable for this project since it performs very well in producing spatially balanced survey designs for irregularly shaped areas of interest, such as polygons defining potential ecosystem types, compared to other sampling approaches (Van Dam-Bates et al. 2018).

5 Results

5.1 Generic sample size look-up table

Within the range of sample sizes examined, the sample size required for acceptable power declined sharply as the mean plot-level probability of observing a positive change (P_{pos}) increased from 0.6 to 0.75 (Figure 1). Declines in required sample size were more modest for P_{pos} values >0.8 . Since resources for biodiversity monitoring are limited, it is unlikely that large sample sizes (i.e. > 10 plots) will be possible for most individual ecosystem types. Table 3 shows that nine plots are required to provide sufficient power at P_{pos} values of 0.925. Consequently, for most ecosystem types we will only be able to reliably detect changes when at least 92.5% of plots experience changes in the same direction. It is possible that even this level of replication will be untenable for most ecosystem types. Thus, we are only likely to be able to reliably detect management effects on biodiversity metrics for individual ecosystem types when the direction of these effects is very consistent across survey plots.

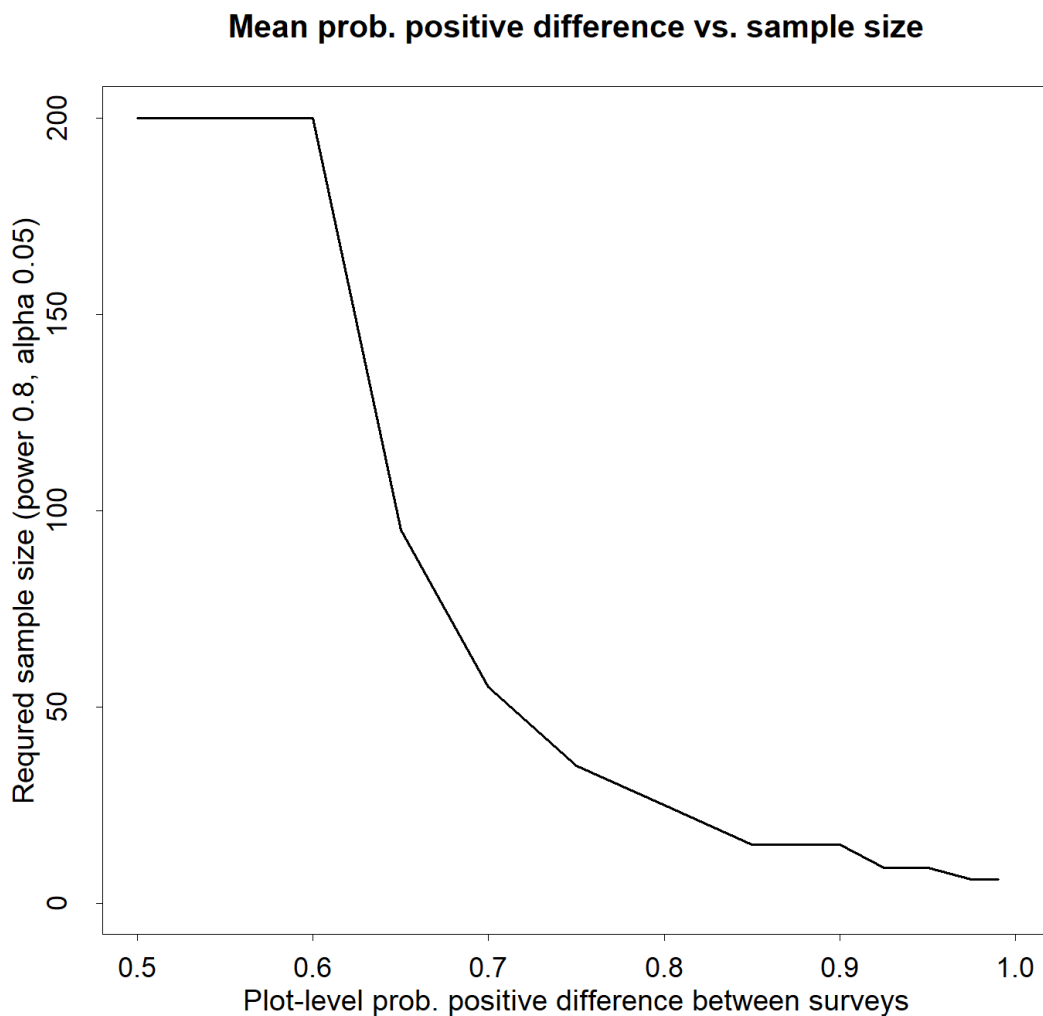


Figure 7. Relationship between effect consistency (plot-level probability of observing a positive difference between surveys) and the sample size required to obtain a significant result at power = 0.8 and alpha = 0.05. The maximum sample size was 200 plots.

Table 3. Look-up table for the sample size required to obtain a significant result with power = 0.8 and alpha = 0.05. P_{pos} is the mean plot-level probability of observing a positive change between surveys, and $Tdir$ is the net plot-level directional change between surveys, where $Tdir = 2(P_{pos}-0.5)$

P_{pos}	$Tdir$	Sample size
0.55	0.1	200
0.6	0.2	200
0.65	0.3	95
0.7	0.4	55
0.75	0.5	35
0.8	0.6	25
0.85	0.7	15
0.9	0.8	15
0.925	0.85	9
0.95	0.9	9
0.975	0.95	6
0.99	0.98	6

Figures 8 and 9 illustrate that the mean effect size required to obtain a given P_{pos} value (and hence the sample size required for acceptable power) can vary for different biodiversity metrics and for different areas of interest. For this reason we use Table 3 to identify required sample sizes and use the simulations described in equation 4 to explore variability in the relationship between effect size and required sample size across different contexts (the entire Bay of Plenty region, the Kaimai Mamaku project area, and individual ecosystem types within the Bay of Plenty region).

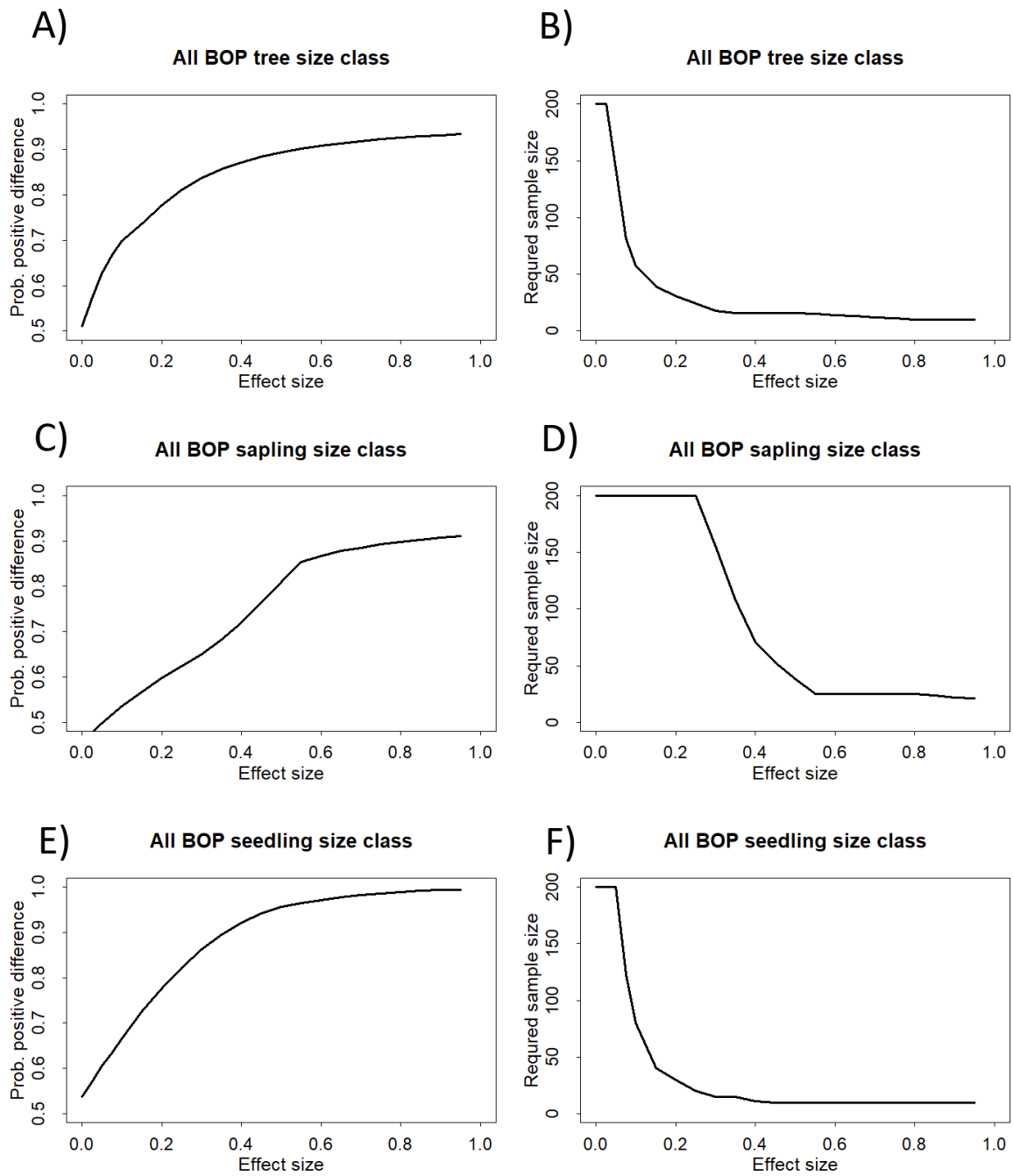


Figure 8. Relationship between effect size ($T2:T1-1$), plot-level probability of observing a positive change between surveys, and sample size required to obtain a significant result where power = 0.8 and alpha = 0.05 for proportional abundance of preferred species in the tree (A, B), sapling (C, D), and seedling (E, F) size classes across the entire Bay of Plenty region.

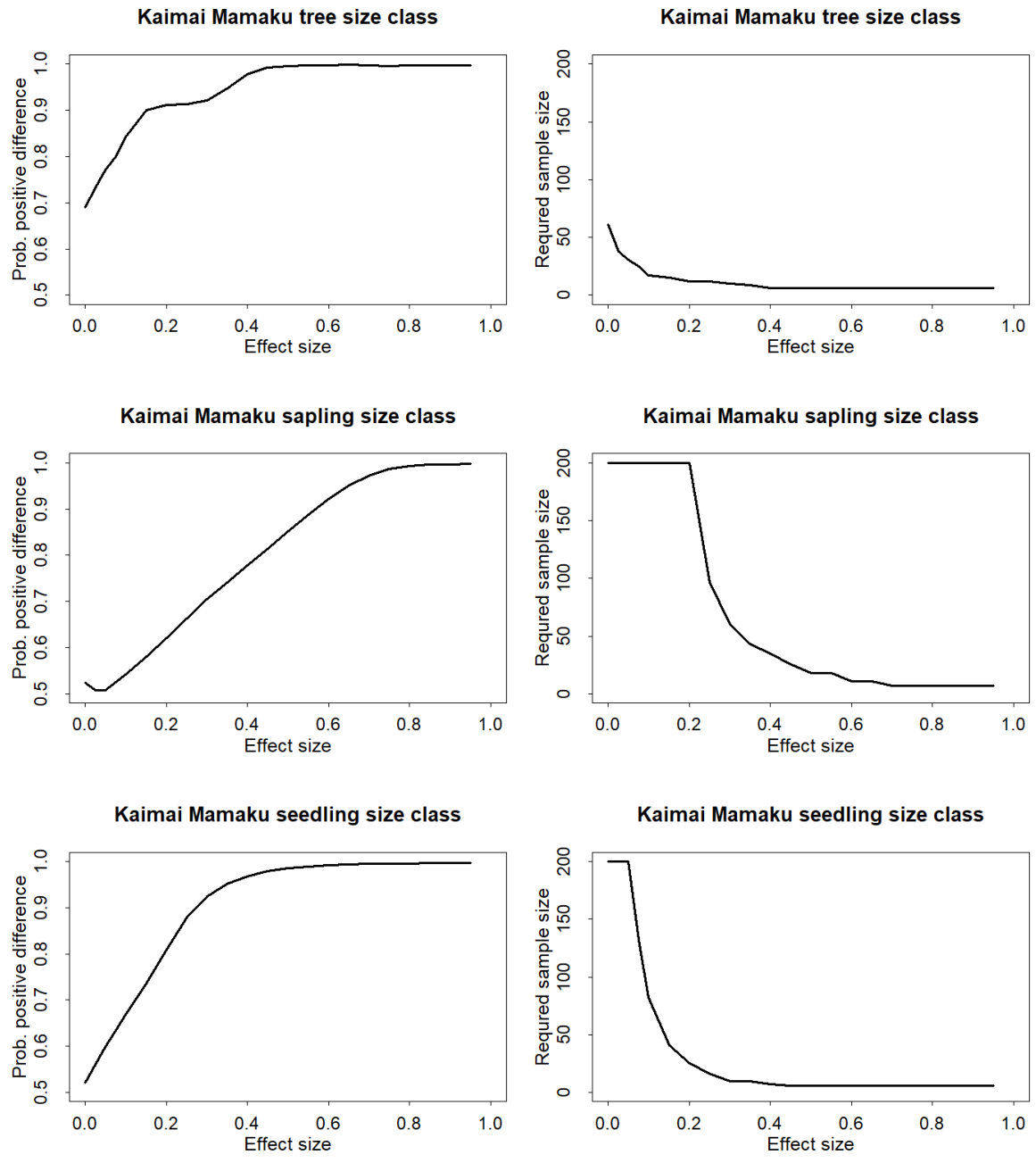


Figure 9. Relationship between effect size ($T2:T1-1$), plot-level probability of observing a positive change between surveys and sample size required to obtain a significant result are power = 0.8 and alpha = 0.05 for proportional abundance of preferred species in the tree, sapling and seedling size classes across the Kaimai Mamaku project area.

5.2 Mean tree diameter

In all but one of the contexts examined (ecosystem type MF7-1 (tawa, mangeao, podocarp forest), 10 or fewer plots provided acceptable power to obtain a significant difference in plot-level mean diameter for effect sizes ≤ -0.25 (i.e. a mean decrease of 25% or more in plot-level mean diameter; Table 4). This is a very large effect size relative to observed variation in effect sizes (SES = -2.2 , a decrease of 2.2 standard deviations). This suggests that management would need to greatly increase recruitment into the tree size class (the primary mechanism by which management is likely to decrease mean DBH) to produce detectable effects on mean DBH within individual ecosystems.

Table 4. Sample size required to detect a decrease in mean DBH across repeatedly measured 20 m × 20 m survey plots with power of 0.8 at 95% confidence (i.e. 80% chance of obtaining a significant result at alpha = 0.05) for various effect sizes.

Effect size	SES	All BOP	Kaimai	MF7-2	MF22	CLF9	MF7-1	WF13	MF8
-0.01	-0.09	200	41	200	200	200	47	200	200
-0.025	-0.22	116	31	83	200	140	30	200	118
-0.05	-0.44	52	23	40	200	58	20	200	35
-0.075	-0.66	33	15	29	75	35	16	68	15
-0.1	-0.88	22	15	20	38	25	15	33	10
-0.15	-1.32	15	13	15	18	15	15	15	6
-0.2	-1.76	9	12	12	14	13	15	9	6
-0.25	-2.20	9	10	9	9	9	15	6	6
-0.3	-2.64	7	9	7	6	9	15	6	6
-0.35	-3.08	6	9	6	6	8	12	6	6
-0.4	-3.52	6	7	6	6	8	9	6	6
-0.45	-3.96	6	6	6	6	7	8	6	6
-0.5	-4.40	6	6	6	6	7	6	6	6

Notes:

Effect size is the proportional change in mean DBH values within survey plots, but between survey periods. SES is the standardised effect size (effect size divided by the standard deviation of effect sizes observed across the Bay of Plenty region). Sample sizes are provided for the entire Bay of Plenty region, the Kaimai Mamaku project area, and individual ecosystem types in the Bay of Plenty region. Only negative effect sizes were analysed, as recruitment in response to ungulate management is expected to decrease mean tree diameter values.

5.3 Change in tree populations

In all but one of the contexts examined (ecosystem type MF8: kāmahi broadleaved podocarp forest), 10 or fewer plots provided acceptable power to obtain a significant difference in plot-level tree populations for effect sizes ≥ 0.35 (i.e. a mean increase of 35% or more in the total number of tree stems per plot; Table 5). This is a comparatively modest effect size relative to observed variation in effect sizes ($SES = 0.46$, a decrease of 0.46 standard deviations). This suggests that increases in recruitment rates that are well within existing levels of variation would be sufficient to produce detectable increases in tree populations.

Table 5. Sample size required to detect a change in tree population size across repeatedly measured 20 m × 20 m survey plots with power of 0.8 at 95% confidence (i.e. 80% chance of obtaining a significant result at alpha = 0.05) for various effect sizes.

Effect size	SES	All BOP	Kaimai	MF7-2	MF22	CLF9	MF7-1	WF13	MF8
0.025	0.03	200	200	200	200	200	109	200	200
0.05	0.07	200	200	200	200	54	77	70	200
0.075	0.10	79	52	200	65	29	58	35	74
0.1	0.13	38	33	113	31	15	41	23	49
0.15	0.20	21	25	34	18	9	27	15	32
0.2	0.26	15	16	21	12	9	15	9	26
0.25	0.33	11	15	15	8	8	9	6	22
0.3	0.40	9	9	14	6	7	6	6	19
0.35	0.46	7	7	9	6	7	6	6	17
0.4	0.53	7	6	8	6	7	6	6	16
0.45	0.59	6	6	6	6	7	6	6	15
0.5	0.66	6	6	6	6	7	6	6	15
0.55	0.72	6	6	6	6	7	6	6	15
0.6	0.79	6	6	6	6	7	6	6	15
0.65	0.86	6	6	6	6	7	6	6	15
0.7	0.92	6	6	6	6	7	6	6	15
0.75	0.99	6	6	6	6	7	6	6	15
0.8	1.05	6	6	6	6	7	6	6	15
0.85	1.12	6	6	6	6	7	6	6	15
0.9	1.19	6	6	6	6	7	6	6	15
0.95	1.25	6	6	6	6	7	6	6	15

Notes:

Effect size is the proportional change in tree population size within survey plots, but between survey periods. Only positive effect sizes were analysed, as recruitment in response to ungulate management is expected to increase tree populations.

5.4 Changes in abundance of preferred palatability class

Across four of the six ecosystem types analysed, more than 10 plots were required to provide acceptable power to detect change in the proportional abundance of preferred species in the tree size class, even at relatively high effect sizes (0.5, or SES of 1.98; Table 6). This suggests we are only likely to reliably detect large changes for this metric (relative to observed variation) within most individual ecosystem types.

Table 6. Sample size required to detect a change in the proportional abundance of preferred species in the tree size class across repeatedly measured 20 m × 20 m survey plots with power of 0.8 at 95% confidence (i.e. 80% chance of obtaining a significant result at alpha = 0.05) for various effect sizes.

Effect size	SES	All BOP	Kaimai	MF7-2	MF22	CLF9	MF7-1	WF13	MF8
0.025	0.10	200	38	200	200	200	119	200	200
0.05	0.20	143	31	200	104	74	80	80	200
0.075	0.30	81	25	200	65	42	53	33	200
0.1	0.40	58	16	150	45	33	36	24	116
0.15	0.60	39	15	76	31	21	20	15	31
0.2	0.79	31	12	51	21	17	15	15	26
0.25	0.99	24	12	40	15	17	13	15	26
0.3	1.19	18	10	35	15	16	12	15	26
0.35	1.39	16	9	32	10	13	12	13	23
0.4	1.59	16	6	29	9	11	13	12	20
0.45	1.79	16	6	26	9	10	14	11	18
0.5	1.98	16	6	23	8	10	15	11	16
0.55	2.18	15	6	21	7	10	15	10	15
0.6	2.38	14	6	19	6	10	15	10	15
0.65	2.58	12	6	18	6	10	15	10	15
0.7	2.78	11	6	16	6	10	15	9	15
0.75	2.98	10	6	16	6	9	14	9	15
0.8	3.17	9	6	16	6	9	14	9	12
0.85	3.37	9	6	16	6	8	14	9	10
0.9	3.57	9	6	16	6	8	13	9	9
0.95	3.77	9	6	16	6	7	13	9	9

Notes:

Effect size is the proportional change in mean DBH values within survey plots, but between survey periods.

Across three of the five ecosystem types with sufficient data for power analyses, more than 10 plots were required to provide acceptable power to detect change in the proportional abundance of preferred species in the sapling size class for all of the effect sizes examined (up to 0.95, or SES of 1.11; Table 7). The comparatively narrow range of SES values spanned by our targeted effect sizes suggests that it might be reasonable to examine power for larger effect sizes. While in this study we have bound effect sizes between 1 and 1, it is possible that effect sizes greater than 1 could occur, especially where initial values are very small.

Table 7. Sample size required to detect a change in the proportional abundance of preferred species in the sapling size class across repeatedly measured 20 m × 20 m survey plots with power of 0.8 at 95% confidence (i.e. 80% chance of obtaining a significant result at alpha = 0.05) for various effect sizes.

Effect size	SES	All BOP	Kaimai	MF7-2	MF22	CLF9	MF7-1	WF13
0.025	0.03	200	200	200	200	200	200	153
0.05	0.06	200	200	200	200	200	200	117
0.075	0.09	200	200	200	200	200	200	98
0.1	0.12	200	200	200	200	200	200	83
0.15	0.18	200	200	200	200	200	182	66
0.2	0.23	200	200	200	200	200	78	56
0.25	0.29	200	98	200	155	210	38	47
0.3	0.35	155	62	200	82	172	18	44
0.35	0.41	108	44	139	52	134	12	40
0.4	0.47	71	35	73	45	105	12	37
0.45	0.53	53	26	52	34	86	12	32
0.5	0.59	38	18	39	22	68	12	28
0.55	0.65	25	18	31	20	55	12	23
0.6	0.70	25	11	30	18	47	12	18
0.65	0.76	25	11	30	16	40	12	18
0.7	0.82	25	7	30	13	37	12	18
0.75	0.88	25	7	30	12	34	12	14
0.8	0.94	25	7	30	12	33	12	11
0.85	1.00	24	7	30	12	32	12	10
0.9	1.06	22	7	30	12	32	12	8
0.95	1.11	20	7	30	11	31	12	7

Notes:

Effect size is the proportional change in mean DBH values within survey plots, but between survey periods.

In all but one of the contexts examined (ecosystem type CLF9: red beech, podocarp forest), 10 or fewer plots provided acceptable power to detect a difference in the proportional abundance of preferred species in the seedling size class at effect size = 0.5 (SES = 0.76, Table 8). This suggests that increases in recruitment rates of preferred species into the seedling size class that are well within existing levels of variation would be sufficient to produce detectable increases in this metric for most ecosystem types.

Table 8. Sample size required to detect a change in the proportional abundance of preferred species in the seedling size class across repeatedly measured 20 m × 20 m survey plots with power of 0.8 at 95% confidence (i.e. 80% chance of obtaining a significant result at alpha = 0.05) for various effect sizes.

Effect size	SES	All BOP	Kaimai	MF7-2	MF22	CLF9	MF7-1	WF13	MF8
0.025	0.04	200	200	200	82	200	200	200	200
0.05	0.08	200	200	200	46	200	200	200	200
0.075	0.11	123	136	79	35	200	200	96	200
0.1	0.15	80	84	54	31	200	122	66	113
0.15	0.23	40	41	32	25	200	60	38	58
0.2	0.30	30	25	22	23	124	33	27	38
0.25	0.38	20	16	15	18	70	16	17	30
0.3	0.45	15	10	15	15	46	12	15	21
0.35	0.53	15	10	13	13	35	8	12	15
0.4	0.61	10	7	9	9	28	6	9	15
0.45	0.68	9	6	9	7	21	6	9	12
0.5	0.76	8	6	9	6	15	6	7	9
0.55	0.83	7	6	9	6	15	6	6	8
0.6	0.91	6	6	8	6	12	6	6	6
0.65	0.98	6	6	7	6	9	6	6	6
0.7	1.06	6	6	6	6	9	6	6	6
0.75	1.14	6	6	6	6	8	6	6	6
0.8	1.21	6	6	6	6	7	6	6	6
0.85	1.29	6	6	6	6	6	6	6	6
0.9	1.36	6	6	6	6	6	6	6	6
0.95	1.44	6	6	6	6	6	6	6	6

Notes:

Effect size is the proportional change in mean DBH values within survey plots, but between survey periods.

5.5 Sampling design to supplement LUCAS survey plots

Figures 10 and 11 display the potential supplementary survey locations required to achieve nine plots per ecosystem type in the Bay of Plenty region and the Kaimai Mamaku project area. These figures demonstrate that for ecosystems that are poorly represented in

the LUCAS plot network, the spatial distribution of survey locations to achieve the required replication differs markedly from the grid-based pattern of the LUCAS network.

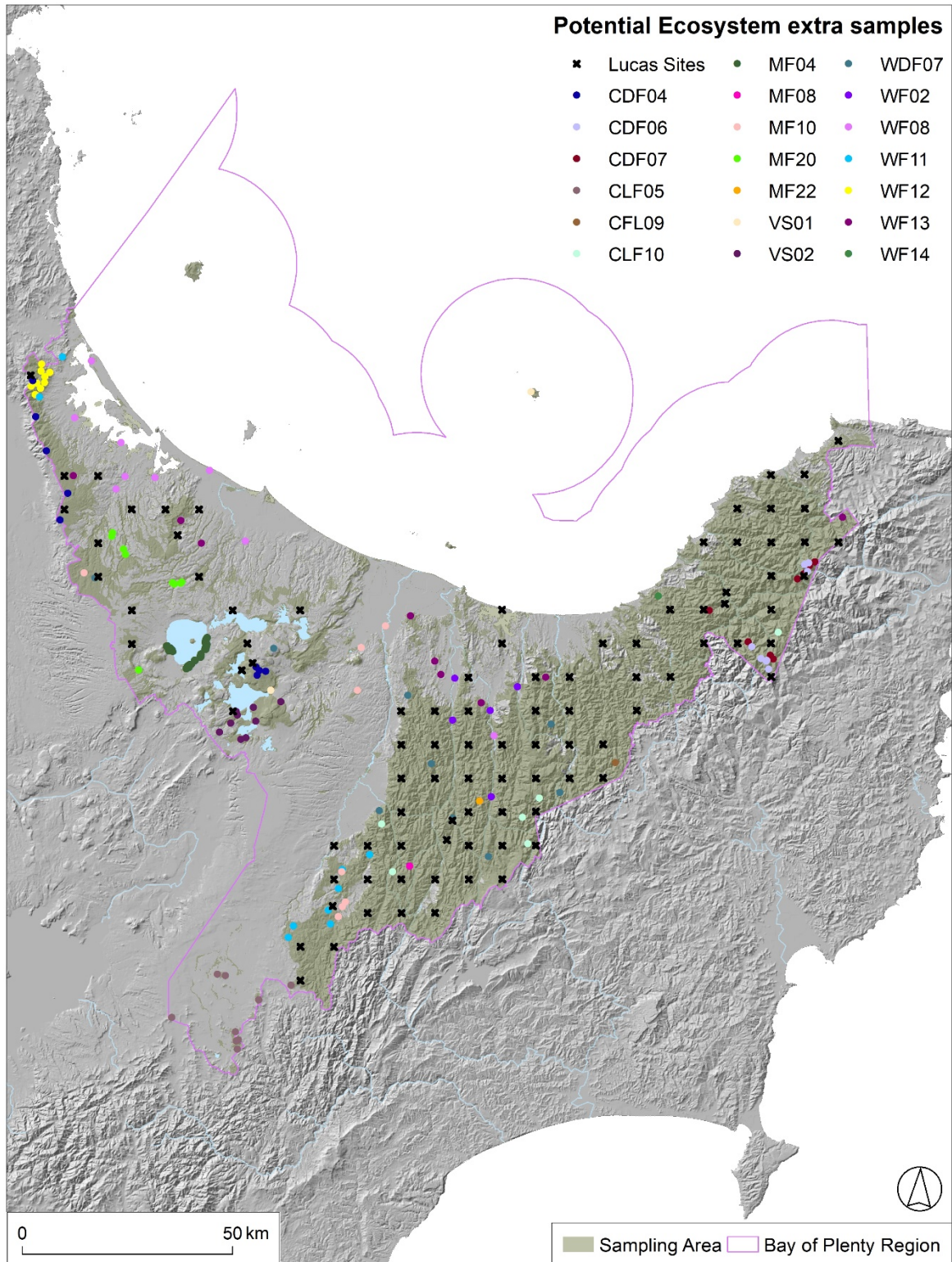


Figure 10. Potential supplementary survey locations required to achieve nine plots per ecosystem type within the Bay of Plenty region.

Notes: Ecosystem types were mapped following Singers 2014. Survey locations were selected by applying the Balanced Acceptance Sampling method of Van Dam-Bates et al. (2018) within polygons of each ecosystem type.

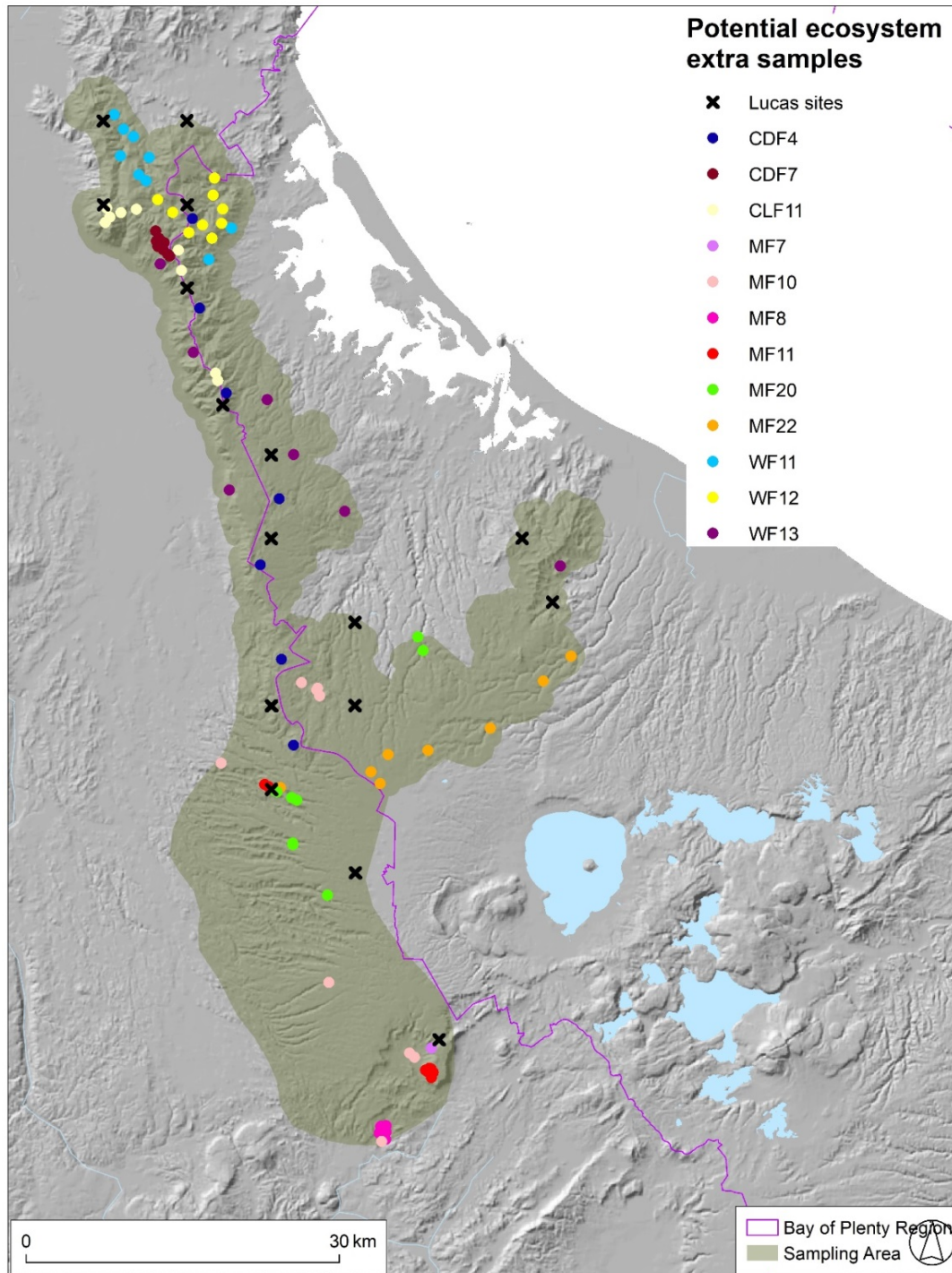


Figure 11. Potential supplementary survey locations required to achieve nine plots per ecosystem type within the Kaimai Mamaku project area.
Notes: Ecosystem types were mapped following Singers 2014 for the Bay of Plenty, and Singers (unpublished)⁶ for the Waikato Region. Survey locations were selected by applying the Balanced Acceptance Sampling method of Van Dam-Bates et al. (2018) within polygons of each ecosystem type.

⁶ Cited here:

https://www.waikatoregion.govt.nz/assets/PageFiles/Waikato%20Biodiversity%20Ranking%202016%20Formatted%20Report_FNL_.pdf

6 Discussion

Our results highlight the challenge of obtaining acceptable power to detect change for individual ecosystems via a permanent plot network following LUCAS and Tier 1 protocols. We found that, depending on the ecosystem in question, a feasible level of sampling (i.e. ≤ 10 plots per ecosystem type) may be insufficient to detect even very large changes in mean tree diameter and preferred species abundance in the tree and sapling size classes. However, there appears to be good potential to detect change in total tree population size and abundance of preferred species in the seedling size class with this level of replication.

Our results for preferred species abundance in the sapling size class may be slightly conservative. Our simulation approach assumes that zero values do not change between survey periods, and there are many zero values for preferred sapling abundance (preferred species are absent from the sapling size class in 40% of LUCAS plots within the Bay of Plenty region) due to large declines between the first and second LUCAS survey periods. It is possible that decreases in herbivore pressure could encourage recruitment from the seedling to sapling size class in plots where preferred species are present as seedlings, but not as saplings.

Figure 12 shows that across the Bay of Plenty region, proportional abundance of preferred species is significantly greater in both the tree and seedling size classes than in the sapling size class. This may suggest that preferred species are occupying both small (Bee et al. 2009; Borkowski et al. 2017) and large (Peltzer et al. 2014) size refuges from ungulate herbivory, and are particularly vulnerable in the sapling size class (there is some local evidence for this (Tanentzap et al. 2009a)). This further suggests there is potential for preferred species to occur in the sapling size class in plots where they are currently missing from this size class. This may either be via direct recruitment from seedlings of preferred species already present in the plot, or after the establishment of seedlings from seed produced by trees of preferred species in the plot.

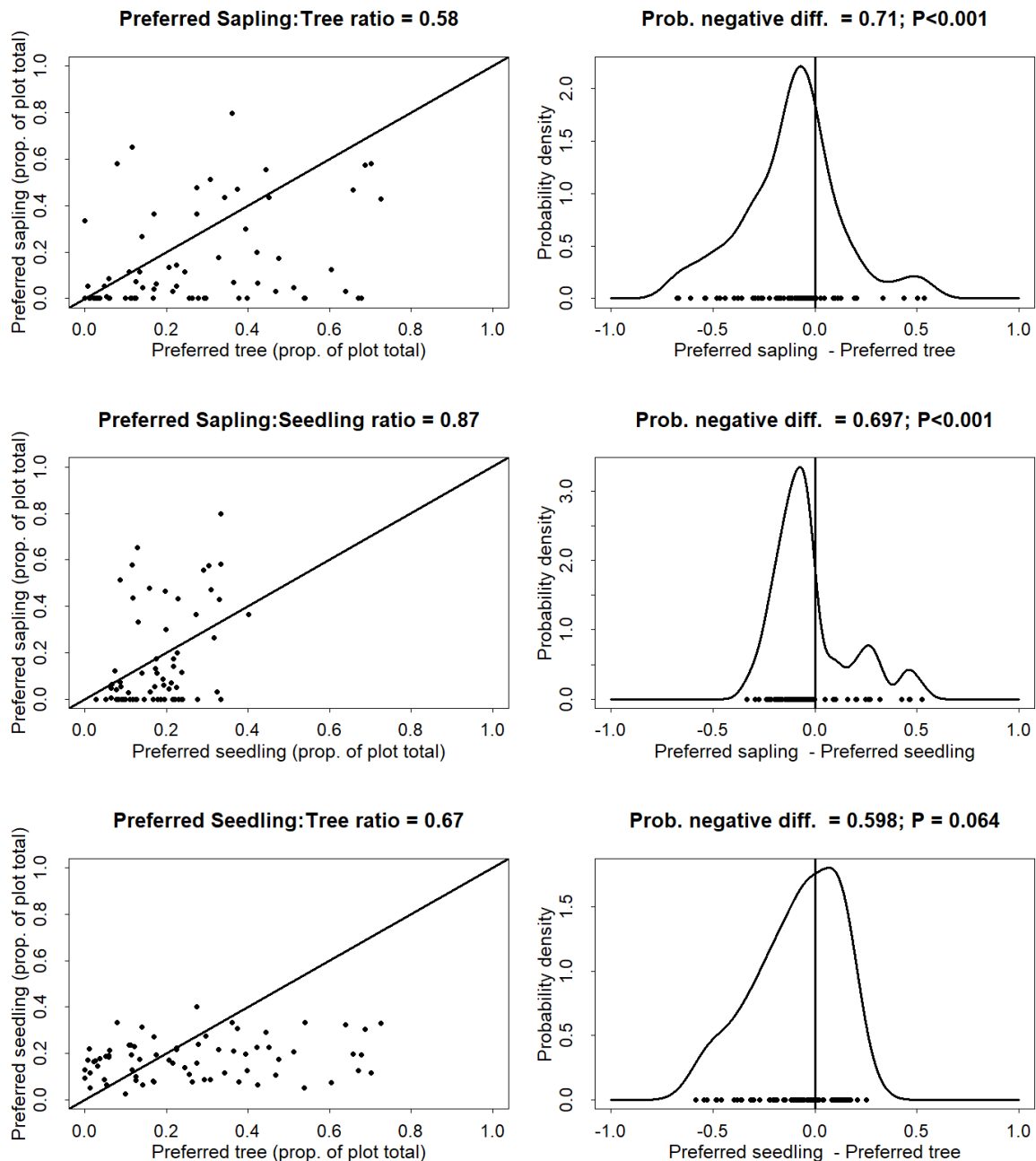


Figure 12. Within-plot comparisons of preferred species proportional abundance in the tree, sapling and seedling size classes for the second LUCAS survey period.

Notes: *P* values were obtained using the significance test described in section 4.2, modified for within-plot comparisons between size classes. These results suggest that both small and large refuges for preferred species may be operating in the Bay of Plenty region, since their proportional abundance is significantly greater in the tree and seedling size classes than in the sapling size class.

The above considerations highlight the difficulty in conducting power analyses for metrics where the mechanistic basis for response to management is poorly documented. We have standardised the targeted effect size for each metric relative to observed variability between LUCAS surveys. However, it is unclear what effect sizes we should expect from ungulate herbivore control operations. Improved demographic modelling tools for both

ungulates and preferred plant species are required to obtain realistic predictions of ungulate population densities and preferred plant population response changes in ungulate densities.

There appears to be considerable uncertainty around ungulate population responses to socially acceptable (i.e. hunting-based c.f. toxin-based) management interventions (e.g. Forsyth et al. 2013). In any case, we currently lack accurate methods for monitoring ungulate density at large spatial extents. The current approach is based on faecal pellet counts in subplots arranged along transects. The weak link between this method and densities has long been known (Forsyth et al. 2011), so that only large differences in density are likely to be reliably detected by this method. It would be possible to use the data presented in Forsyth et al. 2011 to incorporate uncertainty in the pellet count–population density relationship in power analyses based on simulated ungulate population dynamics, but we are not aware of any existing attempts to do this. Another drawback of pellet-based observations is that they cannot reliably discriminate between some ungulate species.

In New Zealand, the relationships between ungulate density and the population dynamics of preferred plant species remain poorly understood at the national scale (particularly impacts on highly preferred species at very low ungulate densities, but see Tanentzap et al. 2009a for a local example). It might be possible to explore on a mechanistic basis (i.e. using simple foraging models) since there is available information on ungulate plant species preferences, based either on gut contents or browsing rates (Forsyth et al. 2002; Tanentzap et al. 2009b) and we should be able to estimate per-individual caloric requirements from available information sources provided by the deer industry⁷ or the scientific literature. We could also build basic movement models based on existing work on wild ungulates as vectors of bovine tuberculosis (e.g. Yockney et al. 2013).

Combining these four information sources – plant species population dynamics, and ungulate species dietary preferences, dietary requirements and movement – would enable the development of simple mechanistic foraging models to estimate ungulate browsing intensity on preferred species at various ungulate population densities. Such models would also provide a useful platform for prioritising research to improve our understanding of vegetation responses to ungulate management. This would benefit all agencies tasked with managing ungulate populations for desired vegetation outcomes.

We have provided an indicative sampling design to improve the representation of individual ecosystem types in monitoring plots beyond what it provided by the LUCAS and Tier 1 plot networks, based on a sample size of nine plots per ecosystem type. This needs to be refined in light of factors such as site safety and ease of access. This can be achieved easily by modifying the sampling universe to exclude areas that do not meet such feasibility criteria. It is possible that other agencies, such as DOC, already have maps defining areas that satisfy predetermined feasibility criteria and which could be applied to modify the sampling universe both for the Bay of Plenty region and for the Kaimai

⁷ <https://www.deernz.org/deerhub/feeding/feeding-deer/intake-requirements/feed-or-energy-intake#.X8Wo-WgzaUk>

Mamaku project area. Where sample locations incur hazards not revealed by spatial information, Tier 1 protocols include objective methods for selecting nearby locations that satisfy safety criteria.

Finally, our focus on detecting a given effect size in selected vegetation metrics is based on past scientific studies and is not strongly informed by stakeholder opinions or objectives. For instance, we are not aware of any clear statements on what might constitute a 'successful' response of vegetation indicators to mammalian herbivore control in the Bay of Plenty, for the Kaimai Mamaku project area, or indeed for New Zealand. Recent work has emphasised the importance of ensuring that forecasts of the impacts of invasive species, and effects of management on these impacts, are relevant to stakeholder objectives (Mason et al. 2020). There appears to be a general need in New Zealand for careful consideration of what the desired outcomes might be for vegetation in response to mammalian herbivore management.

7 Conclusions

Forest ecosystems in the Bay of Plenty region and the Kaimai Mamaku project area appear to have been heavily affected by ungulate herbivory. Our analyses suggest that total tree populations and abundance of preferred species in seedling size class could provide acceptable power to detect the positive impacts of mammalian herbivore management on individual forest ecosystem types in the region with a sample size of ≤ 10 .

It is possible that our analyses have underestimated the potential power of preferred species abundance in the sapling size class to reveal management impacts. Data from LUCAS plots suggest the herbivore impacts on preferred species have been particularly severe in the sapling size class, and that preferred species abundance in this size class could be particularly responsive to ungulate herbivore management.

8 Recommendations

- The sampling universe for the Bay of Plenty region and the Kaimai Mamaku project area should be adjusted to incorporate feasibility criteria.
- Vegetation metrics obtained from 20 m × 20 m permanent survey plots can detect the impacts of ungulate herbivore control within individual ecosystem types, within a stratified region-wide sampling design.
- Improved methods for monitoring ungulate species population density and predicting population responses to management are required.
- Mechanistic models of preferred plant population dynamics at various ungulate population densities are required to realistically simulate vegetation metric responses to management in power analyses. These models should include information on plant demography, ungulate diet preferences, diet requirements and movement.
- Given the apparent impacts of ungulates on forest ecosystems, serious consideration should be given to expanding and intensifying ungulate herbivore management in the

Bay of Plenty region and including ungulate control as a major component of the Kaimai Mamaku restoration project.

- Discussions involving all relevant stakeholders are required to determine the desired outcomes for indigenous forest vegetation in response to mammalian herbivore control efforts.

9 Acknowledgements

Shay Dean facilitated the contract to undertake this work and commented on earlier draft versions. Elise Arnst helped process the data request through the National Vegetation Databank. Meredith McKay (DOC) and Asher Cook (Ministry for the Environment) provided access to the LUCAS plot data. Meredith McKay (DOC) also supplied the data on invasive mammal abundances from Tier 1.

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