Stubble Quail abundance in Victoria

Improved survey methods and updated population estimates

M.P. Scroggie and D.S.L. Ramsey

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Acknowledgement

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Contents

Summary

Context:

In order to ensure the sustainability of licensed hunting for Stubble Quail *(Coturnix pectoralis* Gould*)* in Victoria, the Victorian Government requires a method for accurately and precisely estimating statewide abundance. A previous pilot study undertaken in 2022 to test a distance sampling approach using a single observer, found that responsive movement of birds away from the observer resulted in a small effective search area as well as substantial undercounting. The resulting abundance estimates were therefore strongly negatively biased. Accordingly, ARI was engaged by the Victorian Game Management Authority (GMA) to undertake additional surveys using a revised survey method both to evaluate the efficiency and accuracy of the new method and to provide improved estimates of state and regional abundances of Stubble Quail.

Aims:

(i) To evaluate the effectiveness of a revised survey protocol for Stubble Quail using teams of three observers to assess abundances using line transect distance sampling methods
(ii) To provide updated estimates of total and regional abundance for Stubble Quail in Victoria
(iii) If necessary, provide recommendations for additional modifications to the study design and/or survey methods to further improve the accuracy and efficiency of the surveys.

Methods:

The previous line transect distance sampling method using a single observer was modified such that a team of three observers spaced at 10 m intervals searched the transects together. A total of 71 sites across three different habitat types, selected using a stratified random sampling design, were surveyed for Stubble Quail during January 2023. A total of 4 km of transect were searched for Stubble Quail at most of these sites. The data were analysed using both design-based and model-based distance sampling approaches with the intention of determining statewide and regional population abundances, as well as inferring the pattern of spatial variation in abundance and its relationship with a selection of habitat covariates.

Results:

The revised method led to a marked improvement in the effective area searched, with strip half-widths increasing from 4.3 m to 11.2 m. Furthermore, issues with responsive movement of birds away from the single observer used in the previous survey appear to have been substantially mitigated.

Model-based analysis of the data led to an updated statewide population estimate of 6.7 million Stubble Quail (95%CI 5.1–8.8 million, CV=0.14), which represents a large increase on the earlier (2022) estimate of approximately 3.1 million obtained using the single observer survey method. It seems likely that this apparent increase can be largely attributed to substantial undercounting using the original method.

Design-based analysis of the same data led to a somewhat lower estimate of total abundance (5.8 million) with 95% confidence interval of 4.0–8.4 million (CV=0.18), but the confidence intervals for the model and design-based estimates overlapped substantially.

Quail densities were found to be generally highest in areas of native grassland, with substantially lower densities observed at locations with high coverages of cropping as well as non-native pasture. There was also a negative association of quail with ecotonal habitats around the edges of areas of woody vegetation. Remaining variation in abundance was explained by a spatial smoothing effect in the model, which suggests that much of the spatial variation in quail densities across the state is attributable to unidentified ecological or anthropogenic processes.

Conclusions and implications:

The revised survey method was found to provide a more efficient and reliable means of estimating Stubble Quail abundance. Earlier difficulties with poor survey coverage and responsive movement appear to have been solved by moving to the new three observer method.

The abundance of the Victorian Stubble Quail population is large relative to the numbers being harvested by hunters (an average of approximately 100,000 birds per year), which suggests that current hunting arrangements do not represent a conservation risk to the population or the ecological sustainability of the hunting program.

Recommendations:

- Surveys using the revised method should be conducted at regular intervals (e.g., biennial) to provide a basis for assessing temporal trends in the abundance of quail, and for assessing the impacts and sustainability of recreational hunting on the Stubble Quail population. Data will also assist in gaining a greater understanding of the climatic, habitat and management drivers of Stubble Quail abundance.
- Consideration should be given to monitoring additional sites in Victorian CMAs with very low numbers of survey sites. Most notably, the East Gippsland, West Gippsland, Port Phillip and Westernport, and North East CMA regions. Sites should be selected predominantly in native grassland habitat (if present) to improve the precision of estimated densities for this habitat type.

1 Introduction

In Victoria, recreational hunting of native Stubble Quail *(Coturnix pectoralis* Gould*)* by licenced hunters is permitted during an annual hunting season. Season timing and length, bag limits and hunting methods are prescribed in regulation with the aim of ensuring the sustainable management of the Victorian Stubble Quail population. Harvest statistics compiled from telephone surveys of licensed hunters allow assessment of the total number of quail taken by hunters each year, and therefore provide a measure of the total hunting pressure on the Victorian population (Moloney et al. 2022; Moloney and Flesch 2022). To ensure that the number of quail being harvested is sustainable, the Victorian Government also requires accurate estimates of the abundance of Stubble Quail in Victoria using a transparent and credible survey and analysis methodology. Using such a methodology to track trends in abundance of Stubble Quail over time, together with estimates of the number harvested by hunters, will provide a sound basis for setting appropriate hunting season and bag limit conditions to ensure long-term sustainability of the population.

During 2022, an initial pilot study to survey the Victorian Stubble Quail population was undertaken using line transect distance sampling methods (Buckland et al. 1993) collected at 54 sites across Victoria (Scroggie and Ramsey 2022). This initial assessment yielded a preliminary estimate of the Victorian population of approximately 3.1 million birds. However, the analysis revealed several shortcomings with the survey methodology. Firstly, as the line transect surveys were conducted by a single observer walking along the transect lines, the method only effectively sampled a very narrow strip of habitat, with few quail detected at distances beyond approximately 5 m from the transect line and an effective strip half-width of 4.3 m. This meant that despite a relatively large amount of survey effort (a total length of 282 km of transect was surveyed), the actual area that was effectively searched for Stubble Quail was relatively small and hence, surveys were inefficient. Furthermore, Scroggie and Ramsey (2022) raised concerns that responsive movement of birds away from the observers may have led to substantial undercounting, because birds had the ability to move away from the observer unseen, as detection relied on the birds being flushed and taking flight. This issue was more serious as it limited the scope of the data to effectively extrapolate to larger regional and statewide scales (Scroggie and Ramsey 2022).

To address these issues with the original survey methodology, Scroggie and Ramsey (2022) recommended that modified survey approaches be developed and tested with a view to increasing the effective area searched and addressing the impacts of responsive movement on the survey results. To this end, the survey methodology was modified such that three observers (rather than one) would simultaneously search each transect while walking line-abreast with two secondary observers located 10 m either side of the central (primary) observer. A rope of 20 m total length was carried stretched between the three observers both to maintain constant spacing and to aid in flushing of birds from the 20 m wide survey strip. It was expected that this modified survey methodology would result in increased survey efficiency because a wider strip would make it more difficult for quail to evade the approaching observers by moving away from them.

Scroggie and Ramsey (2022) also noted some deficiencies in the placement of Stubble Quail survey sites across the state and recommended an increase in the total number of survey sites, especially to under-sampled parts of the state to ensure that the survey sites covered a representative sample of the total extent of Stubble Quail habitat in the state.

Based on these considerations, surveys were undertaken during January 2023 to determine whether the modified monitoring design addressed the shortcomings outlined by Scroggie and Ramsey (2022). This report describes the results of these surveys and provides an updated assessment of the Victorian Stubble Quail population based on the new data and methodology.

1.1 Objectives

The aims of this study were to:

(i) update the previous survey design to include additional survey sites.
(ii) collect new abundance data for Stubble Quail in Victoria using the modified survey methodology.

(iii) evaluate the efficiency and accuracy of the modified survey methodology.
(iv) infer statewide and regional abundance of Stubble Quail in Victoria and compare these estimates to the previous estimates reported by Scroggie and Ramsey (2022).
(v) if required, recommend further modifications to the monitoring program (including the survey technique and the number and placement of sites), so that the survey methodology can provide robust and accurate estimates of the abundance of Stubble Quail within Victoria at state and regional scales.

2 Methods

2.1 Monitoring sites

A total of 71 survey sites were included in the study. These were located across Victoria at sites with predominant pasture, dryland cropping and native grassland land uses, and were selected using a stratified random sampling design with strata consisting of the predominant land use classes as well as Catchment Management Authority (CMA) regions. Note, that as of February 2021, the former Port Phillip and Westernport CMA was merged with Melbourne Water[1]. For simplicity and consistency with legacy spatial data, we have retained the old name for this CMA throughout the report. Land use mapping was based on the spatial data products described in White et al. (2020), which estimated the land use at fine scale (25 m pixels) at locations across Victoria during the period 2015–2020, with classification via a machine learning analysis of satellite imagery. We focussed here on three of the land use categories identified by White et al. (2020), namely: a) native grassland, native pastures and other native grass dominated ecosystems (hereafter 'native grassland'); b) pastures (exotic/non-native); and c) dryland cropping (including grains, oilseeds and pulses). Most of the 71 sites were the same as the 54 sites that had previously been surveyed during January 2022 and were reported on by Scroggie and Ramsey (2022), with additional sites added to improve the spatial coverage of the sampling design. The geographic distribution of the sites, and of the three land use categories considered in our analysis are illustrated in Figure 1. Difficulties with accessing suitable survey sites in some parts of the state meant that the amount of survey effort in some CMA regions was quite low (Table 1). For example, only single sites were surveyed in the North East and West Gippsland CMAs, and only two sites within the Port Phillip and Westernport CMA. In addition, access issues meant that around 35% of sites could not be located near the originally selected coordinates. These sites were replaced by a nearby site of similar habitat within a radius of 20 km (Scroggie and Ramsey 2022).

Each site contained multiple transects, with most sites consisting of four distinct 1 km transects (usually laid out in parallel and located on the same property). To minimise the likelihood of double counting flushed birds that may have moved into adjacent transects, transects were spaced at least 200 m apart. Logistic and habitat constraints meant that less than 4 km of total transect length was assessed at some sites; however, all the subsequent analyses accounted for the actual effort applied at each site. Total effort at a few sites exceeded 4 km.

[1] https://www.melbournewater.com.au/about-us/what-we-do/news/port-phillip-and-westernport-catchment-authority-integration-melbourne

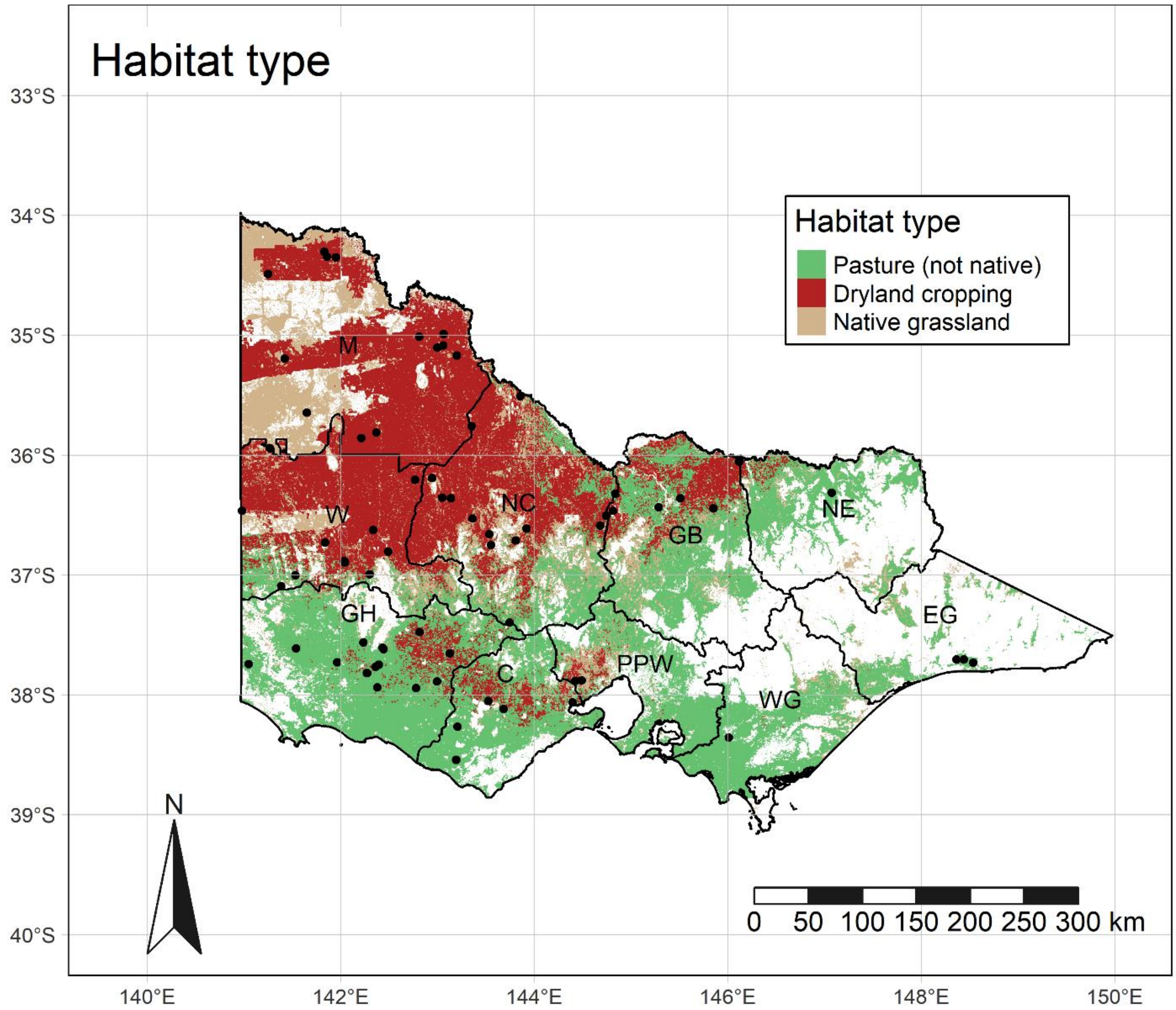


Figure 1. Map showing the study sites (black dots) where Stubble Quail surveys were undertaken during January 2022 with a simplified mapping of major land use categories underlaid (land use data were obtained from White et al. 2020). The black lines are the boundaries of Victorian Catchment Management Authority (CMA) areas. M – Mallee, W – Wimmera, NC – North Central, GH – Glenelg Hopkins, C – Corangamite, PPW – Port Phillip and Westernport, GB – Goulburn Broken, NE – North East, WG – West Gippsland, EG – East Gippsland.

2.2 Survey methods

Stubble Quail were sampled using line transect distance sampling. Line transect distance sampling is a robust and popular method for estimating the abundance of bird populations, and has been widely used to assess abundances of ground-dwelling game birds (e.g. Warren and Baines 2011; Willebrand et al. 2011), including quail (Rollins et al. 2005). The method assumes that all quail located at zero-distance from the transect line are detected with certainty, and that detection probability decreases with increasing distance from the transect. By comparing the number of birds detected at varying distances from the transect line, it is possible to estimate overall detection probabilities for birds located in the vicinity of the transect, and hence, to correct for the number of birds missed by observers (Buckland et al. 1993).

Table 1. Numbers of survey sites within each Catchment Management Authority (CMA) area and each broad land use category. Tabulation of habitat types is based on mapped land use at the site centroid.

CMA	Number of sites
Corangamite	5
East Gippsland	3
Glenelg Hopkins	15
Goulburn Broken	6
Mallee	14
North Central	13
North East	1
Port Phillip and Westernport	2
West Gippsland	1
Wimmera	11
TOTAL	**71**

Land use category	Number of sites
Non-native pasture	35
Dryland cropping	30
Native grassland	6
TOTAL	**71**

At each site, transects were searched by a team of three observers walking line-abreast with the outer, secondary observers positioned 10 m either side of the central, primary observer walking the transect line. All data were recorded relevant to the transect line (Figure 2). A 20 m length of rope was spread between and held by all three observers, and dragged along the ground. The purpose of the rope was to ensure consistent spacing as they walked the transect, and to assist with flushing birds from the vegetation. The trio of observers walked along the transect line following a pre-determined compass bearing, which was usually oriented parallel to fence lines. When Stubble Quail were flushed, the compass bearing to the initial location of the flushed bird(s) was recorded, along with the distance and angle from the transect line (measured using a laser rangefinder and compass) and the group size. The resulting angle of the flush location (difference between the transect bearing and flush location bearing) and distance were then used to calculate the perpendicular distance from the transect (Figure 2). The locations where any flushed birds settled, were also noted to avoid inadvertent double counting of displaced birds further along the transect. Distances between multiple transects on the same site were a minimum of 200 m, so flushing of birds onto adjacent transects was considered unlikely. The relationship between birds' perpendicular distance from the transect and the probability of a flush occurring was modelled using standard line transect distance sampling methods (Buckland et al. 1993) and used to correct the counts of Stubble Quail seen by the observers for imperfect detection. Only quail that were positively identified as Stubble Quail were included in the analysis. Numerous Little Button Quail *(Turnix velox* Gould*)* and a few Brown Quail *(Coturnix ypsilophora* Bosc*)* were detected, but are not considered further in this report. Hunting of these species is not permitted.

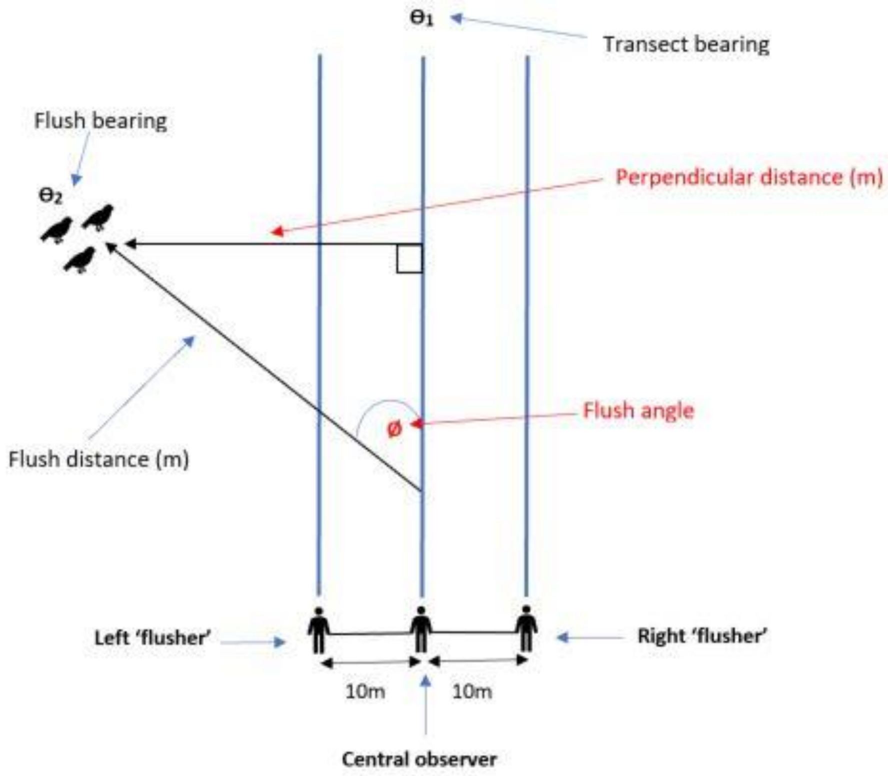


Figure 2. Line transect field data recording. The central observer and left and right 'flushers' walk along a transect travelling in direction θ_1 (the transect bearing). When quail flush in response to any observer, both the flush distance (m) and the flush bearing θ_2 to the initial location of the flush are recorded, along with the number of birds in the group. The resulting flush angle (ϕ) is later used to calculate the perpendicular distance from the transect line. All distances and angles are measured with respect to the transect line walked by the central observer.

2.3 Estimating Stubble Quail abundance

2.3.1 Distance sampling

As the Stubble Quail counts were collected using line transect distance sampling, a two-stage modelling approach was adopted (Buckland et al. 2016). Firstly, a detection function was fitted to the distance data to estimate the effective detection distance of groups of birds from the transect line (the transect half-width) and, by extension, the average detection probability of birds within this effective transect width. Fitting of distance-detection functions was carried out using the functions provided in the *R* package *Distance* (Miller et al. 2019). We considered several alternative models for the distance-detection probability relationship. These were hazard-rate, half-normal and uniform functions, with and without cosine, polynomial or Hermite adjustment terms (Buckland et al. 1993). Adjustment terms were progressively added to the basic (key only) models until there was no further reduction in Akaike's Information Criterion (AIC) (Burnham and Anderson 2002). Models with and without a group-size effect were also included in the analysis as it was considered probable that larger groups of Stubble Quail may have been more readily detected by observers (Marques et al. 2007). Selection of a preferred distance-detection model was guided by (i) AIC, (ii) visual inspection of the fit of models to the field data, and (iii) formal Chi-squared goodness-of-fit tests, which compared the expected and observed numbers of detections that fell within distinct distance bands ('bins') from the transect line.

2.3.2 Design-based estimates of density and abundance

Initially, a simple design-based approach was used to estimate the average densities of Stubble Quail in each of the three major habitat types that comprised the overwhelming majority of the available habitat and sampling effort. These habitat types were dryland crops (including stubble), native grassland and non-native pasture. Standard Horvitz-Thompson approaches (Buckland et al. 1993) were used to estimate the mean density and abundance of Stubble Quail in these three habitat types, including the uncertainty around these estimates [coefficients of variation (CVs) and 95% confidence intervals (CIs)]. A similar analysis using stratification of sites by CMA was not possible due to the low numbers of sites in some CMA regions, making design-based estimates unreliable.

The purpose of these initial design-based estimates, was to gain a simple understanding of typical Stubble Quail densities in the three habitat types using an approach that relied on minimal ecological or statistical assumptions. The inferences from these design-based analyses provide a useful check on the plausibility of more sophisticated spatial modelling approaches (see below), which extended on these results to consider the influence of habitat and spatial covariates on densities of quail at a site level.

2.3.3 Model-based estimates of abundance

Since the survey design consisted of spatially referenced samples, we next used density surface models (DSMs, Miller et al*.* 2013; Buckland et al*.* 2016) to estimate quail density and abundance within the available habitat in Victoria that was subject to sampling. DSMs are spatial models that seek to determine a statistical relationship between spatially varying abundance (determined using distance sampling) and corresponding environmental variables. Using the statistical relationship between habitat and abundance determined from the field data, it is then possible to predict abundance or density at all locations across the study region (instead of only at the 71 locations where Stubble Quail were sampled).

The estimates of detection probability derived from analysis of the distance-detection data, along with a measure of survey effort at each site (total transect length) were incorporated as offset terms into a series of generalised additive models (GAMs, Wood 2017), with the observed Stubble Quail counts as the response variable and a selection of environmental covariates as explanatory covariates. By incorporating the detection probabilities and their uncertainties estimated from the fitted detection function, it was possible to account for any Stubble Quail that were present on the transect, but not detected during the surveys. Fitting of the DSMs was carried out using the *R* package *dsm* (Miller et al. 2020)*,* which provides a wrapper around the more general functions for fitting GAMs provided in the package *mgcv* (Wood 2017)*.* The resulting DSM was then used to predict Stubble Quail density across the full extent of suitable habitat in Victoria, and to derive estimates of total abundance for the state and subregions of management significance (CMA areas).

Structure of the spatial models (DSM)

Several habitat variables were considered *a priori* as likely influences on the abundance of Stubble Quail. These were selected on the basis of known or hypothesised ecological significance to Stubble Quail or other similar ground-dwelling birds. It was also necessary for each habitat variable to be available in mapped (raster) format for the entire study area (Victoria), to allow prediction of the abundance across the state. We collated raster grid data on the following attributes for inclusion in a small set of candidate models:

1. Land cover data (White et al. 2020) mapped at 25 m resolution, which was based on machine-learning classification of satellite imagery. This dataset classified each 25 m pixel into major habitat and vegetation categories including the dryland crops, non-native pasture and native grassland habitats that are known to be used by Stubble Quail (Figure 1). The original 25 m resolution data for each habitat type of interest was aggregated to a coarser resolution of 1 km, with the value associated with each 1 km cell being the proportion of subsidiary 25 m pixels that were of the specified habitat type. Although areas of woody vegetation were not surveyed for quail, the extent of woody vegetation in each 1 km cell was also included as an influence on quail abundance.
2. As it was considered possible that habitats that were ecotonal between woody vegetation, and more open vegetation types such as grassland, crop, or pasture might be favoured by Stubble Quail, the amount of woody edge habitat in each 1 km cell was calculated from the raster of 25 m resolution woody vegetation types using a 3 x 3 cell Sobel filter (Fortin et al*.* 2000).
3. A remote-sensed (MODIS) measure of vegetation greenness across the state (NDVI, Didan 2015) during the same month (January) as the Stubble Quail surveys were obtained for the study area using the online remote-sensing data portal Google Earth Engine (Didan 2015; Gorelick et al. 2017). NDVI was considered to be a potentially useful surrogate for overall environmental aridity, and has been found to be widely applicable as a correlate of density and/or habitat suitability for a variety of animal species (Pettorelli et al*.* 2005; Pettorelli et al. 2011). The original spatial resolution of the

spatial data set was 250 m. The satellite imagery was collected during January 2023 to coincide with the timing of the Stubble Quail surveys.

4. Rasters with cell values equal to the site latitude and longitude to allow estimation of spatial smoothing splines to detect large-scale spatial gradients in abundance.

Prior to conducting the density surface modelling, all rasters were resampled from their original resolutions to a cell size of 1 km. For the landcover rasters, these resampled rasters had values equal to the proportional cover of each habitat type in each 1 km grid cell. For vegetation greenness (NDVI), the cell values were the means of all smaller cells covered by the resampled cell.

Modelling proceeded by initially fitting five models, which related the inferred abundances of Stubble Quail observed at each site to a series of covariates as follows:

1. A null model with no covariates (i.e. constant Stubble Quail density across all habitats).
2. A spatial trend model that included only latitude and longitude covariates, specified as a bivariate thin-plate spline (Wood 2003).
3. A model that included only vegetation greenness (NDVI). The relationship between Stubble Quail density and NDVI was modelled using a thin plate spline term.
4. A model with both habitat (proportional land use) and NDVI covariates, all specified as thin plate splines. Initial fits included all land use categories and NDVI, with uninfluential variables being progressively eliminated until no further reduction in AIC was noted.
5. As above, but with a bivariate spatial spline also included in the model to account for spatial variation in quail density that was not explained by either land use or NDVI.

The models accounted for differences in total sampling effort (transect length) among sites by including total transect length as an offset term. We compared the performance of versions of the candidate models with Poisson, Negative Binomial and Tweedie error distributions. Alternative models were compared using AIC with the intention of maximizing model parsimony, and hence predictive performance.

The preferred spatial model was used to predict variation in the density of Stubble Quail across suitable habitat for the entire state, and to infer the total abundance for the state and for each CMA region.

3 Results

3.1 Survey results

3.1.1 Field observations

The total survey effort (length of the line transects) across all 71 monitored sites was 269 km, with distance observations of visually detected Stubble Quail obtained at 30 of the 71 sites. This comprised a total of 453 individual Stubble Quail. Groups of Stubble Quail sighted during the surveys varied in size between 1 and 10 birds, with most sightings being of single birds (201 sightings), pairs (52 sightings), groups of three (15 sightings) or groups of four or more (an additional 18 sightings). The mean group size across all sightings was 1.6 birds.

3.1.2 Analysis of distance-detection data

The recorded detections of Stubble Quail groups were truncated at a distance of 20 m from the transect (i.e. extending 10 m either side of the outer flushers). Only six detections (~2% of the total) were at distances greater than 20 m. This truncation helped to stabilise the model-fitting process by reducing the undue influence of a few rare, long-distance detections of birds. Due to apparent lumping of distances and an apparent 'spike' in distances close to the transect lines, it was necessary to arrange the detection distances into 'bins' for analysis. By trial and error, we selected an uneven placement of bins (Figure 3). Alternative binning boundaries did not result in substantially different inferences regarding the preferred distance model, it's shape, or the resulting estimate of mean detection probability ($\hat{p}$).

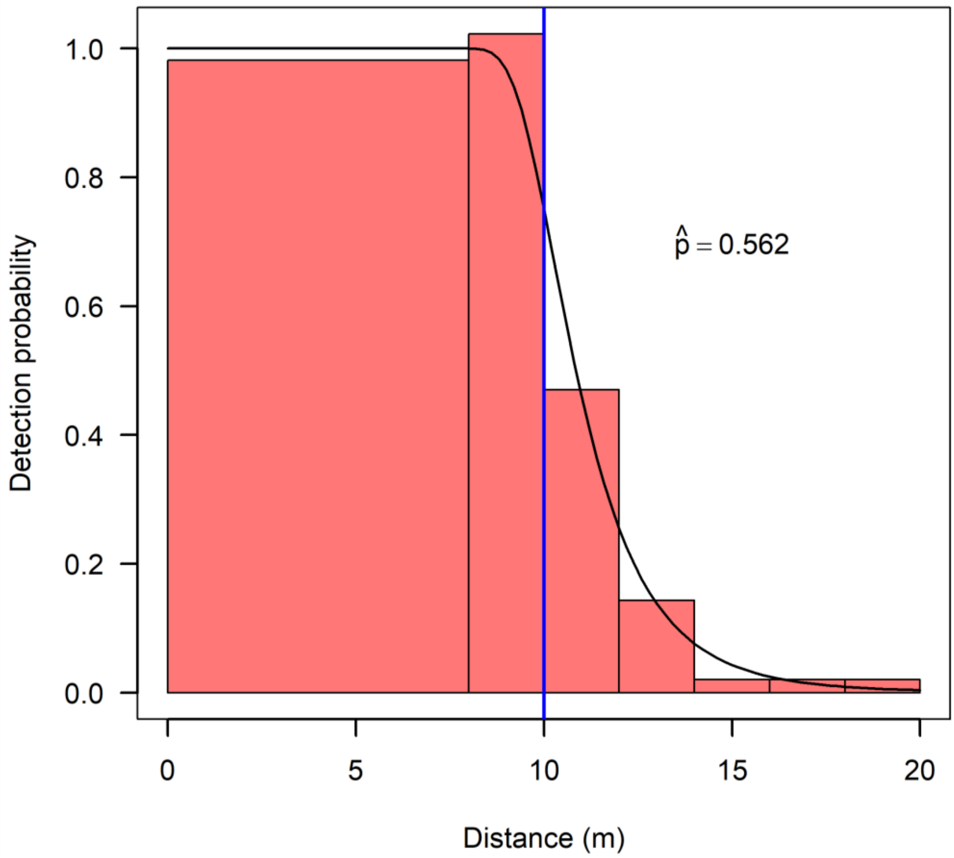


Figure 3. Histogram of binned distance data, with the fitted hazard-rate function (black curve) overlaid. The estimated probability of detection for Stubble Quail located within 20 m of the transect line is given and was calculated by integrating the hazard rate function. The vertical blue line denotes the location of the secondary observers, who walked 10 m either side of the primary observer, who, in turn, walked along the transect line. The distance data were truncated at 20 m to remove the influence of a very small number of detections beyond this distance on the fitted distance function.

The best supported distance-detection model (a hazard-rate model with no adjustment terms or covariates) is illustrated in Figure 3. The histogram, and associated fitted distance function shows the rapid drop-off in detections as the distance from the primary observer approaches 10 m. This distance coincides closely with the locations of the secondary observers relative to the primary observer (see Methods). Out to the truncation distance of 20 m, it was estimated that slightly more than 50% of all birds present were detected ($\hat{p}$=0.562). A very high proportion of birds located within 10 m of the transect were detected, but only a minority at distances greater than 10 m. The effective half-width of the transect was 11.2 m. While several alternative distance models had similar performance to the preferred hazard-rate only model (∆AIC < 2), there was little difference in the estimates of $\hat{p}$ or effective strip width amongst the best supported models in the set (Table 2). A Chi-squared goodness of fit test did not reveal any evidence of poor goodness of fit for the selected distance-detection model ($\chi 2$=2.90, df=4, P = 0.575).

Table 2. Summary statistics for the distance-detection models ranked by AIC.

Key function	Adjustment	Covariate	df	AIC	∆AIC	$\hat{p}$	Effective half-width (m)
Hazard-rate	-		2	514.2	0	0.562	11.2
Hazard-rate	Hermite		3	516.2	1.99	0.563	11.3
Hazard-rate	Cosine		3	516.2	1.99	0.563	11.3
Hazard-rate		Group size	3	516.2	1.99	0.563	11.3
Half-normal	Cosine		3	524.4	10.34	0.535	10.7
Half-normal	Hermite		2	528.7	14.55	0.487	9.7
Half-normal	Poly.		2	535.4	21.34	0.441	8.8
Hazard-rate	Poly.		3	535.5	21.39	0.596	11.9
Uniform	Cosine		1	536.5	22.37	0.500	10.0
Half-normal	-		1	537.4	23.30	0.422	8.4
Uniform	Hermite		2	539.2	25.10	0.516	10.3
Half-normal		Group size	2	539.3	25.17	0.422	8.4
Uniform	Poly.		3	549.1	35.00	0.559	11.2

A smaller AIC indicates a more parsimonious model with better expected predictive performance. $\hat{p}$ is the area under the fitted distance function out to the right-truncation distance of 20 m, and gives the probability of detecting each quail group actually present within the 10 m strip either side of the central observer. The effective transect half-width is the equivalent transect half-width (m) for a hypothetical transect survey that detects all groups actually present. Key = key function, Adjustment = adjustment series, df = degrees of freedom, AIC = Akaike information criterion; ∆AIC = the difference between the AIC of the model and the AIC of the model with minimum AIC.

3.2 Abundance estimates

3.2.1 Design-based estimates of density and abundance

Based on the preferred distance-detection model, design-based inferences were made regarding the total abundances and mean densities of Stubble Quail in each of three habitat types (Table 3). The transects with the highest mean densities of Stubble Quail were located in native grassland, with somewhat lower densities in dryland crops and non-native pastures. The degree of uncertainty (expressed as the coefficient of variation – CV) in these estimates varied considerably, with relatively low CVs for the estimates for dryland crops and non-native pasture, and a somewhat greater CV in the estimate for native grasslands (Table 3). The design-based estimate of total population abundance was 5.8 (95% CI 4.0–8.4) million Stubble Quail, which provides a useful point of comparison with that obtained from the more sophisticated model-based approach.

Table 3. Design-based estimates of abundance ($\widehat{N}$, rounded to the nearest thousand) and density (individuals per km^2) for Stubble Quail based on stratification of survey sites into three major habitat types. Figures in parentheses are the 95% confidence intervals for the density and abundance estimates. CV = coefficient of variation.

Stratum	Area (km2)	Sites	Effort (km)	Abundance estimate ($\widehat{N}$)	Density (Quail per km2)	CV
Dryland crops	52,831	35	138.3	2,734,000 (1,665,000–4,490,000)	51.7 (31.5–85.0)	0.25
Native grassland	20,046	6	20.7	1,465,000 (494,000–4,343,000)	73.1 (24.7–216.6)	0.44
Non-native pasture	50,781	30	110.6	1,633,000 (944,000–2,824,000)	32.2 (18.6–55.6)	0.27
TOTAL	**123,658**	**71**	**269.6**	**5,832,000 (4,046,000–8,407,000)**	**47.2 (32.7–68.0)**	**0.18**

3.2.2 Model-based estimation of density and abundance

DSMs assuming a Tweedie error distribution all fitted the data much better than equivalent Poisson or Negative Binomial models. Five alternative Tweedie models for abundance were compared using AIC (Table 4), with a smaller AIC indicating a more parsimonious model that would be expected to have superior predictive performance. On the basis of this model comparison, a model that included latitude/longitude splines, proportional cover of dryland crops and pastures, and the amount of wood-edge habitat was the best supported model and explained 36.7 % of the total deviance (first row of Table 4). This preferred model was identified after removing uninfluential covariates (in this case grassland, woody vegetation and NDVI) until no further improvement in AIC was apparent. The best model performed substantially better than simpler models that included either the latitude/longitude terms alone, or only the habitat covariates. A model which included only vegetation greenness (NDVI; row 5) performed no better than a null (intercept only) model. Summary statistics for the five models are given in Table 4.

Table 4. Summary statistics for the set of candidate spatial models (density surface models – DSMs) for the density of Stubble Quail in Victoria. All models used the Tweedie distribution for the response.

Model	edf	AIC	ΔAIC	Deviance explained (%)
s(longitude, latitude) + s(crop) + s(pasture) + s(wood_edge)	15.9	407.5	0	36.7
s(ndvi) + s(crop) + s(pasture) + s(wood_edge)	9.2	412.6	5.1	20.3
s(longitude, latitude)	8.2	417.6	10.1	13.3
Null (intercept only)	3	419.9	12.3	0
s(NDVI)	3	419.9	12.3	0

AIC = Akaike's information criterion; ΔAIC = the difference between the AIC of the model and the AIC of the minimum AIC model; edf = effective degrees of freedom; s(x) = non-linear smooth terms (thin-plate spline).

Goodness of fit of the selected (minimum AIC) spatial model was checked using a series of diagnostic plots (Figure 4) prepared using R package *gratia* (Simpson 2020). These checks showed a good fit of the model to the Tweedie distribution [quantile-quantile plot – (QQ plot)], residuals that were approximately normally distributed and did not vary greatly with the linear predictor, and a reasonable correspondence between the observed and fitted values in the model. Collectively, these checks suggest that the model is a reasonable fit to the observed data.

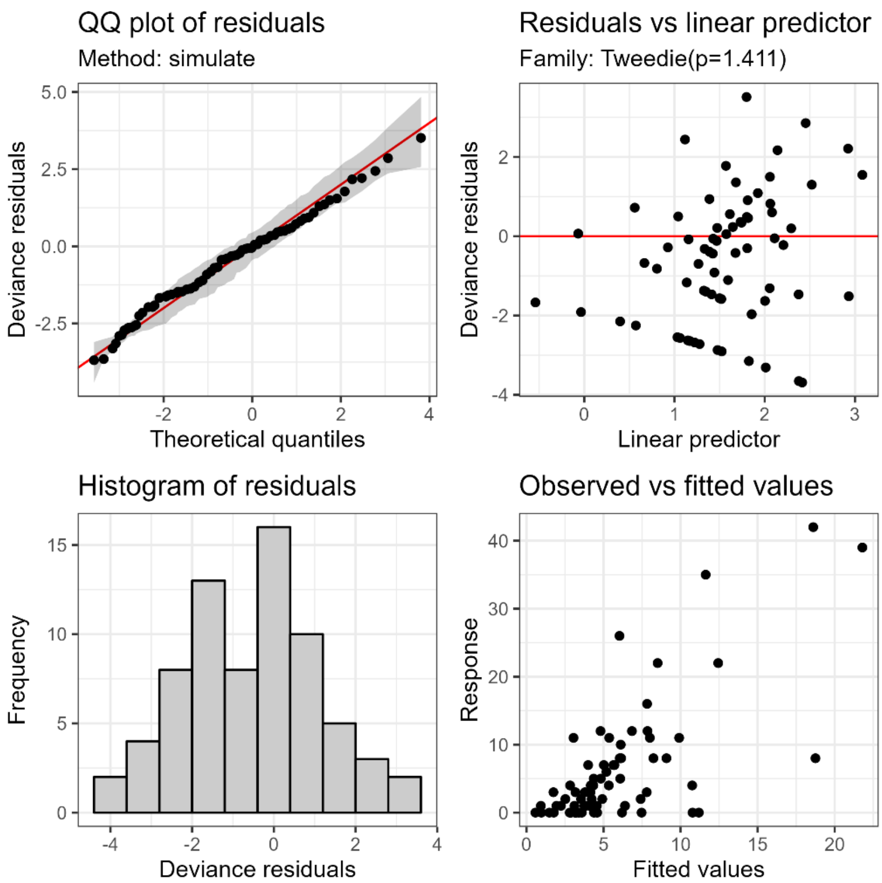


Figure 4. Diagnostic plots for the Tweedie density surface model for spatial variation in Stubble Quail abundance in Victoria.

The effects of each of the three covariates in the preferred spatial model on Stubble Quail density were examined by plotting partial dependence plots between each covariate and the log-density of Stubble Quail (Figures 5 and 6) using the functions provided in package *gratia* (Simpson 2020). These plots show an apparently optimal level of crop cover of around 30%, with lower abundance recorded in landscapes with very high proportions of crop cover. Low levels of pasture cover led to high Stubble Quail densities, with progressively lower abundances as pasture cover increased to levels around 60%. Interestingly, the fitted curve suggested that abundance would again begin to slightly increase where pasture cover exceeded 75%, although uncertainty (95% confidence intervals) around the fitted curve is large, meaning that a monotonically decreasing effect is also a plausible conclusion from the data. The amount of ecotonal, wood-edge habitat had a negative effect on the abundance of Stubble Quail (Figure 5). Three habitat covariates (proportions of grassland and woody vegetation, and NDVI) were found to be uninfluential and were removed in order to improve model parsimony. It is important to recognise that exclusion of these variables from the model does not imply that these habitat types are not suitable or important for Stubble Quail, but simply that their inclusion in the model did not increase the models explanatory or predictive power.

The preferred model also included a bivariate spatial smoothing effect, which is depicted in Figure 6. This quantity represents spatial variability in the abundance of Stubble Quail that is not explained by the other covariates included in the model. Areas of lower than otherwise expected abundance included parts of the state’s far north-west and central regions (blue shading), with higher than expected abundances recorded in much of western Victoria and in East Gippsland (red shading).

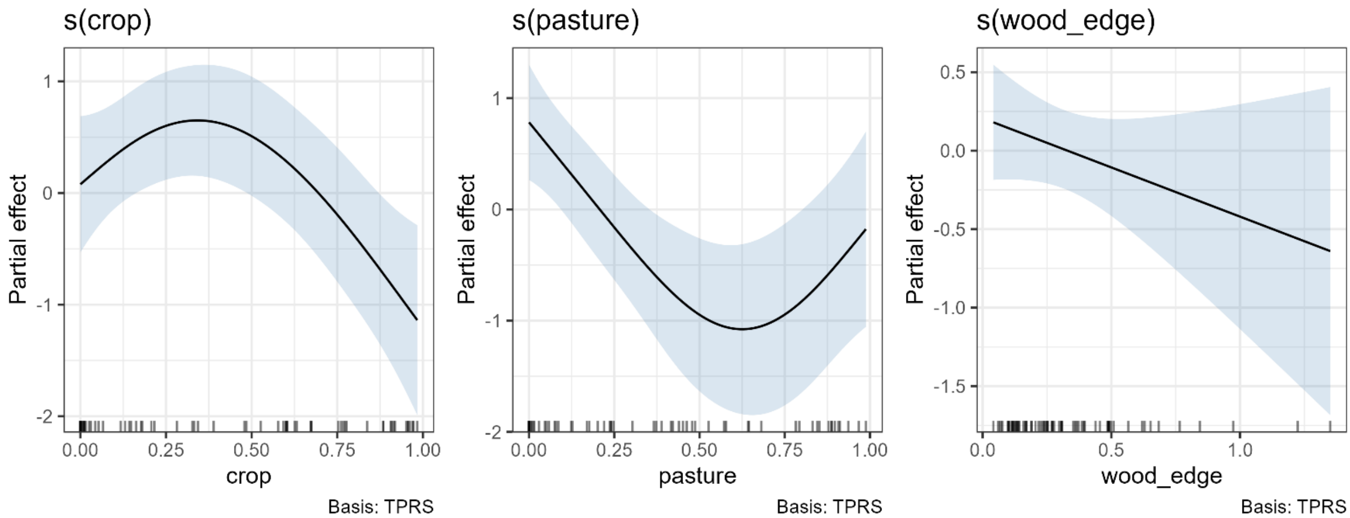


Figure 5. Partial effects of proportional cover of dryland crops, pasture and amount of ecotonal, woody edge habitat on the log-abundance of Stubble Quail. The solid lines are the estimated partial effects, and the shaded areas are the 95% confidence intervals. Internal tick-marks on the *x*-axes give the observed covariate values at the survey sites.

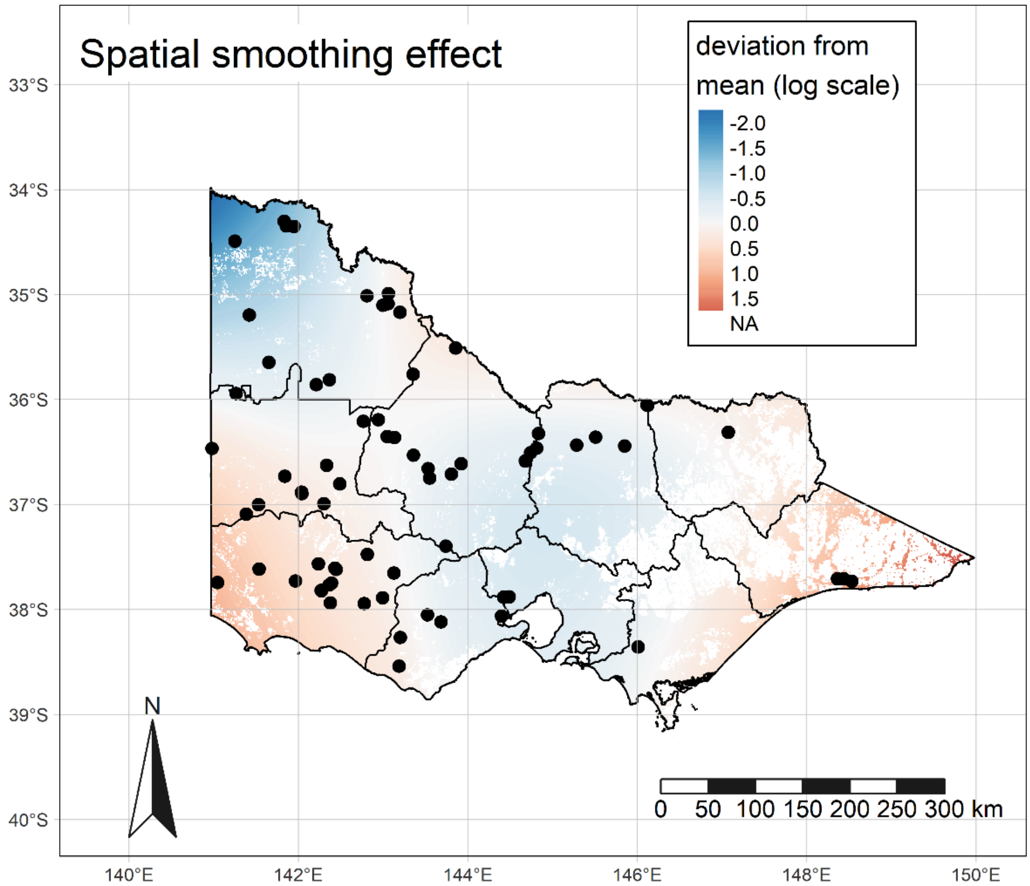


Figure 6. Spatial smoothing effect from the preferred model for the abundance model of Stubble Quail. The mapped quantity represents the component of spatial variability in the log-abundance of Stubble Quail that is not explained by the habitat covariates explicitly included in the model. NA – no applicable habitat. Black dots denote the study sites.

The preferred model was then used to predict the density of Stubble Quail (Stubble Quail per km^2) across the state, excluding areas where there was no habitat that was mapped as pasture, native grassland or crops (Figure 7). The relative uncertainty in the model's prediction of density (expressed as the CV) was also calculated for this same spatial domain. Maps were prepared using the *R* package *tmap* (Tennekes 2018).

Estimated densities of Stubble Quail at the time of the surveys showed a complex spatial trend, with the highest densities being observed in parts of the cropping and pastoral landscapes of northern Victoria, and on the volcanic plains of the south west of the state. Densities in the far north-west of the state and in central Victoria were markedly lower, although these were also the regions with the highest relative uncertainty in the predicted density of Stubble Quail. Uncertainty was also very high in south and west Gippsland, possibly reflecting the very small amount of survey data that was collected in this part of the state.

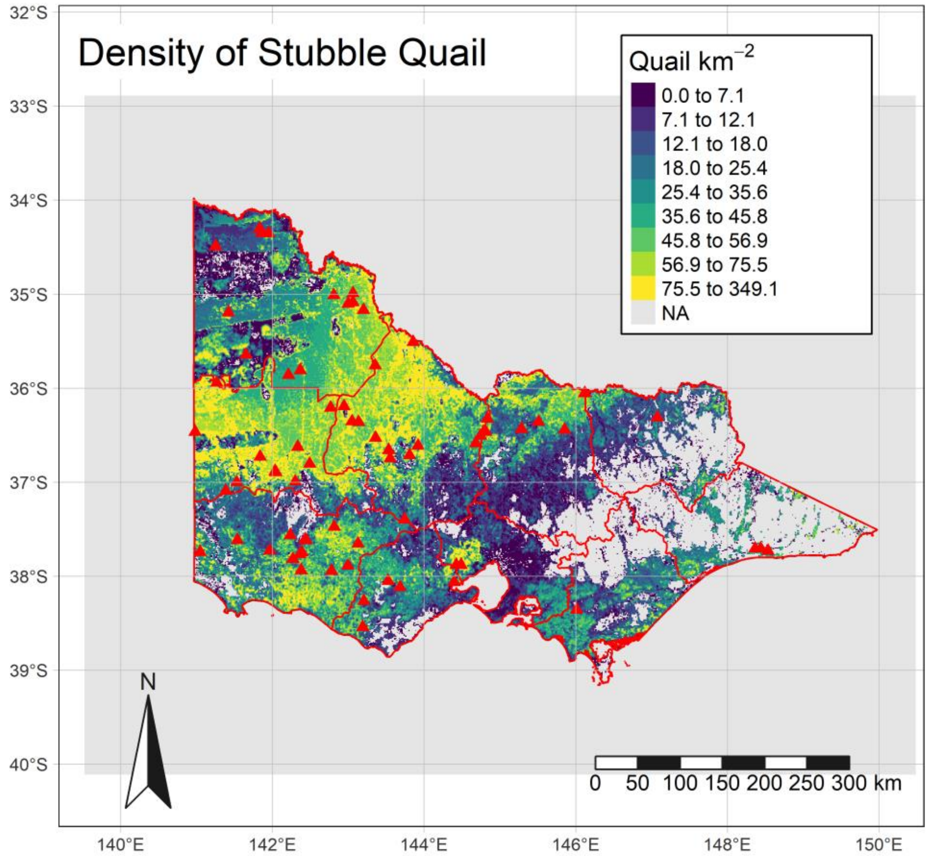
The preferred spatial model was used to compute an estimate of the total abundance of Stubble Quail in the entire study area (Victoria), and the uncertainty around this estimate. This estimate applied only to the parts of Victoria mapped as crop, pasture or native grassland. Uncertainty estimates were obtained for the model's predictions using the delta method (Miller et al. 2013), and these assumed that the observation errors of the distance sampling and the abundance-habitat components of the model were independent (Bravington et al. 2021). The estimated total Victorian abundance of Stubble Quail within the habitats considered in the model was 6.7 million (95% CI 5.1–8.8 million). The CV for this total population estimate was 0.140, which is indicative of a high level of precision in the population estimation process. The total CV of 0.140 was attributable to components CVs of 0.031 in the estimation of the distance–detection function, and of 0.135 in the estimation of the spatial GAM.

Estimates of abundance for each CMA area were also obtained using an identical methodology (Table 5). These estimates of abundance ranged between approximately 149 thousand quail for the East Gippsland CMA through to approximately 1.6 million in the North Central CMA. Uncertainty in the CMA-level population estimates was mostly low-to-moderate, with CVs ranging between 0.21 for the North Central CMA through to a maximum of 0.61 for the West Gippsland CMA. As with other population estimates reported here, these estimates apply only to those areas within each CMA that were mapped as crops, pasture or native grassland, with other land use types being excluded from explicit consideration in the abundance estimates.

The numbers of sites located within each CMA varied substantially, including two CMAs (North East and West Gippsland) with only a single site surveyed, and two CMAs with two and three sites, respectively (Port Phillip and Westernport, and East Gippsland). Inferences regarding the abundances of Stubble Quail within these CMAs relied heavily on extrapolation and assumed a spatially constant relationship between the density of Stubble Quail and the covariates. It is notable that CMAs with very few study sites mostly reported higher uncertainties (CV>0.4) in their population estimates relative to those CMAs where five or more sites were surveyed.

3.2.3 Comparison of design-based and model-based estimates of abundance and density

The estimates of abundance and density of Stubble Quail for each of the three main habitat types, and for the entire area of the three habitats combined obtained using model-based inference and design-based inference were broadly similar (Figure 8). Generally, 95% confidence intervals of model-based estimates overlapped the design-based point estimates and vice versa, indicating that the two estimates were essentially consistent with each other (Figure 8). The overall model-based estimate for the state (6.7M) was 15% higher than the design-based estimate (5.8M) although again, confidence intervals for the two estimates overlapped. Model-based estimates had higher precision, and hence, correspondingly narrower 95% confidence intervals compared with the design-based estimates, especially for grassland habitat (Figure 8).



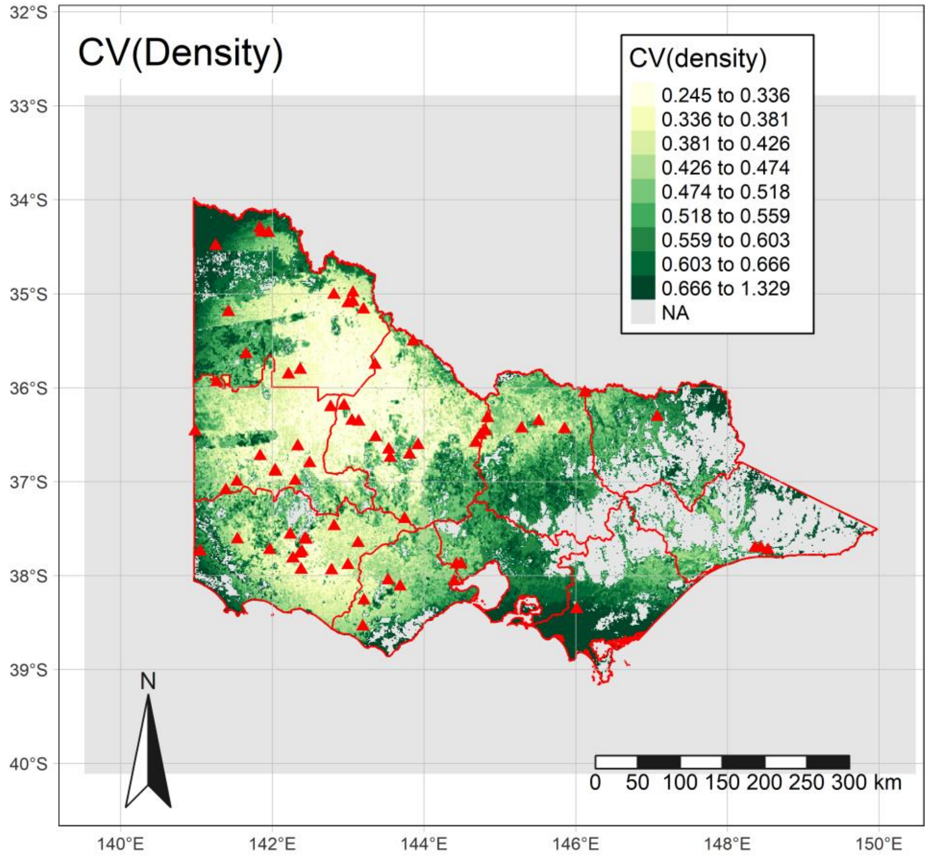


Figure 7. Predicted density (per km^2) of Stubble Quail in Victoria during January 2023. The top panel gives the expected mean, while the bottom panel gives the conditional uncertainty in the predictions expressed as coefficients of variation (CV). Greater values imply higher relative uncertainty about the density of Stubble Quail. The survey sites where the Stubble Quail distance sampling was undertaken are shown as red triangles; the catchment management authority area boundaries are shown as red lines. NA – no applicable habitat.

Table 5. Model-based estimates of abundance ($\hat{N}$, rounded to the nearest thousand) and density of Stubble Quail ($\hat{N}$) within each Victorian catchment management authority (CMA) region, and for the entire state. Note, these estimates apply only to areas mapped as crop, pasture or grassland.

CMA	Area of crop, pasture and grassland (km2)	Sites	Abundance estimate, $\hat{N}$	Density (Quail per km2)	CV
East Gippsland	1980	3	149,000 (64,000–347,000)	75.2 (32.3–175.2)	0.45
Port Phillip and Westernport	5781	2	192,000 (87,000 - 424,000)	33.1 (15.0–73.3)	0.42
North East	5468	1	194,000 (85,000 - 441,000)	35.5 (15.6–80.6)	0.43
West Gippsland	6142	1	244,000 (82,000 - 730,000)	39.8 (13.3–118.8)	0.61
Corangamite	8374	5	298,000 (161,000–552,000)	35.6 (19.3–66.0)	0.32
Goulburn Broken	12,895	6	471,000 (259,000–856,000)	36.5 (20.1–66.4)	0.31
Glenelg Hopkins	16,825	15	846,000 (527,000–1,359,000)	50.3 (31.3–80.8)	0.25
Mallee	25,976	14	1,272,000 (799,000–2,025,000)	49.0 (30.8–78.0)	0.24
Wimmera	17,740	11	1,389,000 (898,000–2,147,000)	78 (50.6–121.0)	0.23
North Central	22,476	13	1,638,000 (1,075,000–2,496,000)	72.9 (47.8–111.1)	0.21
TOTAL	123,658	**71**	**6,694,000 (5,111,000–8,766,000)**	**54.1 (41.3–70.9)**	**0.14**

CMAs are arranged in order of increasing estimated population size ($\hat{N}$). CMA = catchment management authority; CV = coefficient of variation. Population estimates apply only to the areas mapped as native grassland, dryland crop or non-native pasture by White et al. (2020). Values given in parentheses are the 95 % confidence intervals for the abundance and density estimates.

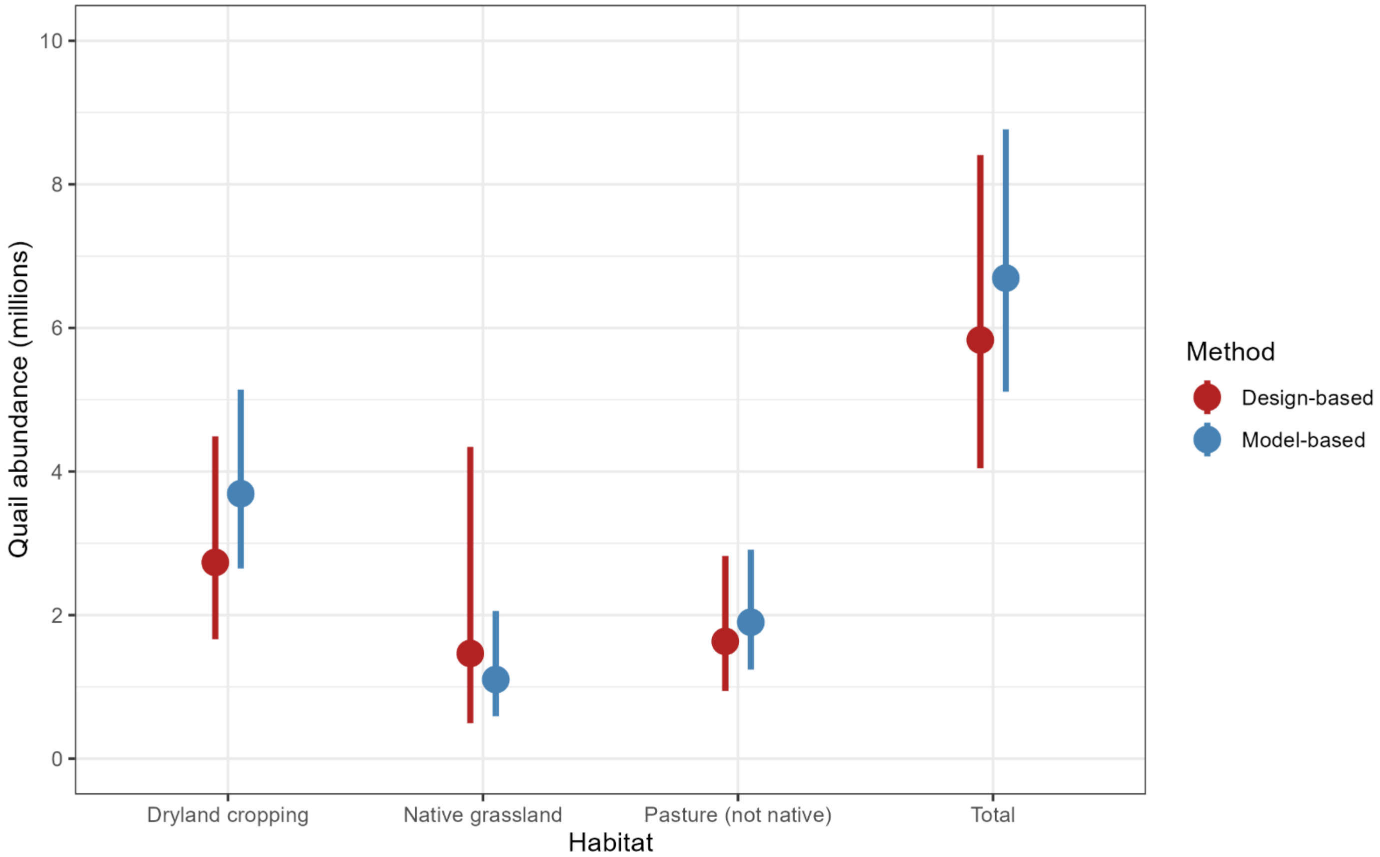


Figure 8. Comparison of design-based and model-based estimates of total quail abundance (points) in the three main habitat types, and for the total area of crops, grasslands and pasture combined. Vertical line intervals are the 95% confidence intervals of the estimates.

4 Discussion

The results of this study provide an updated and improved understanding of the distribution and status of the Stubble Quail population in Victoria. Most notably, the estimate obtained using the new survey methodology is substantially higher (around 7 million) than the previous estimate of 3.1 million obtained by Scroggie and Ramsey (2022). This finding is consistent with the suggestion by Scroggie and Ramsey 2022 that the original methodology was likely to be substantially undercounting Stubble Quail due to responsive movement of birds away from the single observer used during that study, which meant that many birds in close proximity to the transect were likely remaining undetected.

The revised survey methodology (using teams of three observers) led to a marked increase in the effective transect half-width (11.2 m) when compared to the previous study, which reported a half-width of 4.3 m. Detection of Stubble Quail was near-certain out to distances of 10 m either side of the central observer, with detection declining rapidly at distances beyond 10 m. This increased effective transect width greatly increased the efficiency of the surveys, as over a typical transect of 1 km length, the effective area searched using the new methodology was approximately 2.24 hectares (1000 m x 11.2 m x 2). This compares with the earlier result of Scroggie and Ramsey (2022) where the effective area searched per transect kilometre was only 0.86 hectares. The new methodology therefore represents a 2.6-fold increase in the effective area searched, and reduces (if not entirely eliminates) negative biases attributable to responsive movement of undetected birds away from the transects.

Simple, design-based estimates of mean densities of Stubble Quail in three major habitat types (crops, non-native pasture and native grassland, Table 3) were all substantially higher than previous estimates, with the highest density estimates applying in native grasslands, although this estimate had large uncertainty due to the smaller number of sites of this habitat type that were surveyed. The simple design-based analysis was complemented by a more sophisticated model-based analysis that examined the influence of a set of site-level covariates on Stubble Quail density. Design-based and model-based estimates of abundance in each of the three habitat types were broadly similar, with 95% confidence intervals overlapping point estimates in both cases. Given that design-based estimates rely on a minimal set of assumptions, they provide a useful check on model-based estimates. However, design-based estimates can be inefficient, as evidenced by the wider confidence intervals compared with the corresponding model-based estimates. Design-based estimates are also dependent on the use of random sampling, with sampling units having known probabilities of selection. Although a stratified random sampling design was employed for site selection for the present survey, some sites were required to be replaced by nearby sites (within a 20 km radius) due to access issues. While replacement sites were selected in the same habitat type and without any knowledge of quail densities, this selection procedure may have caused some unknown amount of bias in design-based estimates. However, these issues should have minimal impacts on model-based estimates.

Modelling illuminated the influence of land use variables on Stubble Quail densities, with densities of quail generally declining as the proportion of non-native pasture and dryland crop in the surrounding landscape increased, although the relationships did exhibit some non-linearity (Figure 5). A negative effect of the amount of ecotonal woody vegetation edge habitat was also noted in the analysis, pointing towards an avoidance of these habitats by Stubble Quail. In interpreting the inferred relationships between land use (especially agricultural land use) and population density, it is important to emphasise that the analysis is based on data collected during late summer of 2023. At this time of year, grain and other dryland crops have already been harvested and it is unknown whether patterns of habitat use by quail differ substantially at other stages of the annual seasonal (and cropping cycle). It is possible for example that use of dryland crop habitat by quail during the period immediately prior to harvest might be quite different, with either higher or lower densities applying. Similarly, associations with crops, pastures and grasslands could potentially vary substantially from year to year in response to prevailing climatic conditions and changes in agricultural land use, such as growing of alternative crop types and transitions between cropping and grazing land uses. As a species with a strong tendency toward nomadism (Frith and Waterman 1977), Stubble Quail have the capacity to move large distances in response to prevailing conditions, meaning that a model fitted to data from a single year of sampling may perhaps not well reflect spatial variation in abundance in years with different climatic or agricultural conditions.

The preferred model also included a spatial smoothing effect, which describes broad spatial trends in density of quail that are not captured by the effects of the habitat covariates. The need for a spatial smoothing term in the model suggests that it may be necessary to identify and add further habitat covariates to future versions of the model to better explain spatial variation in abundance across the state. It is also possible that exploration of interactive effects of multiple habitat variables may lead to improvements in model performance. The model in its present form is structured to incorporate non-linear effects of each covariate using spline terms (Wood 2017), but it does not currently include interactive (non-additive) effects of multiple covariates. The presence of two distinct areas of lower than expected abundance in the semi-arid north west of the state and in central Victoria requires further examination and suggests that there are likely to be multiple ecological processes that drive the density of quail, but which are not captured by the present set of covariates and/or the model's structure. Collection of further abundance data and fitting of models containing a wider suite of covariates and/or a more complex model structure have the potential to improve both the predictive and explanatory power of the spatial model.

Notwithstanding the difficulties of interpretation and ecological explanation presented by the inferred spatial pattern in density, the model in its present form still provides a firm basis for inferring the abundance of Stubble Quail at both state and regional scales in Victoria. It is clear from the available data that Stubble Quail are presently widespread and abundant in suitable habitats across the state.

While determining impacts of hunting on population viability is a complex task, an initial step is to estimate the proportion of the population that is taken by recreational hunting each year. As the present study has yielded a precise estimate of abundance, and there are regular annual estimates of the number of Stubble Quail taken by hunters in Victoria (Moloney et al. 2022; Moloney and Flesch 2022), it is possible to provide an initial assessment of the likely proportion of the population that is being taken by recreational hunting annually. The estimated numbers of Stubble Quail taken by hunters each year are known to have varied substantially over time, with some evidence of higher numbers being harvested during La Niña climatic conditions (Moloney et al. 2022), when south-eastern Australia usually experiences cooler and wetter climatic conditions. Lower numbers were usually harvested during average or El Niño years. For example, during the strong La Niña in 2011, analysis of the hunter survey data suggested a total harvest of over 600,000 birds, while total harvests during typical or El Niño years (i.e. for 13 of the 14 years sampled) averaged around 100,000 birds (Moloney et al*.* 2022; Moloney and Flesch 2022; Moloney and Flesch 2023). Reduced hunter activity during the period of COVID-19 lockdowns and public health restrictions (2020–2021) complicates the interpretation of total harvest data collected since 2019; however, if the statewide abundance of Stubble Quail estimated during the present study (6.7 million) is taken as being typical, then even the highest estimated annual harvest of more than 600,000 birds would represent less than 10 % of the total Victorian population. More typical harvest of around 100,000 birds per year would imply an even lower harvest rate of less than 2 % of the current population estimate. On the other hand, it should be noted that the population estimate from the current study was obtained at the end of a prolonged period of above average rainfall conditions in Victoria, meaning that current abundances of Stubble Quail in Victoria may be atypically high. Future surveys under drier conditions would be necessary to examine this question.

While more sophisticated population modelling could provide a more thorough assessment of conservation risks of different levels of hunting pressure, this simple analysis of likely harvest rates of between 2 and 10% suggests that impacts of harvesting by licensed hunters on the Victorian Stubble Quail population are relatively small. It should be noted that this year's population estimate coincides with the end of a period of prolonged cool, wet weather in Victoria due to a long-lasting La Niña event. It is likely that quail populations will fluctuate with changing weather conditions, including the possibility that abundances may drop substantially during prolonged drought periods. Data on temporal changes in abundance of Stubble Quail in south-eastern Australia are currently unavailable. During periods when quail abundances are suppressed by drought, then a typical harvest of 100,000 birds could represent a somewhat higher proportion of the population, with attendant increases in the risk of driving populations to low abundance due to overharvesting. As data to assess risks of overharvesting are limited, a conservative approach to setting harvest conditions is recommended, together with ongoing monitoring of the quail population so that harvest conditions can be matched to the status of the population.

The revised sampling methodology using teams of three observers on each transect was found to work well, and seems to have eliminated the problems of poor efficiency and responsive movement encountered during last year’s pilot survey. Accordingly, it is recommended that future surveys for Stubble Quail in Victoria should use the methodology described in this report. Repeating the surveys at regular intervals (perhaps every two years) will allow trends in statewide and regional abundances to be detected, and for the information to be used to inform the processes for setting season lengths and hunter bag limits.

It is also apparent that increasing the number of sites included in the survey has contributed to improving the population estimates. However, sampling coverage in some regions of the state (North East, Gippsland and Port Phillip and Westernport CMAs) remains inadequate, meaning that inferences regarding the abundance of Stubble Quail in these areas relies heavily on extrapolation from elsewhere in the state, and on the assumption that relationships between habitat covariates and abundance are constant across the state. However, it should also be noted that the CMA regions with the least amount of sampling either contained relatively little high-quality Stubble Quail habitat (East Gippsland), or were projected to have below-average densities of Stubble Quail (West Gippsland, North East) (Table 5, Figure 7). Accordingly, the impacts of low sampling effort in these regions on the precision of the overall population estimate for Victoria as a whole, are probably small. If more precise and reliable estimates of abundance for these CMA areas is desired, then consideration should be given to increasing the number of survey sites in these regions to match the numbers that were typical of other, better sampled CMAs. Sites should be selected predominantly in native grassland habitat (if present), as this habitat type had relatively less precise estimates of mean density than other land use classes due to the relatively low number of sampled sites occurring in this habitat type.

As data accumulates from repeating the present survey (possibly with minor modifications to improve coverage in under-sampled regions) it will become possible to infer trends in abundance of Stubble Quail over time and to gain an understanding of the climatic, habitat and management drivers of Stubble Quail abundance. Most importantly, tracking changes in population size over time will give confidence to decision makers faced with the task of setting sustainable season lengths, bag limits or other regulatory mechanisms that influence the number of birds that hunters remove from the Stubble Quail population.

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Appendix 1

This Appendix contains visualisations of the covariates used in the development of the spatial model for Stubble Quail abundance in Victoria. All covariates were resampled to a cell size of 1 km² from their original resolutions (see Methods for details).

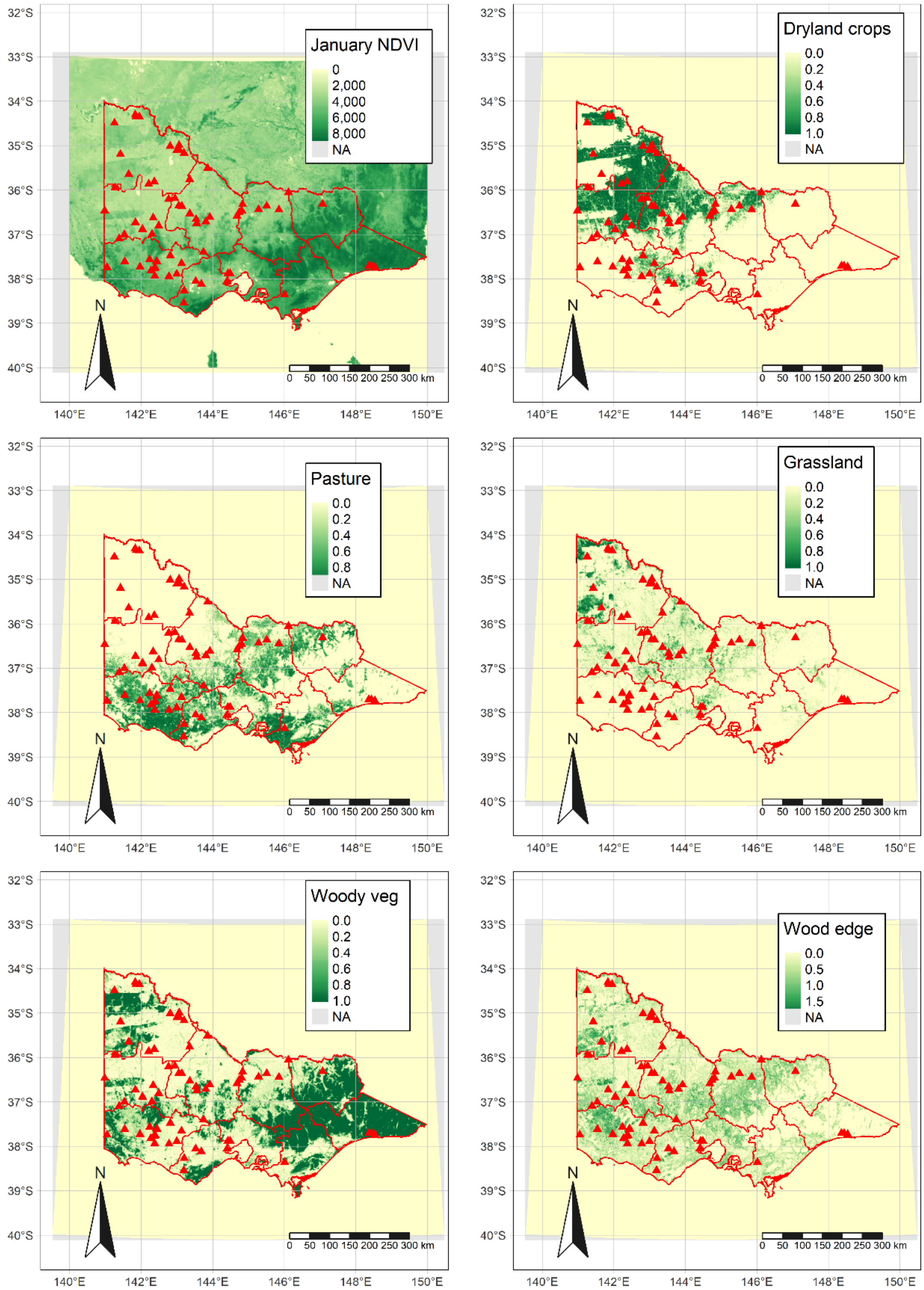

Figure A1. Maps of the covariates (1 km pixel size) used in developing the spatial abundance model for Stubble Quail in Victoria. The red dots represent Stubble Quail survey sites; the red lines represent catchment management authority area boundaries. See Methods for sources of the data and details of pre-processing.

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