Assessing disturbance lags: re-surveying Koala density in 2023 three years after timber harvesting

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Summary

A before-after selective timber harvesting experiment in 2019-2020 assessed the immediate impacts on koala density and detected no impact. Ongoing monitoring to assess lag effects on koalas was undertaken in 2023 using acoustic arrays to estimate male density from bellowing activity. This monitoring was a repeat survey of the six acoustic arrays (each ~ 400 ha) that previously sampled replicate areas that were harvested in state forest and control areas in national park. Continued monitoring three years after harvesting in 2023 did not detect a significant effect of selective harvesting on male koala density at the array-scale, which is consistent with the assessment immediately after harvesting (Law et al. 2022a). However, a significant decline at control national parks was detected, with these dynamic changes potentially associated with drought and canopy dieback. Low intensity fire had also occurred at two state forest arrays prior to survey. Further monitoring of these sites will be of value to assess ongoing changes in koala density and should aim to avoid periods soon after fire (and if possible, drought).

Background

The NSW Government requested that the Natural Resources Commission (the Commission) deliver independent research to better understand how koalas respond to harvesting in state forests in the upper and lower northeast Coastal Integrated Forestry Operations Approval (Coastal IFOA) regions. The request was made under the NSW Koala Strategy (2021-26) and funded by the NSW Department of Climate Change, Energy, the Environment and Water. This research will build on the Commission's previous koala research program delivered between 2019-22.

This research investigates the following research question:

- How do koala populations respond following selective harvesting at varying levels of intensity?

Introduction

In 2019 NSW Department of Primary Industries and Regional Development established a BACIP (before-after-control-impact-paired) experiment to assess the impact of selective harvesting on koala density. Harvesting occurred in state forest and was compared to controls established in nearby national parks. Large acoustic arrays covering about 400 ha (~ 750 ha including surrounding array buffer) at each site were used to estimate male koala density based on male bellowing activity and using Spatial Count (SC) modelling (Law et al. 2022a). No immediate impact of harvesting on koala density was detected in the study and similar densities were found between national parks and state forests.

The acoustic array method was previously validated across five different sites in NSW and was found to produce plausible and reliable estimates of koala density (Law et al. 2021). An independent estimate of density was also derived for one site (Kalateenee State Forest) by genotyping fresh scats located using koala detection dogs (Gonsalves et al. 2021). The number of different genotypes (individuals) per area sampled was similar to the density estimated by the acoustic array (assuming a 1:1 sex ratio). Sex typing of scats also confirmed the sex ratio was not significantly different from 1:1. Of the 90 scat samples collected from the Kalateenee search area, a total of 26 individual genotypes were identified. Of these, ten were female, 13 were male and three were of unknown sex (56.5% males), indicating no significant difference from a 1:1 ratio (chi-square=0.391, p=0.531).

The aim of this report is to analyse the same six acoustic arrays re-deployed in late spring 2023, three years after selective harvesting. This resurvey thus extends the original assessment to assess disturbance lags by estimating change in koala density over a longer period (3 years post-harvest).

Methods

At each site sensors were typically deployed in a 5 x 5 array, with 400 m spacing, though this was varied to align with harvest plans. The spacing was selected to allow for correlated detections between adjacent sensors (Law unpubl. data) as required by Spatial Count models, given koala movements and that under ideal conditions koala bellows are recorded up to ~300 m with SM4 sensors. The appropriateness of the applied spacing of sensors was formally assessed using the sigma parameter which is generated as part of the spatial count modelling (see below), with optimum spacing of sensors being 2 σ (Clark, 2019; Sun et al., 2014). A single acoustic sensor (Song Meter SM4, Wildlife Acoustics, Maynard USA) was deployed at each point for ~ 14 nights in November - December 2023, the breeding season for koalas and when males are most vocal. Sensors were programmed to record from sunset until sunrise, the peak calling period of koalas, with a sampling rate of 22050 Hz, and resolution of 16 bits per sample. Each State Forest and National Park pair was sampled simultaneously before switching to a new pair. SM4's were re-deployed at original locations using GPS coordinates.

Further details of the study area and harvesting can be found in Law et al. (2022).

Automated analysis of Koala bellows

Acoustic files (.wav) from each sensor location for all grids were scanned for male koala bellows in AviaNZ software using an algorithm developed by DPIRD to detect male koala bellows in .wav files (Version 5 - Koala_CNN_LG_071223;

https://www.dpi.nsw.gov.au/forestry/science/forest-ecology/fauna-identification-service). This recogniser was an update to the version used in the 2020 assessment (Law et al. 2022), which had improved recall and precision. It is important to note that spatial count modelling (see below) adjusts for variations in detection probability that would be expected with improved recall for koala bellows. Since sounds produced by different sources (e.g., koalas, planes, kookaburra, etc.) can have characteristics that are superficially similar and/or overlap, the classifier picks out signals from different sources if they have similar characteristics to the training data used in its development. For each site, signals that matched the koala recogniser were manually validated as koala calls or as false positives. It is important to note that the recogniser may not detect very faint bellows, particularly if there is other low frequency noise (e.g., machinery, wind, rain) being generated at a greater amplitude. However, Spatial Count modelling of density accounts for call detectability (see below).

Spatial count model specifications

SC models use spatial correlation (among sensors) in temporally (within night) replicated counts across occasions K (nights). These data generate spatially referenced counts of bellows and along with a modelled encounter rate (see below), are used to infer the location of activity (i.e., home range) centres. Specifically, N (abundance) is estimated as a subset of data augmentation variable M, an oversized population (e.g. metapopulation) of which our population is a part (Royle and Dorazio, 2012). As such, spatial correlation of calls within a night are used to generate spatially referenced counts which informs the location of activity centres. The activity centres and likelihood of encounter (lambda) are used to determine whether multiple activity centres represent multiple koalas or the same koala. Abundance is estimated by summing inferred activity centres and density (D) is calculated by dividing N by the estimated study area, or state-space S, that encompasses potential activity centres for all individuals with a non-negligible probability of being detected by our detector traps over the study period.

In addition to estimating density, SC models, like all SCR (Spatial Capture-Recapture) models, also estimate the baseline encounter rate —$\lambda 0$, the probability of encounter of an individual if their activity centre is at the detector location— and a spatial scale parameter —σ, a measure of the rate of decay of encounter as the distance between the activity centre and the detector location increases (Royle et al., 2014). The σ parameter is thus related to home range size and it is recommended that detectors are placed ~2 σ apart (Clark, 2019; Sun et al., 2014). For all arrays, σ was 2.2±0.1 (220 when converted to metres), indicating that sensors were adequately spaced. This is consistent with trials of acoustic arrays and spatial count modelling in different parts of NSW (Law et al.2022b). We considered the detector locations, plus a 750 m buffer around the minimum rectangle envelope defined by the detector locations J, as the state-space S (~1158-1576 ha; range for all arrays) within which we estimated density. Our models did not consider potential habitat differences within S. We applied SC models using Poisson encounter models assuming bivariate normal movement in a Bayesian framework (Chandler and Royle, 2013). We ran SC models using JAGS (ver 4.2.0; Plummer, 2003), interfacing through R using the rjags package (Plummer, 2016). We specified a λ 0 prior with a uniform distribution between 0 and 100, a ψ prior with a beta distribution, shape and scale set to 1. We trialled two different σ priors: one weakly informative (calculated for a home range size ranging between 10-90 ha, and one strongly informed prior (site-specific home range of 40 ha as per Law et al. 2022). The weakly informative prior accounts for the fact that koala home range size is unknown in the study area. All σ priors assumed a gamma distribution with the shape and spread varying based on home range size. We provide graphical results of estimated density for all models. For each model, we set M = 500 after trialling smaller values. We ran one chain of the JAGS models for 50,000 iterations with a burn-in of 10,000 (after an adaptive phase of 1,000) and did not thin the posterior distribution. Model convergence was assessed by calculating the Gelman-Rubin statistic using the R package *coda* (Plummer et al., 2006), where values <1.1 indicated model convergence. Modelled male koala density was also visualised to explore the spatial variation in density.

Statistical analysis of BACIP design

Testing for a change in male koala density originally followed the classic application of a BACIP analysis that compares the Before and After paired differences using a two-sample t-test. This design relies heavily on matching of paired sites, which was appropriate at the start of the study. However, at the time of the 2023 survey several differences were apparent between pairs such as some sites having burnt and others displaying severe canopy dieback (see below). To account for any differences associated with local conditions at each site, we analysed the resurvey data using the BACI approach but in a Generalised Linear Mixed Model (GLMM) framework, treating site as a random effect and treatment*time as fixed effects, with a gamma distribution and log link function. In this BACI-style analysis, a significant interaction is used to demonstrate change over time due to a treatment effect.

Spatial variation in density

We overlayed the spatial variation in density at each array, as modeled by spatial count, with mapped forest age classes, environmental prescriptions (exclusions) and recent harvest polygons as recorded by GPS in harvesting machinery. Mean male koala density of each pixel in each forest category was then calculated before and after harvesting for each array. It should be noted that density values per pixel are likely to be indicative only and will be most meaningful when averaged over larger contiguous blocks of a forest category rather than small patches. Standard errors were derived for each category using the variation in density among polygons in each category.

Results

Number of bellows – naïve occupancy

In all, 3803 bellows (with each bellow separated by >1 min) were recorded across all six arrays (Table 1). Naïve occupancy was generally high (0.73-1.00), with koalas detected at all sensors in two arrays (Kumbatine NP and Lower Bucca SF). Naïve occupancy was lowest at Cowarra SF. The total number of bellows recorded was greatest at Kumbatine NP and lowest at Cowarra SF (Table 1).

Table 1. Summary showing the number of sites at which koala bellows were detected and the total number of bellows recorded.

Grid	No. of sites detected	No. of sites sampled	Naïve occupancy	Total number of bellows
BAB	21	25	0.84	369
COW	19	26	0.73	238
KAL	21	22	0.95	346
KUM	21	21	1.00	1554
LOW	23	23	1.00	885
ULI	18	19	0.95	411

Koala density at the array level

Koala density varied considerably at some arrays in 2023 compared to previous surveys (Fig 1). Notable declines in density were recorded at several sites (Fig 2):

- Cowarra State Forest, which had been burnt by a large, low-severity, patchy hazard reduction burn in July 2023 and associated trail maintenance. The array may have been influenced at the edge of its array by construction of the Guulabaa Koala Sanctuary in 2023;
- Kumbatine National Park, where there was a substantial drought-associated forest dieback evident during song meter deployment in November 2023 (Fig 3; Fig 4). This short, but intense drought impacted the mid-north coast study area in spring 2023, although drought-breaking rains fell soon after acoustic sampling finished;
- Ulidarra National Park, but with no obvious mechanism, except the spring drought. Canopy dieback was not evident here.

Lower Bucca State Forest had a 27 % increase in koala density (Fig 2). Kalateenee State Forest had stable density, although it was extensively burnt by a low-moderate severity hazard reduction/backburn in September 2023, two months prior to acoustic sampling (Fig 5).

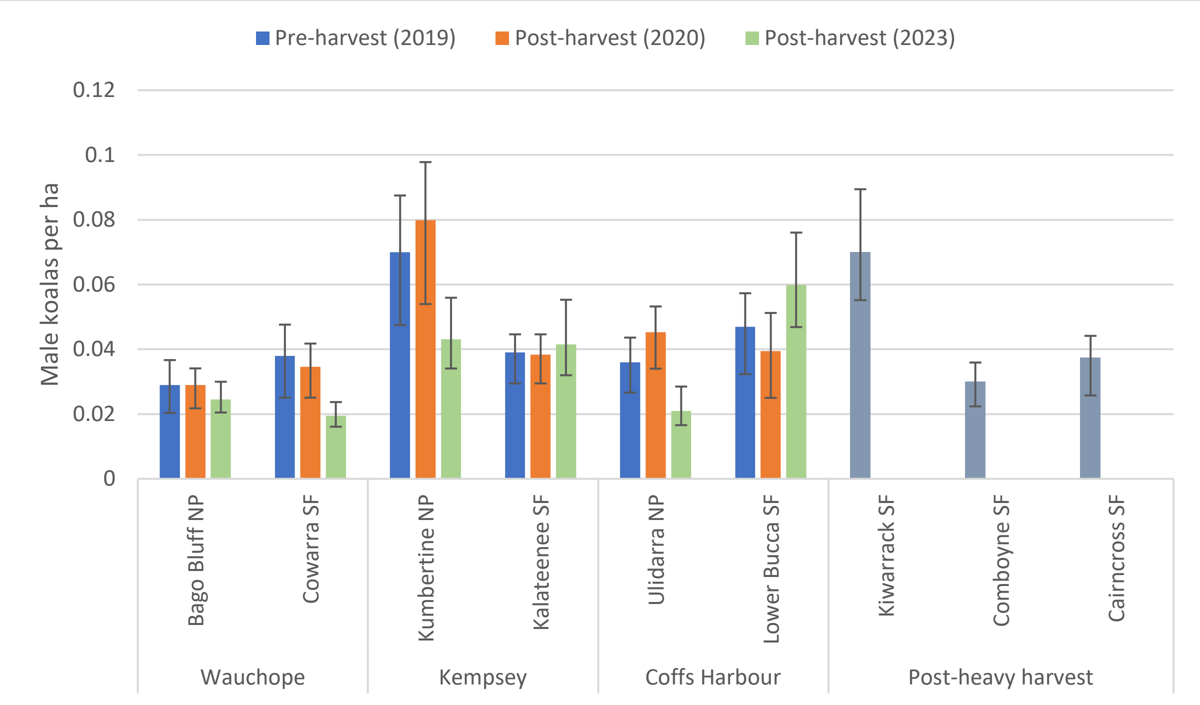


Fig 1: **Male koala density before and after harvesting.** Modelled male koala density (mean ± 25-75 % credible interval) in pre- (2019) and post-harvest years (2020 and 2023) at BACIP sites and three additional sites 5-10 years post-heavy harvest surveyed in 2020. Density was estimated by Spatial Count analysis of acoustic data collected from arrays.

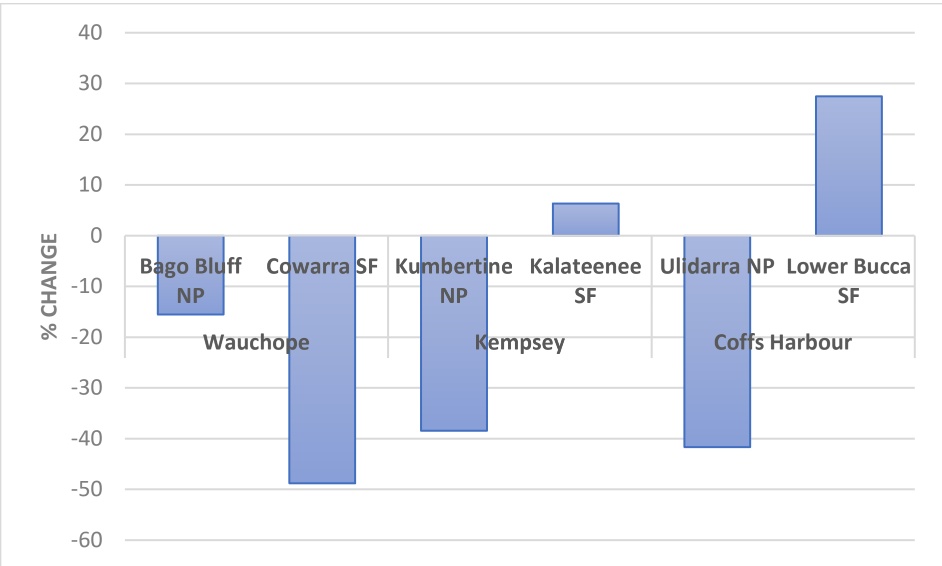


Fig 2: % change in male koala density from 2019 to 2023 at six acoustic arrays.

Fig 3: Canopy and understorey dieback in Kumbatine National Park (November 2023).

November 2023

Fig 4: Aerial view of canopy dieback at Kumbatine NP showing true colour and NDVI (Copernicus) for the array in November 2023.

Fig 5: Low severity fire in a portion of Kalateenee State Forest (19 September 2023).

Statistical analysis using GLMMs found a significant interaction with a decline in mean koala density in control (national park) sites in 2023 (Fig 5; Table 2). The average change by treatment was -5 % at harvested arrays vs -31.9 % at controls (Fig 6). Although replication is low, inspection of Fig 1 and Fig 2 shows changes in density were not related to harvesting, in that density at two national parks and one state forest declined considerably, while one state forest increased.

Table 2: Analysis of Deviance Table (Type III Wald chisquare tests) showing effects of disturbance (group), year (time) and the interaction between the two.

Response: Density	**Chisq**	**Df**	**Pr(>Chisq)**
(Intercept)	268.702	1	<0.001
as.factor(Group)	0.813	1	0.3674
as.factor(Time)	12.65	2	0.0018
as.factor(Group):as.factor(Time)	6.081	2	0.0478

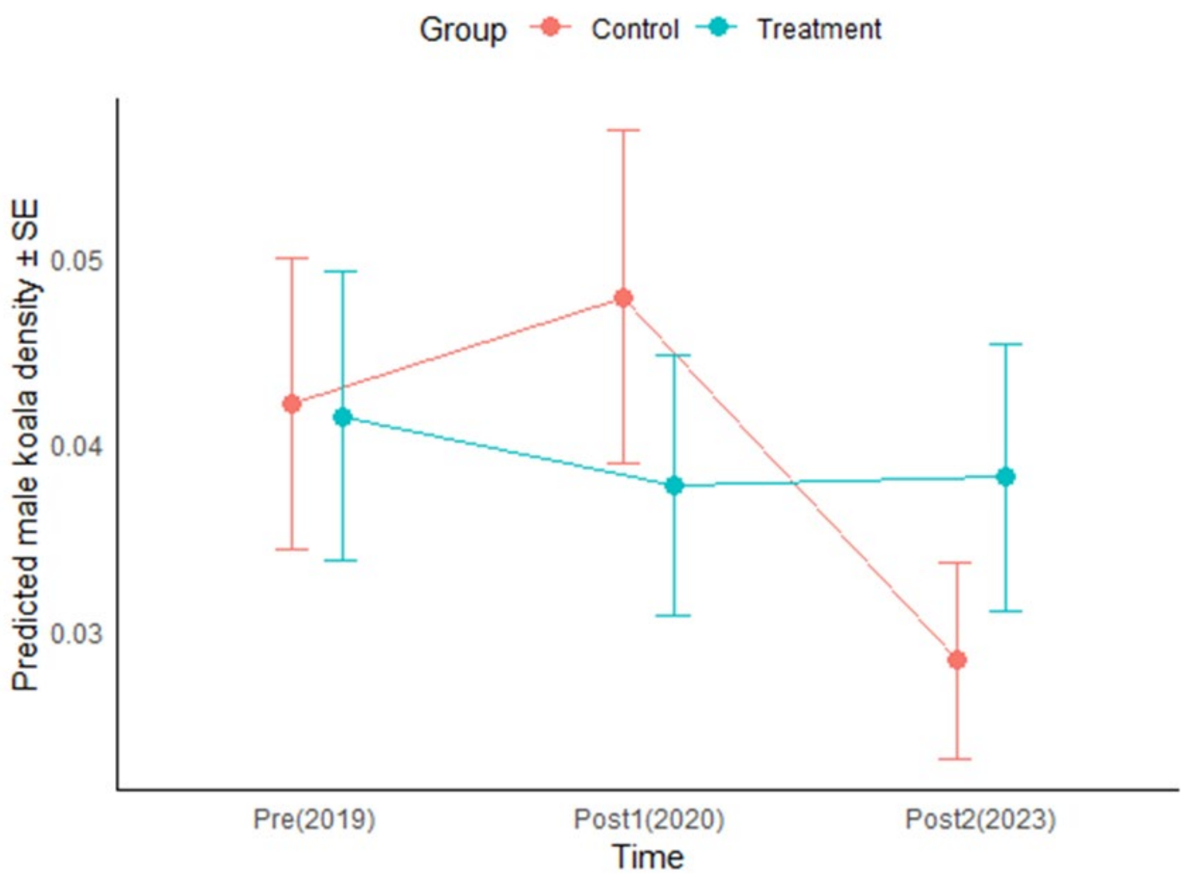


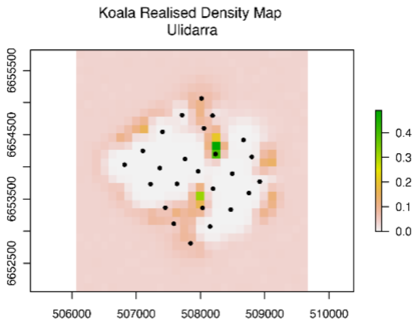
Fig 6: **Male koala density before and after harvesting.** Modelled male koala density (mean ± standard error) in pre- (2019) and post-harvest years (2020 and 2023) at study sites. Density was estimated by Spatial Count analysis of acoustic data collected from arrays.

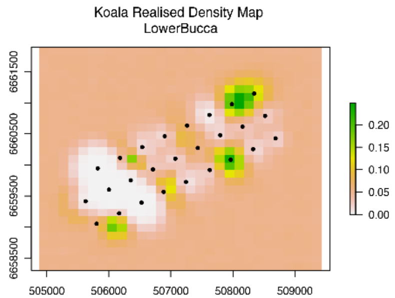
Spatial variation in koala density

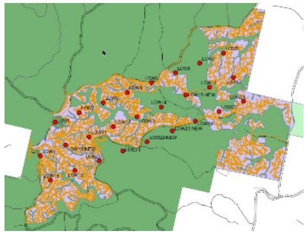
Male koala density was highly variable within each array and across years. Variation included areas equivalent to the “average” density for the array (0.03-0.07 males ha^{-1}) as well as above (e.g. 0.3 males ha^{-1}) and below average density (e.g. <0.01 males ha^{-1}) (Fig 7). Such variation is not surprising given the mosaic nature of north-east NSW forests, with the presence of rainforest and other unsuitable koala habitat types. A common feature across all arrays was 70-100 % detection at each sensor, even where density was predicted to be low (e.g. single detection on one night), as well as small hot spots of higher density. Hot spots were localised areas of above average density, with typically 2-4 hot spots per array. Yearly variation within arrays was evident in both national parks and state forests.

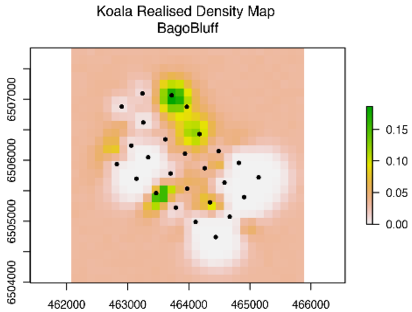
When the spatial variation in density at each harvested array was overlayed with different forest categories, areas that were recently selectively harvested showed a decrease in density in 2023 at two arrays (Cowarra and Kalateenee), but not at Lower Bucca (Fig 8). Density in the mapped recently harvested areas were comparable to other forest categories, except at Cowarra where it was substantially lower.

2019

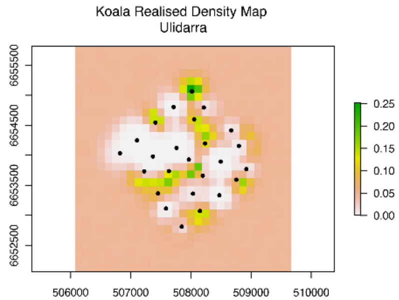


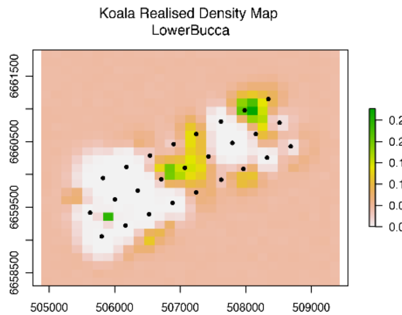


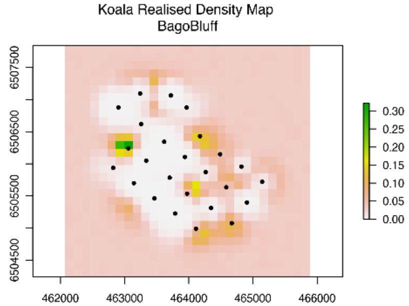




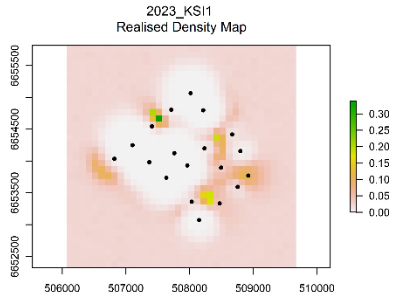
2020

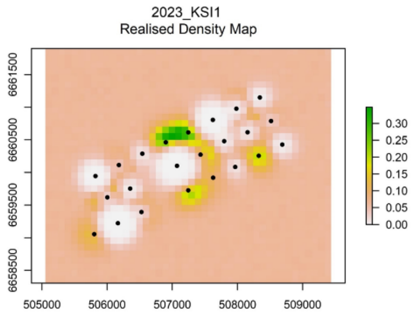


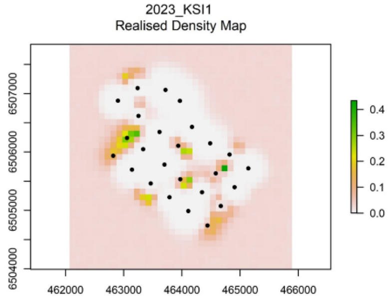




2023







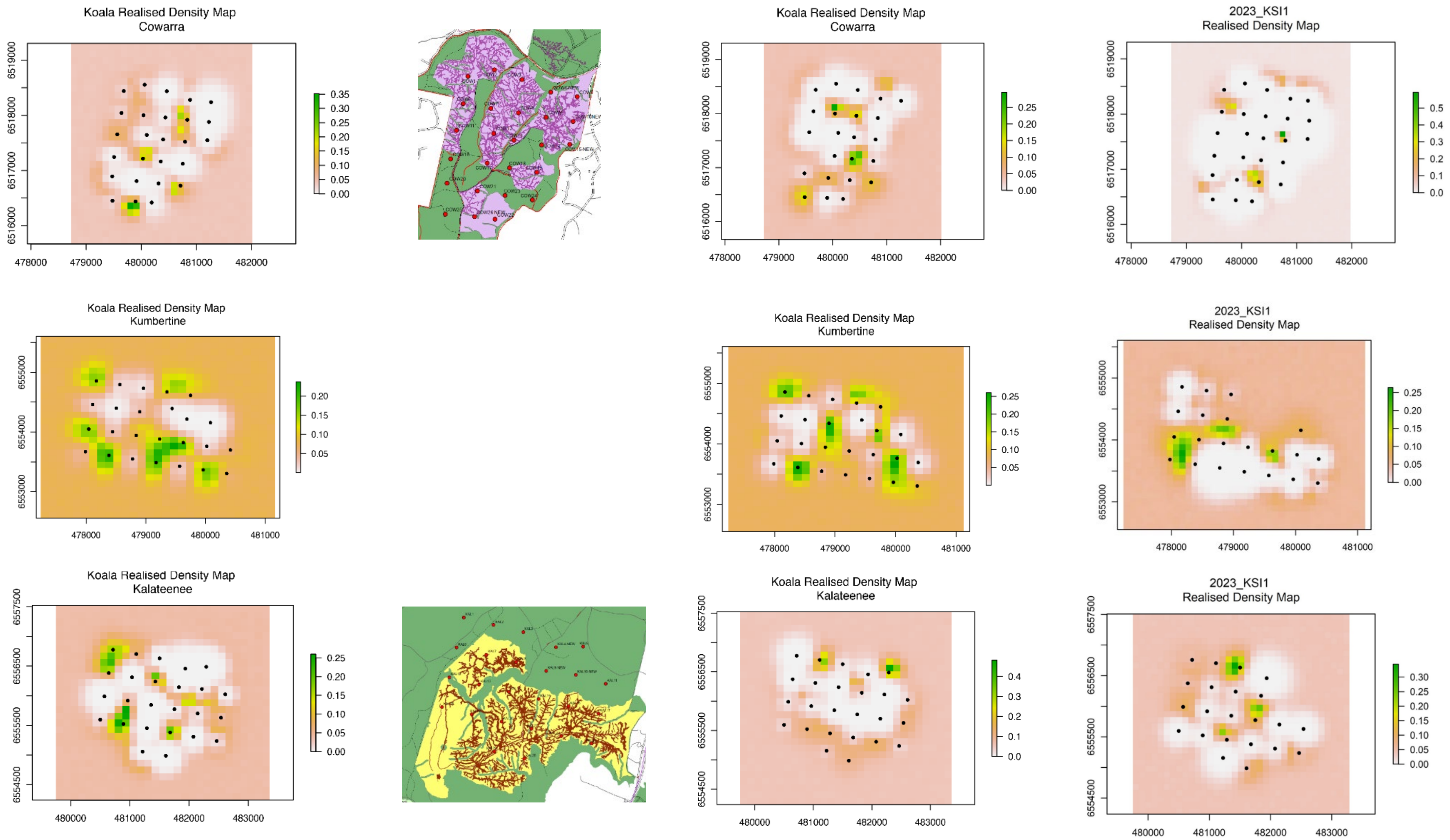


Fig 7: **Spatial variation in male koala density before (2019) and after (2020 and 2023) selective harvesting**. Variation in density across each array before and after harvesting with paired control sites in National Parks (BACIPS experiment). Legend is males ha^{-1}, but note different scales for each array. Harvest area (coloured), harvest tracks and arrays (dots) are also shown for the three treatment areas.

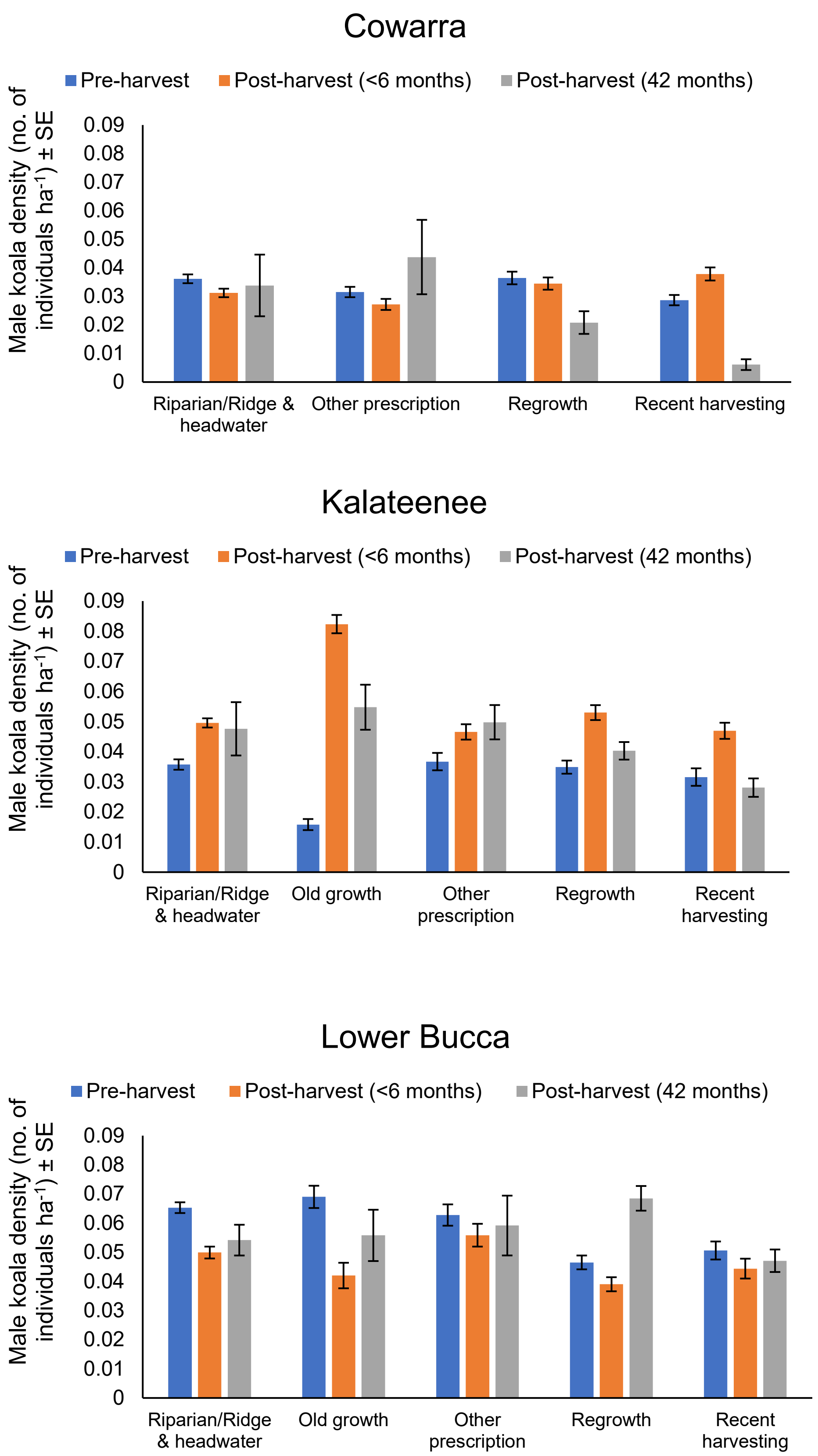


Fig 8: Mean male koala density in different forest age classes/harvesting prescriptions (exclusions) before and after selectively harvesting at three acoustic arrays. Note that no mapped old growth occurred within the Cowarra array.

Discussion

Monitoring of six arrays in 2023 revealed changes in male koala density at both harvested (state forest) and control (national park) arrays. The largest changes were a decline in density at Kumbatine NP, Ulidarra NP and Cowarra SF and an increase at Lower Bucca SF. Overall, the experiment did not detect a significant effect of selective harvesting on male koala density at the array-scale three years after harvesting in 2023, which is consistent with immediately after harvesting (Law et al. 2022a). However, a significant decline at control national parks was detected. These dynamic changes were potentially associated with drought (dieback) and/or fire, but with little support for an influence of timber harvest (see below).

Resilience to selective harvesting is supported by radiotracking male and female koalas 5-10 years after harvesting, where they preferred medium-sized trees for shelter during the day and most commonly used medium-sized trees at night for browse, with little difference between males and females (Law et al. 2022c). Animals maintained stable home ranges and bred in the forestry landscape (Law et al. 2024). Importantly, GPS-tracked koalas used the whole of their local landscape and displayed no selection for areas classed as harvested exclusion, nor regeneration or retained trees in the net harvest area (Law et al. 2024). Harvesting under the CIFOA since 2018 is excluded from 50-60 % of the state forest landscape (DPI unpubl. data), resulting in a network of environmental protections with mature forest that can serve as refuge areas until trees regenerate in harvested patches.

However, it was evident at the sub-array scale that koala density declined at two sites in areas that had been harvested as compared to exclusion areas. This was most noticeable at Cowarra, but was also evident at Kalateenee State Forest, both of which also burnt in 2023. The size of the Cowarra fire was recorded as 617 ha, but mapping appears to be currently unavailable. The Kalateenee fire was also moderately large surrounding the acoustic array, although only about 25 % of the array itself was burnt. Each fire was patchy and considered low to moderate severity. Previously koala density has been found to be little affected by low severity fire (Law et al. 2022c). Koala density was stable in the harvested areas of Lower Bucca where there had been no recent fire.

Over the study period three potential disturbance drivers may have influenced how koalas use habitat: harvesting, fire, and drought. The intensity of sampling limited the total number of plots that we were able to establish and monitor, although an extensive area of forest was sampled (~2,600 ha). As a consequence, the study could not disentangle the effects of individual drivers or their potential interactions. The substantial variability in outcomes in harvested and control sites suggests that forest management activities may not be the primary driver of changes in koala density within these landscapes. For example, a short but intense dry period was experienced in winter of 2023 and declines in density were also experienced at all three national park control sites, with severe dieback noted at one (Kumbatine NP). Whether areas of recent harvesting experienced higher severity fire or slower post-fire regeneration is unclear at present. Fire severity mapping should become available to assess the spatial pattern of fire extent at each array.

The acoustic array monitoring has been cost-effective and able to identify changing patterns in density both over time and between treatments. The BACI design that included control sites in national park has been essential for identifying declines in koalas in those areas and the potential effects of drought manifesting through forest dieback. A separate deployment of two acoustic arrays a year earlier in 2022 for a different project, estimated a density of 0.07 males per ha at Kumbatine and 0.02 males per ha at Bago Bluff, almost identical to estimates from 2019 and 2020 (DPIRD unpubl. data). These data add further support to the role of drought in 2023 as contributing to the detected declines. Whether this dieback is temporary, and the forest will recover with sufficient summer rain, is unknown at present. However, most of the areas impacted by both drought and fire in 2019/20 had similar rates of recovery to those impacted only by fire, although a "double disturbance" hindered recovery in some areas (Hislop et al. 2023). Additional array measurements were collected by DPIRD at Bago Bluff and Kumbatine NPs in 2022, as part of a study on koala response to and recovery from the Black Summer fires (Law et al. 2022d). When analysed, these data will provide additional insights into between-year variability at control national parks.

Further monitoring of these sites will be of value to assess ongoing changes in koala density. Extraneous environmental influences such as drought and fire complicate the interpretation of monitoring data aimed at understanding response to harvesting. However, variable conditions are part of the prevailing environment that koalas are exposed to, in addition to timber harvesting. Ideally, the next monitoring survey should take place with an intervening period of no fire and, if possible, no drought for at least two years to minimise the effects of these confounding factors. That would suggest a repeat survey would be appropriate in 2025 or 2026, assuming current conditions do not change.

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