Abundance estimates for Stubble Quail in Victoria

Results from the 2022 survey

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

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Acknowledgement

We acknowledge and respect Victorian Traditional Owners as the original custodians of Victoria's land and waters, their unique ability to care for Country and their deep spiritual connection to it. We honour Elders past and present, whose knowledge and wisdom has ensured the continuation of culture and traditional practices.

We are committed to genuinely partnering, and meaningfully engaging, with Victoria's Traditional Owners and Aboriginal communities to support the protection of Country, the maintenance of spiritual and cultural practices and their broader aspirations in the 21st century and beyond.

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Results from the 2022 survey

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Contents

Summary

Context:

Little is known of the population status of Stubble Quail (*Coturnix pectoralis*) in Victoria, other than through harvest statistics collected from hunters each year. To support a transparent assessment of the sustainability of recreational hunting of Stubble Quail, robust and accurate estimates of the statewide abundance l are required. Despite the popularity of Stubble Quail hunting, there has been no monitoring data available that can be used to estimate the abundance of this species within Victoria. Recently, a monitoring program for Stubble Quail in Victoria was developed to obtain estimates of Stubble Quail densities and abundance throughout Victoria over time. A pilot study to test the suitability of the methodology and output of the monitoring program was implemented during January 2022.

Aims:

The aims of this study were:

(i) to conduct an analysis of the data from the Stubble Quail monitoring program pilot survey to determine whether the data were suitable for estimating the distribution and abundance of the quail within habitat strata across the state

(ii) if required, to make recommendations on modifications to the monitoring program, including the survey techniques, so that the surveys will provide data suitable for making robust and accurate estimates of the abundance of Stubble Quail within Victoria.

Methods:

A stratified random sample of 80 sites was selected across Victoria, with the strata consisting of habitat categories known to be favoured by Stubble Quail (e.g. Dryland Crops, Native Tussock Grasslands, Non-native Pasture, and Seasonal Wetlands). At each site, line-transect distance sampling of Stubble Quail was undertaken, with a single observer walking 4 km of transects at each site while recording distances to flushed birds.

The densities of Stubble Quail within each habitat type sampled were estimated using the distance-sampling data, which corrected for imperfect detection of birds on the transect. These data were also extrapolated to estimate densities and abundances across the state, using relationships between Stubble Quail counts and environmental variables (e.g. land-use classes, vegetation greenness) and analysing the distance-sampling data within a density surface model.

Results:

Only 54 of the 80 randomly selected sites were sampled due to difficulties accessing suitable properties at some sites. Distance observations of visually detected Stubble Quail were obtained at 23 of these 54 sites, with group size varying between 1 and 14 birds. Densities of Stubble Quail were lowest in Native Tussock Grasslands and Dryland Crops stubble (0.18/ha and 0.24/ha, respectively) and highest in Pasture and Seasonal Wetland habitats (0.40/ha and 0.61/ha, respectively).

Across Victoria, relatively lower abundances of Stubble Quail were estimated in areas with higher proportions of Dryland Crops (e.g. north-western Victoria) compared with areas with higher proportions of Pasture and Native Tussock Grasslands (south-western and north-eastern Victoria). The densities were positively associated with a remotely sensed measure of vegetation greenness, the normalised difference vegetation index, within a 2-km radius of the sampled site. The total abundance of Stubble Quail within Dryland Crops and Pasture/Native Tussock Grasslands habitat within Victoria was estimated to be 3.1 million, with a 95% confidence interval of 1.78–5.36 million. The coefficient of variation for the population estimate was 0.29.

Conclusions and implications:

There was some evidence that the distance-sampling methods used here were inefficient, as the estimate of the effective width of the transect was only 4.3 m. Hence, observers were only effectively searching around 1.7 ha of habitat at each site. Also, the detection function showed some evidence that birds may have moved

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in response to the observer before being detected, violating one of the assumptions of the distance-sampling method. In addition, there was evidence that birds were present at some sites (through recording of calls), but they were not observed during distance sampling. These observations suggest that the current line-transect distance sampling may be failing to detect a greater proportion of birds than explicitly allowed for in the distance-sampling model. Hence, the resulting density and abundance estimates may be lower than the true population values (i.e. there may be a negative bias).

Recommendations

- Investigate potential improvements to the distance sampling methods for Stubble Quail that will reduce the chance of birds moving before being detected. One potential modification that should be investigated is to conduct distance sampling with multiple observers (say, 3–5) walking abreast (i.e. a ‘drive count’). Combining drive counts with distance sampling should also result in improvements to the coverage of the habitat at sampled sites, increasing efficiency.
- Investigate potential improvements to the land-use categorisation by applying machine-learning classification models to contemporaneous satellite imagery, to provide more relevant and accurate classification of land-use types (e.g. to distinguish between stubble and standing crops). In addition, investigate the influence of other potential drivers of Stubble Quail abundance (e.g. recent rainfall).
- Revise the number of sites required to be sampled to provide improved precision of statewide and regional abundance estimates. Further sites should be allocated such that currently under-sampled regions of the state are better represented. However, determination of revised sample sizes and selection of additional sites should only be undertaken once the sampling methodology has been satisfactorily refined, as the sample size requirements will depend on the efficiency (i.e. effective area searched) of the improved survey methods.

1 Introduction

Despite being the most common quail species in Australia and an important game species, little is known about the ecology and population biology of Stubble Quail (*Coturnix pectoralis*). Stubble Quail are distributed throughout Victoria and are mainly granivorous, but also consume insects (McNally 1956; Frith et al. 1977). Consequently, Stubble quail are often found in grasslands, cultivated cereal fields, and improved pasture (Toop 1994). Possibly due to the pulsed nature of the food resources in these habitats, Stubble Quail can be very nomadic, travelling large distances in the search of suitable habitat (Frith and Waterman 1977). Recent analysis of hunting returns for Stubble Quail have indicated that recreational harvest offtake during the hunting season averages around 170,000 birds (Hampton and Moloney 2020). Despite the popularity of Stubble Quail hunting, there has been no monitoring data available that can be used to estimate the abundance of Stubble Quail within Victoria. Robust and accurate estimates of the statewide abundance of Stubble Quail are required for a transparent assessment of the sustainability of recreational hunting and to monitor population trends in response to environmental drivers, particularly given the species now mostly occurs on highly modified agricultural lands.

A recent survey of Stubble Quail was undertaken in agricultural regions of South Australia during November and December 2021 (Godson 2021). A total of 108 sites in cereal, oilseed, legume and forage crops were sampled using a combination of drive counts (several observers walking abreast) counting flushed birds, as well as counts of birds flushed by harvesting machines during crop harvest. Survey effort in terms of the area of crop monitored were recorded, with the counts at each site assumed to be a census of the monitored area. Quail densities estimated using these methods ranged from 0.75 to 6.7 birds/ha, with a total abundance across the approximately 3.85M ha of estimated Stubble Quail habitat calculated to be 12M birds, with a range from 6.2M to 12.8M (Godson 2021). Although lacking a rigorous treatment of survey design, observation error, and statistical analysis, this study nevertheless illustrates that this species is widespread and abundant within suitable habitat in South Australia, with Stubble Quail detected at all but six of the monitored sites.

A monitoring program for Stubble Quail in Victoria has been developed that aims to estimate variation in quail density and abundance spatially and temporally throughout Victoria (Fanson and Ramsey 2016). The monitoring program is based on a stratified random-sampling design, with the state of Victoria stratified into 10 regions, based on catchment management authority (CMA) boundaries. Each CMA was then further stratified by suitable quail habitats. A total of 80 sites were randomly chosen, using sample unit inclusion probabilities that were calculated proportional to the availability of each habitat stratum to ensure adequate sampling coverage of each stratum. A pilot study of the monitoring program for Stubble Quail was recently implemented during January 2022.

1.1 Objectives

The aims of this study were:

(i) to conduct an analysis of the data from the Stubble Quail monitoring program pilot survey to determine whether the data were suitable for estimating the distribution and abundance of the quail within habitat strata across the state

(ii) if required, to make recommendations on modifications to the monitoring program, including the survey techniques, so that the surveys will provide data suitable for making robust and accurate estimates of the abundance of Stubble Quail within Victoria.

2 Methods

2.1 Monitoring sites

Monitoring sites were selected across Victoria using a stratified random design, with the strata consisting of four main habitat types known to be used by Stubble Quail:

- Dryland Crops (cereal, oilseed, legume)
- Native Tussock Grasslands
- Non-native Pasture
- Seasonal Wetlands.

A total of 80 sites across the state were selected, with 20 sites allocated to each habitat stratum. However, as the sites were primarily on private property, some sites could not be accessed. In these cases, a search was conducted for an alternative site (of the same habitat type), within a 20-km radius of the original site location. Despite this modification, data were ultimately obtained from only 54 sites, due to difficulties with obtaining access to suitable properties. The sites were monitored in January 2022, which ensured that the majority of cereal crops had already been harvested at the time they were surveyed. The survey timing was based on the assumption that habitat conditions for Stubble Quail should be optimal in crops shortly after harvest due to the abundance of spilt grain (Toop 1994). Sampling was undertaken principally in the morning (sunrise to 11 am) and in the afternoon (2 pm to sunset) and was avoided during rain, high winds and periods of intense heat.

A map of the study sites with a simplified mapping of the underlying agricultural land-use categories (see Spatial modelling section below) is given in Figure 1. Mapping of the four habitat types used for the stratification process is given in Fanson and Ramsey (2016).

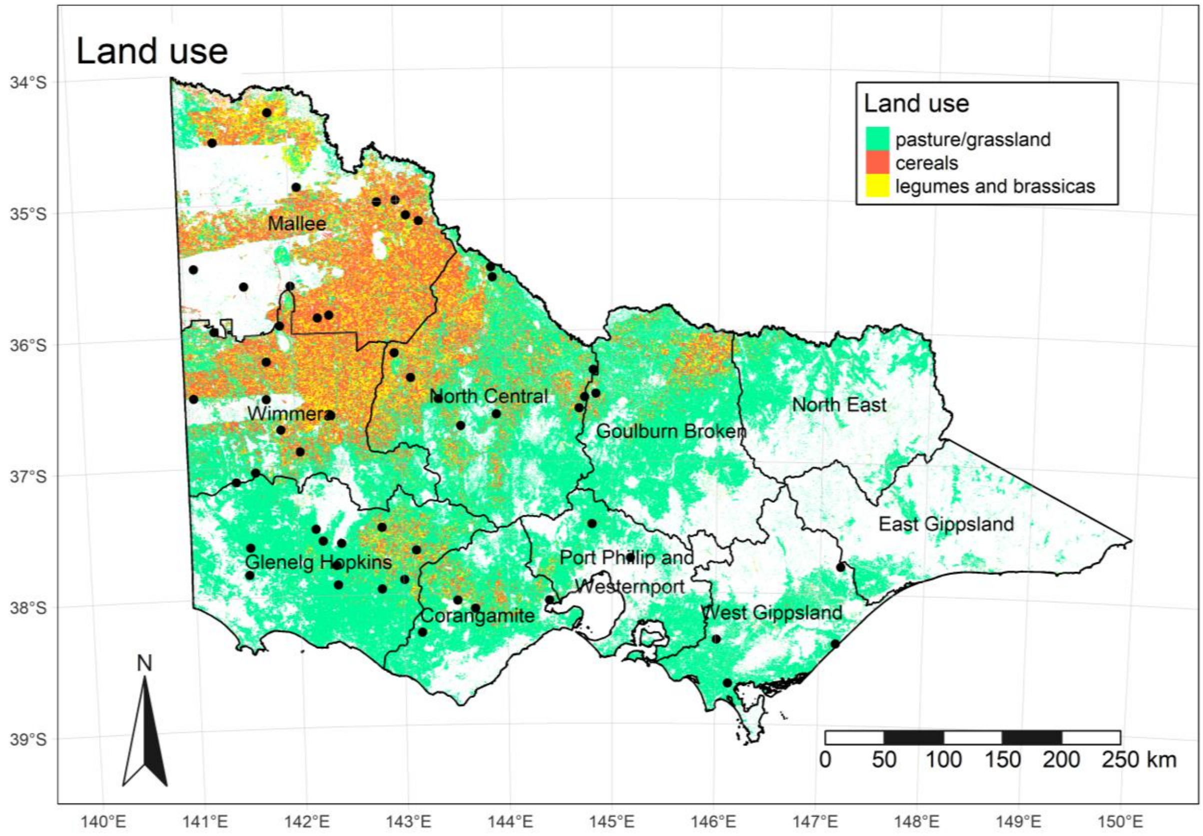

Figure 1. Map showing the study sites (black dots) where Stubble Quail surveys were undertaken during February 2022, with a simplified mapping of major land-use categories underlay. (Land-use data for 2017 were obtained from Morse-McNabb et al. 2018.) The black lines are the boundaries of the Victorian CMA regions.

2.2 Survey methods

Stubble Quail were sampled using line transect distance sampling methods (also referred to as distance sampling) on transects located within the designated habitat type at each site. The line transect distance sampling method is a widely used and accepted method used for counting birds and has been suggested to be the most accurate, non-marking method for quail (Rollins et al. 2005). Distance sampling assumes that all quail located directly on the line transect are detected and that detection decreases with distance from the line transect. By comparing the number of birds detected at various distances from the line transect, it is possible to estimate detection rates with distance from the transect and hence, correct for the number of birds missed by observers (see Buckland et al. 2001 for more details). A total of 4 km of transects were traversed at each site. The line transect method involved the observer walking along the transect line following a pre-determined compass bearing, which was usually oriented parallel to fence lines. When Stubble Quail were flushed in response to the observer, the compass bearing to the initial location of the flushed bird(s) was recorded, along with the distance from the transect line (measured using a laser rangefinder). The resulting angle of the flush location (difference between the transect bearing and flush location bearing) and distance was then be used to calculate the perpendicular distance from the transect (see Figure 2). A note was taken of the locations where flushed birds settled, so that these were not double counted further along the transect. The likelihood of a flush occurring with increasing perpendicular distance from the transect was modelled using standard line transect methods (Buckland et al. 1993) and was used to correct the counts of Stubble Quail seen by the observer for imperfect detection of birds on the transect.

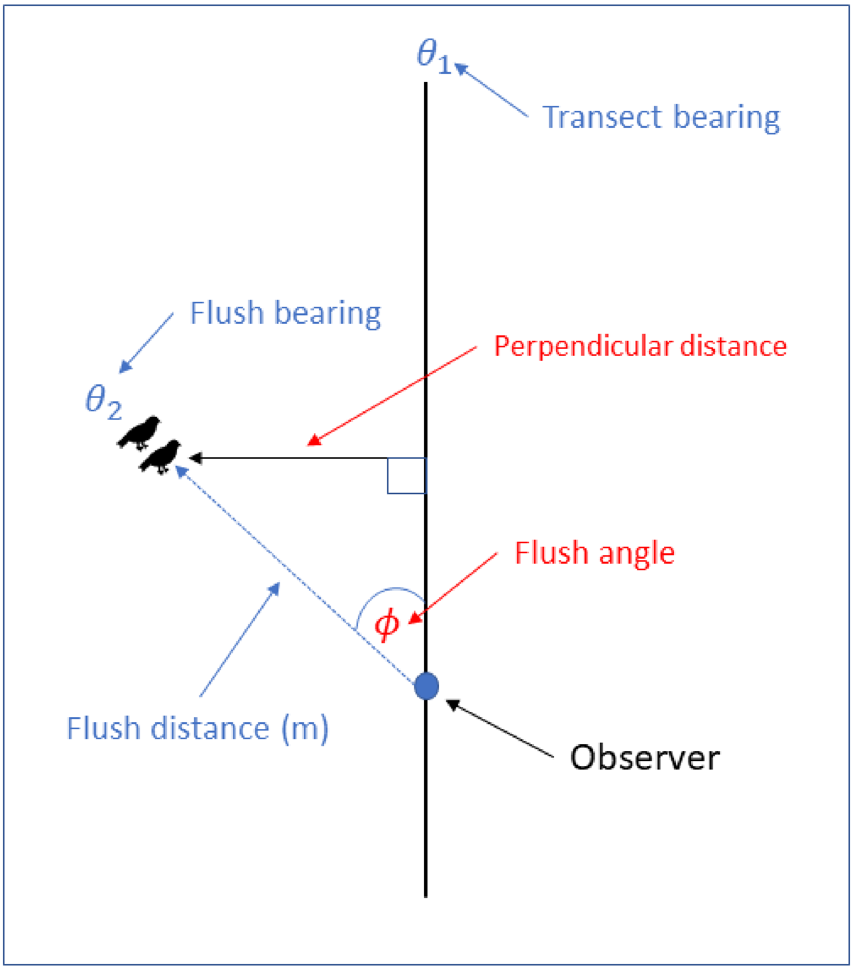

Figure 2. Line transect field data recording. The observer walks along a transect travelling in direction θ_1 (the transect bearing). When quail flush in response to the observer, both the flush distance (m) and the flush bearing θ_2 to the initial location of the flush are recorded, along with the number of birds in the group. The resulting flush angle (ϕ) is later used to calculate the perpendicular distance from the transect line.

2.3 Estimating Stubble Quail abundance

2.3.1 Distance sampling

Since the survey design consisted of spatially referenced samples, we used density surface models (DSMs) (Miller et al. 2013; Buckland et al*.* 2016) to estimate the total quail densities and abundance within the available habitat within Victoria that was subject to sampling. DSMs are spatial models that seek to construct a statistical relationship between spatially varying abundance (usually determined using distance sampling) and corresponding environmental variables. With the relationship between habitat and abundance determined from the field data, it is then possible to predict abundance or density over the entire study region, not just the areas that have been sampled.

As the Stubble Quail counts were collected using line-transect distance sampling, a two-stage modelling approach was adopted. A detection function was first fitted to the distance data to estimate the effective detection distance 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). As the sightings during the surveys were of groups of Stubble Quail (which contained various numbers of individuals), and because a priori we expect that group size might influence the probability of detection, all models included group size as a covariate on the scale parameter of the detection function (Marques et al*.* 2007). Alternative models for the distance-detection function (half-normal, hazard-rate) were compared using Akaike's information criterion (AIC; Burnham and Anderson 2002).

Initially, a simple design-based approach was used to estimate the average densities of Stubble Quail in each of the four main habitat types applied during the initial site stratification. These habitat types were Dryland Crops (including stubble), native Tussock Grasslands, Non-native Pasture, and Seasonal Wetlands. Observations from a few transects conducted on other habitat types (such as Heath) were excluded from this part of the analysis. Standard Horvitz-Thompson approaches (Buckland et al*.* 1993) were used to estimate the mean density of Stubble Quail in these four habitat types, including the uncertainty around these estimates [coefficients of variation (CVs) and 95% confidence intervals (CIs)].

To extend the distance sampling analysis to allow estimation of the Stubble Quail density across the entire study area, a model-based distance-sampling approach (DSMs; Miller et al*.* 2013; Buckland et al*.* 2016) was used to relate the abundances of the Stubble Quail observed on the transects to estimated abundances in several habitat types with large spatial coverage in the study area that are of known or suspected significance to Stubble Quail (see section 2.3.2). The estimate of detection probability derived from analysis of the distance-detection data was incorporated as an offset term into a series of generalised additive models (GAMs, Wood 2017), with the observed counts as the response variable and selected environmental covariates as potential explanatory variables (see section 2.3.2). By incorporating the detection probabilities' estimated detection function, it was possible to account for the Stubble Quail present in the vicinity of the transects 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 abundance across Victoria, as well as to derive estimates of total abundance for the state and for subregions of management significance (CMA regions).

2.3.2 Spatial modelling

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 that each habitat variable was available in mapped (raster) format for the entire study area (Victoria), to allow prediction of the abundance across the state.

First, the most recently available (2017) landcover mapping was obtained for the entire state in raster format (Morse-McNabb et al*.* 2018). This dataset, obtained by automated classification of MODIS satellite imagery, classifies the entire state into land-use categories at a 250-m-raster cell size. The full list of categories (13 in all) is provided in Morse-McNabb et al*.* (2018). From this full set of land-use categories, we identified several that were of likely significance to Stubble Quail on the basis of known habitat associations. These categories also reflect the habitats in which hunting of Stubble Quail is most likely to occur. The habitat types considered in our spatial model differed somewhat from those used in the initial sample stratification, in that all grassland/pasture habitat types were combined into a single category, and we did not consider the influence of wetland habitats in the spatial model, as these generally represented a very small percentage of the total area of quail habitat in each CMA (Fanson and Ramsey 2016). As the sample size for the model was moderate (54 sites), it was necessary to constrain the complexity of the models, and to focus on habitat types that constituted the majority of the total area of habitat in the study area. As Seasonal Wetlands comprised less than 5% of the study area (Fanson and Ramsey 2016), the influence of this habitat type on abundance was not considered in the spatial model. The habitat categories used in the spatial model were Pasture/Grasslands, Cereal Crops, Oilseed (brassica) Crops, and Legume Crops. For the purposes of the analysis, most other land-use categories were treated as non-habitat when estimating the statewide abundance of Stubble Quail using the models. Note, there will likely be an unknown additional number of Stubble Quail occurring in at least some of these other habitats, such as Native Forests and Woodlands, Urban Areas, etc.; however, given that the field sampling was restricted largely to crops, pastures and grasslands (with some sampling in Seasonal Wetlands), the data do not provide a basis for robustly extrapolating modelled density into these other habitats, so for the purposes of the current analysis they are ignored.

From the raw land-use rasters, we extracted binary rasters encoding for the presence/absence of all crops including cereals, oilseeds and legumes (All Crops), cereal crops only (Cereal Crops), and combined non-native pasture and native grasslands combined (Pasture/Grasslands).

Second, data on a remote-sensed (MODIS) measure of vegetation greenness across the state (NDVI, Didan 2015) at the time of the Stubble Quail surveys were obtained for the study area using the online remote-sensing data portal Google Earth Engine (Gorelick et al. 2017). The raw MODIS NDVI imagery was resampled (using a bilinear method) to match the pixel size and extent of the land-use data.

Both the landcover and NDVI data were spatially aggregated by applying a focal filter, such that the value at each cell was either the mean value (in the case of NDVI) or the proportional cover of each landcover class (All Crops, Cereal Crops, and Pasture/Grasslands) for a circle with a 2-km radius around each point. This approach reflects the relative mobility of Stubble Quail, and the fact that they likely select habitat at a scale larger than the pixel size of the raw raster data (250 m x 250 m = 0.0625 km^2). Thus, for each grid cell in the study area, we determined values for the proportional cover of All Crops, Cereal Crops, and Pasture/Grassland as well as an estimate of mean vegetation greenness in the surrounding landscape (in a 2-km radius). Spatial filtering operations were carried out using the functions provided in the *R* package *terra* (Hijmans 2022). Maps of the spatially aggregated habitat variables used in the model are provided in Appendix 1.

As default (null) models for spatial variation in abundance of Stubble Quail, we also fitted an intercept-only model and bivariate spatial smoothing (easting and northing, Vicgrid projection) to detect broad geographic trends in density. The fitted DSMs were compared using the AIC, and the preferred model (minimum AIC) was used to estimate spatial variation in Stubble Quail density, total abundance at a statewide scale, and abundances for each Victorian CMA area.

2.4 Updating the monitoring design

Based on the level of precision and the predictive accuracy achieved by the model of Stubble Quail abundances, we have recommended modifications to the survey methodology to improve the accuracy and/or the precision. These may include potential changes to the monitoring methods to improve detection of the quail. For example, too few quail may be detected during line-transect sampling, as quail may avoid flushing in response to the observer. If it is suspected that too many quail are actively avoiding detection, then consideration may need to be given to alternative or enhanced sampling techniques. In addition, too few samples might be obtained from some parts of the state or from certain habitat types, resulting in poor estimates for that particular stratum or attribute. If these strata/attributes are important for describing variation in quail abundances, then sampling may have to be increased in those strata/attributes to increase the precision and/or accuracy of the overall abundance estimate. In addition, overall sample size may have to be increased to reach the desired predictive accuracy and/or precision.

3 Results

3.1 Survey results

3.1.1 Field observations

Line-transect data with distance observations were collected at a total of 54 sites across the study area (Figure 1). The total survey effort (length of the line transects) across all sites was 282.0 km. Distance observations of visually detected Stubble Quail were obtained at 23 of the 54 sites. Groups of Stubble Quail sighted during the surveys varied in size between 1 and 14 birds, with most sightings being of single birds (44 sightings), pairs (4 sightings) or groups of three (3 sightings). The mean group size was 1.69 birds.

The presence of the Stubble Quail was also confirmed at five sites based on auditory detection during the surveys. These detections included two sites where Stubble Quail were not visually detected on the transects. These data were not included in the density/abundance calculations.

An additional 35 distance observations of Stubble Quail were incorporated into the distance-sampling analysis (see below) to allow more precise estimation of the distance–detection function. These observations were obtained during a trial of the field methodology conducted near Werribee, Victoria, during May 2021.

3.1.2 Analysis of distance-sampling data

The recorded detections of Stubble Quail groups were truncated at a distance of 18 m from the transect, removing a few more extreme distance observations (out to more than 50 m from the transect) from the analysis. This truncation helped to stabilise the model-fitting process by reducing the undue influence of rare, long-distance detections of quail in the fitted distance-detection models.

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 a bin width of 1.5 m, which eliminated the spike at zero and substantially reduced the presence of lumping in the histogram of distances (Figure 3). Standard hazard-rate and half-normal detection functions were fitted to the distance data, as described in the Methods*.* Both of these models included an effect of group size on detection probability, as it was considered likely that large groups of Stubble Quail would be more detectable by the field observers. Selection between the models (on the basis of AIC, with smaller AIC being better: Table 1) indicated the superiority of the hazard-rate model. The inferred probabilities of detection out to the 18-m truncation distance ($\hat{p}$) and the effective transect half-widths for the two distance models were similar for the half-normal and hazard-rate models. (Table 1).

Table 1. Summary statistics for the detection models.

Model	AIC	ΔAIC	$\hat{p}$	Effective transect half-width (m)
Hazard-rate	314.6	0	0.239	4.3
Half-normal	329.0	14.4	0.388	6.9

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 maximum distance of 18 m and gives the probability of detecting each quail group actually present within the 18-m strip either side of the transect. The effective transect half-width is the equivalent transect width (m) for a hypothetical transect survey that detects all groups actually present. AIC = Akaike information criterion; ΔAIC = the difference between the AIC of the model and the AIC of the minimum AIC model

Goodness-of-fit testing for the selected distance model (the hazard-rate model) was carried out using a χ^2 test on the binned detection data and revealed no significant evidence of lack of fit of the distance model (P = 0.14). However, visual inspection of the histogram of distances (Figure 3) does show an apparent excess of detections at distances of between 5 and 10 metres. This may be indicative of responsive movement (movement in response to the observer before detection) by a portion of animals, and may be habitat-specific.

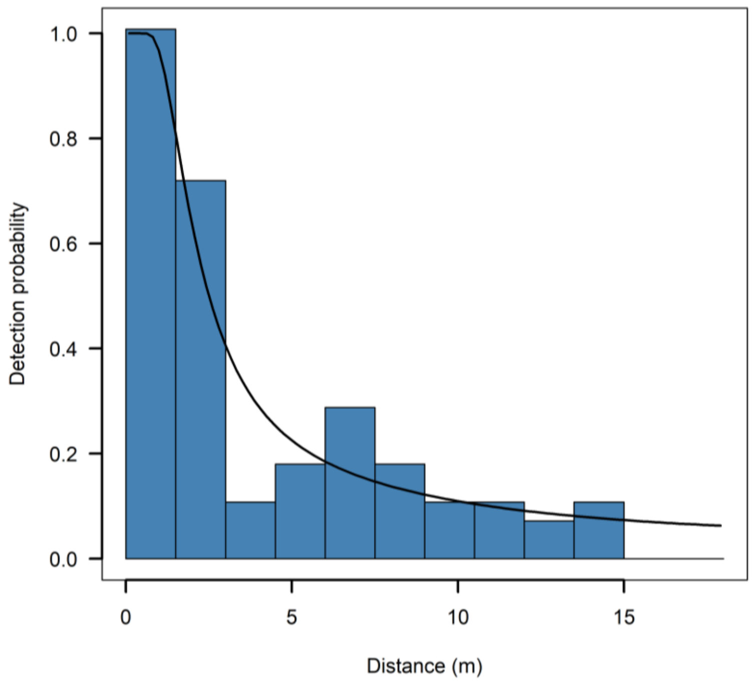

Figure 3. Histogram of binned (1.5-m) distance data, with the fitted hazard-rate function overlay. The distance data were truncated at 18 m to remove the influence of a very small number of detections beyond this distance.

3.2 Design-based estimation of habitat-specific Stubble Quail densities

Based on the distance-sampling data, design-based inferences were made regarding the mean densities of Stubble Quail in each of the four habitat strata used for transect-site selection (Table 2). The transects with the highest mean densities of Stubble Quail were in Non-native Pasture and Seasonal Wetlands habitats, with lower densities being found in Native Tussock Grasslands and Dryland Crops habitats. 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 somewhat greater CVs in the estimates for Native Tussock Grasslands, and Seasonal Wetlands (Table 2).

Table 2. Design-based inferences regarding mean densities (individuals per km^2) of Stubble Quail at sites categorised into four habitat types.

Stratum	Mean	CV	95% CIs
Dryland Crops	24.1	0.33	12.8, 45.4
Native Tussock Grasslands	18.1	0.61	5.7, 57.4
Non-native Pasture	40.2	0.30	22.7, 71.2
Seasonal Wetlands	61.4	0.52	22.9, 164.4

Uncertainty in the estimates is expressed using coefficients of variation (CVs) and 95% confidence intervals (CIs).

Spatial modelling of abundance

Both Tweedie and Negative Binomial DSMs were considered during initial fitting of DSMs to the data. All Negative Binomial models had very poor fit, so these were not considered further in the analysis. The four alternative Tweedie spatial models of abundance were compared using the AIC (Table 3), with a smaller AIC indicating a more parsimonious model that would be expected to have superior predictive performance. On the basis of this comparison, a model that included the non-linear smoothed effects of All Crops (crops) and Pasture/Grassland (grass) cover and NDVI (ndvi) [all as thin-plate splines (Wood 2017)] was identified as the preferred model. Summary statistics for the four models are given in Table 3.

Table 3. Summary statistics for the spatial 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(crops)+s(grass)+s(ndvi)	15.62	174.46	0	52.5
~s(cereal)+s(grass)+s(ndvi)	19.65	177.35	2.89	62.1
~s(easting, northing)	9.73	182.89	8.43	31.9
~intercept	3.00	586.27	411.80	<1

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() = non-linear smooth term (thin-plate spline).

Goodness of fit of the selected (minimum AIC) spatial model was checked using a series of diagnostic plots (Figure 4). 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 good 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.

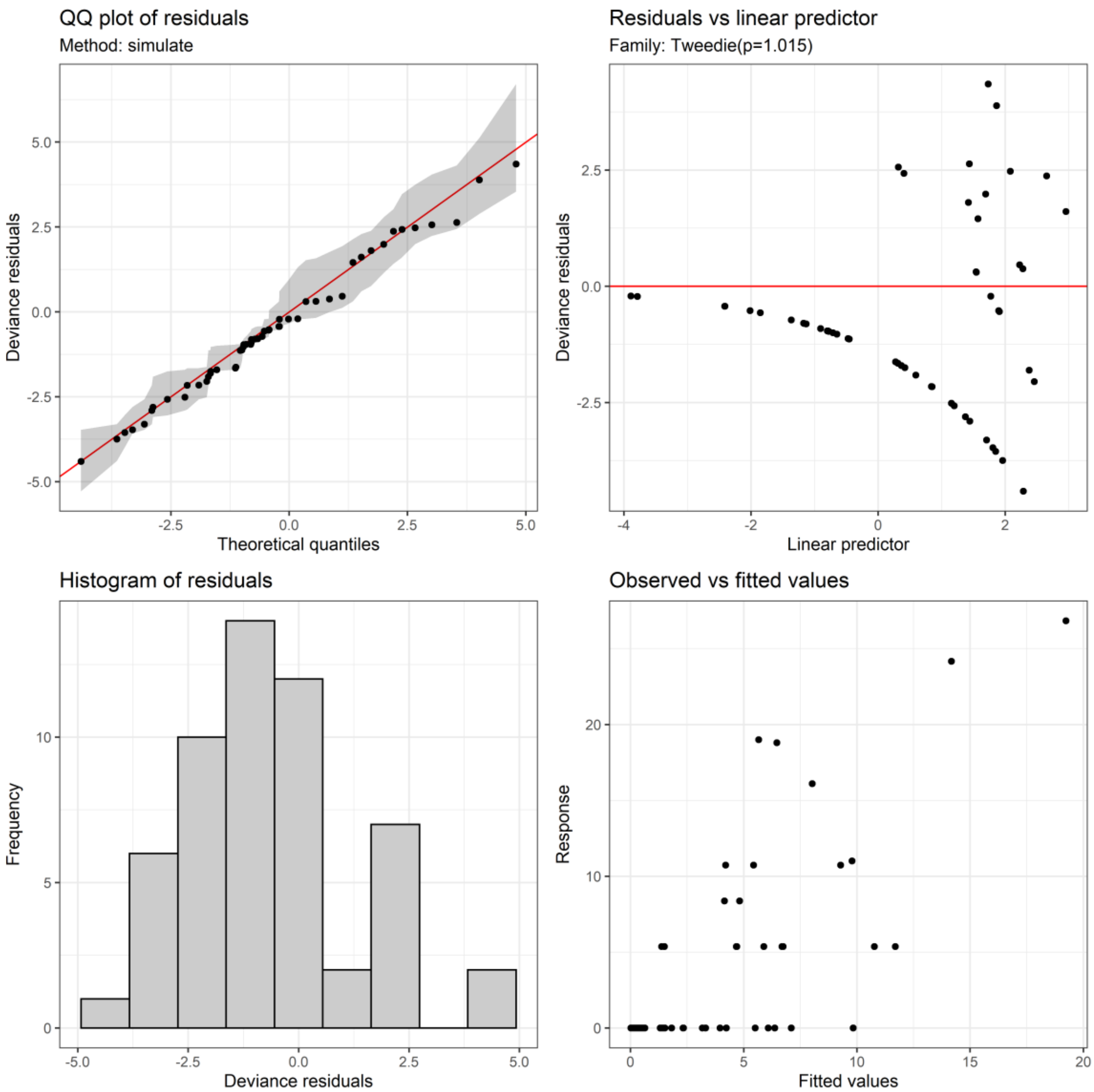

Figure 4. Diagnostic plots for the Tweedie density surface model for spatial variation in Stubble Quail abundance in Victoria.

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 (Figure 5). These plots showed that there were generally positive effects of all three variables on the abundance of Stubble Quail, with some evidence of non-linear, asymptotic relationships in the effects of Pasture/Grassland cover and NDVI (Figure 5).

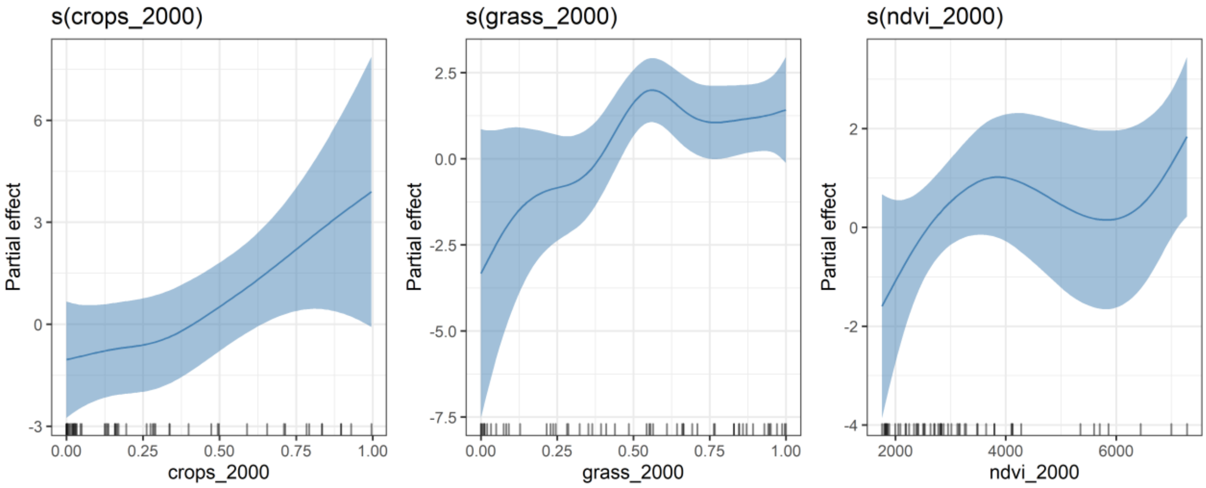

Figure 5. Partial effects of proportional cover of All Crops (crops_2000), Pasture/Grassland (grass_2000) and mean normalised difference vegetation index (ndvi_2000) on the log-abundance of Stubble Quail. The solid lines are the estimated partial effects, and the shaded areas are the 95% confidence intervals. Internal tick-marks on the *x*-axes give the observed covariate values at the survey sites.

The model with the greatest support (lowest AIC) was then used to predict the density of Stubble Quail (Stubble Quail per km^2) across the state, excluding areas that were not mapped as pasture, grassland or crops (Figure 6). The relative uncertainty in the model's prediction of density (expressed as the CV) was also calculated for the 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 clear spatial trend, with higher densities being observed in the south and north east of the state. Densities were especially high on the volcanic plains of south-western Victoria, and on pastoral country to the north of the Great Dividing Range. Densities across the cropping zone of north-western Victoria were markedly lower, although this was also the region with the highest relative uncertainty in the predicted density of Stubble Quail.

The fitted model was also used to estimate 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 grassland. Uncertainty estimates were obtained for the model's predictions using the delta method (Miller et al*.* 2013), and assumed that the observation errors of the distance sampling and the abundance–habitat components of the model were independent.

The estimated total Victorian abundance of Stubble Quail within the habitat considered in the model was 3.1 million (95% CI 1.78 million–5.36 million). The CV for this total population estimate was 0.29. This was attributable to a CV of 0.20 in the estimation of the distance–detection function, and of 0.29 in the estimation of the spatial GAM ($CVtotal^2 = CVdist^2 + CVgam^2$).

Estimates of abundance for each CMA region were obtained using the same methodology (Table 4). These estimates of abundance ranged between approximately 80,000 Stubble Quail for the Mallee CMA and approximately 670,000 for the Glenelg Hopkins CMA. Uncertainty in the CMA-level population estimates was moderate, with CVs ranging between 0.28 for the North Central CMA and 0.60 for the Mallee CMA. As with other population estimates reported here, these apply only to those areas within each CMA that were mapped as crops, pasture or grassland, with other land-use types being excluded from consideration.

The numbers of sites located within each CMA also varied substantially, including two CMAs (East Gippsland and North East) with no sites surveyed, and one CMA with only a single site surveyed (Goulburn Broken). Inferences regarding the abundances of stubble quail within these CMAs rely heavily on extrapolation of the model and assume a spatially constant relationship between density of stubble quail and the habitat variables.

Table 4. Estimates of abundance of Stubble Quail ($\hat{N}$) within each Victorian catchment management authority (CMA) region. Note, these estimates apply only to areas mapped as crop, pasture or grassland.

CMA	Number of survey sites	$\hat{N}$	95% CI	CV
Corangamite	4	300,344	145,541–619,800	0.38
East Gippsland	–	131,436	40,736–424,083	0.66
Glenelg Hopkins	11	669,549	352,094–1,273,228	0.34
Goulburn Broken	1	527,329	273,954–1,015,048	0.34
Mallee	12	80,399	27,277–236,973	0.60
North Central	10	582,257	342,139–990,894	0.28
North East	–	156,386	66,332–368,699	0.46
Port Philip and Western Port	2	144,297	66,167–314,686	0.41
West Gippsland	4	177,442	79,958–393,779	0.42
Wimmera	10	319,358	181,988–560,416	0.29
Victoria	**54**	**3,088,798**	**1,781,429–5,355,630**	**0.29**

CI = confidence interval; CMA = catchment management authority; CV = coefficient of variation.

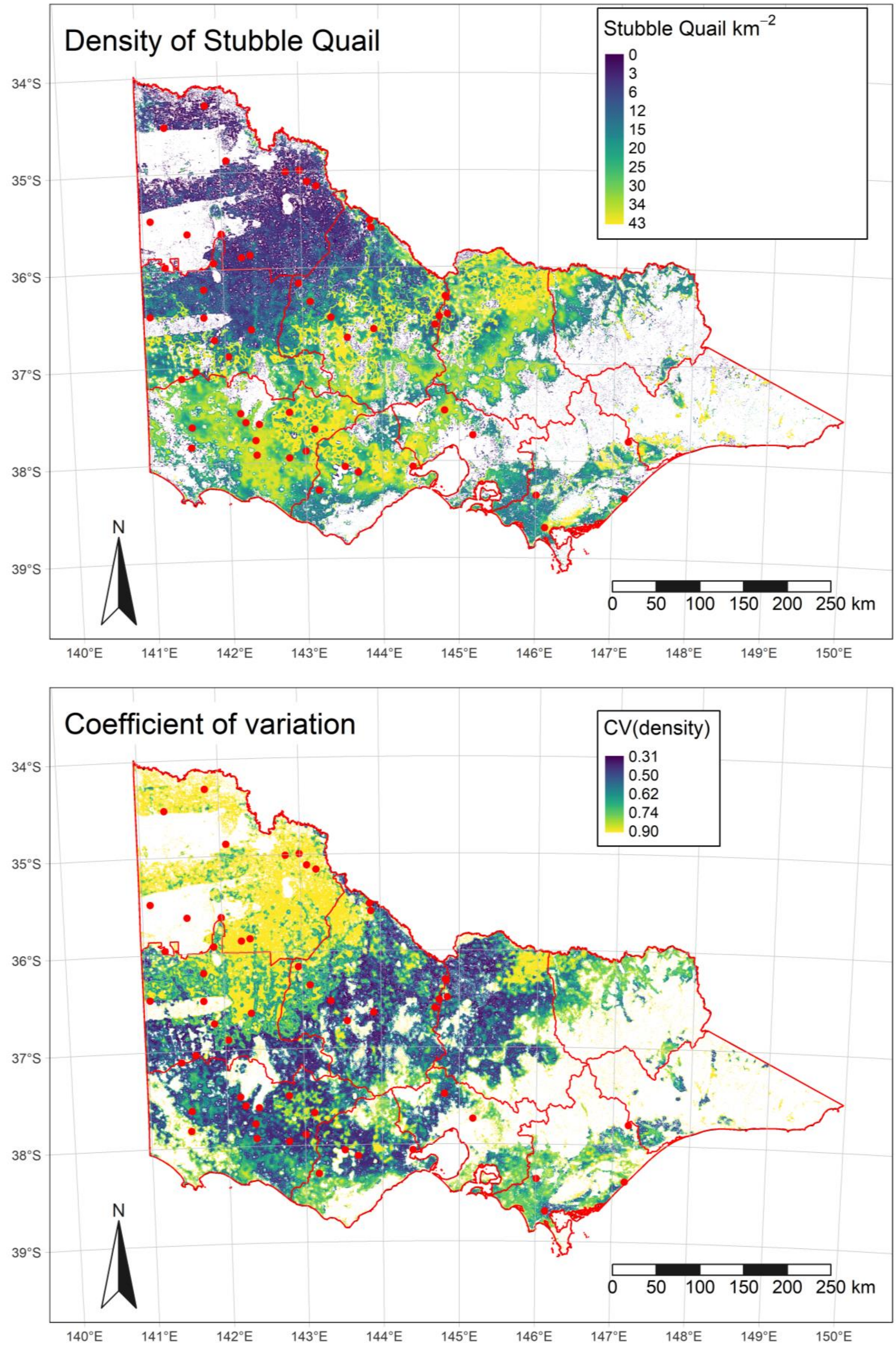

Figure 6. Predicted density (per km^2) of Stubble Quail in Victoria during February 2022. The top panel gives the expected mean, while the bottom panel gives the conditional uncertainty in the predictions expressed as coefficients of variation (CV). Greater values imply higher relative uncertainty about the density of Stubble Quail. The survey sites where the Stubble Quail distance sampling was undertaken and count data were collected are shown as red dots; the catchment management authority area boundaries are shown as red lines.

4 Discussion

This study represents the first attempt to estimate regional and statewide abundances and densities of Stubble Quail in Victoria using distance sampling, a widely accepted method for estimating the abundances of birds (including quail) and other animals. Stubble Quail are difficult to survey due to the fact that they are small, well camouflaged and cryptic, and can actively evade observers. This pilot study presented an opportunity to test the survey methodology prior to its potential adoption in an ongoing monitoring program for Stubble Quail in Victoria.

Stubble Quail are an important game species in Victoria, with an average of around 170,000 birds harvested each year (Hampton and Moloney 2020). However, harvest estimates have fluctuated quite markedly since recording of recreational offtake using telephone surveys began in 2009, which could be related to fluctuations in the abundance of birds over this period (Moloney et al. 2022). Hence, to ensure that future recreational use is sustainable, it is essential that robust and defensible estimates of the abundance of Stubble Quail are available. Such estimates also allow greater insights into the environmental, bioclimatic and management factors (e.g. agricultural practices) that drive fluctuations in abundance, and provide valuable information for managers seeking to sustainably manage and conserve Stubble Quail populations.

Analysis of the detection data from this study suggests that the current line-transect distance-sampling method, which uses a single observer to flush birds, is somewhat inefficient. The estimated effective strip half-width of a typical line transect is only 4.3 m, beyond which detection of birds is very low. This means that, given the 4-km transects typically traversed at each site, observers were only sampling an effective area of 1.7 ha per site. In addition, the relationship between detection probability and distance from the transect suggested that birds may have been responding to the observer by moving away from the transect line before being detected. This violates the central assumption of the distance-sampling model (all individuals occurring on the transect line are detected), potentially resulting in a degree of negative bias in the abundance estimates. Incidental observations of calling male Stubble Quail were recorded at many sites, despite birds not being detected during line-transect sampling, which also reinforces the idea that the current methods are inefficient at detecting Stubble Quail presence. Hence, to improve sampling efficiency, consideration should be given to modifying the distance-sampling method. One potential improvement could involve the use of multiple observers walking abreast on the transect (e.g. drive counts[1]). Having multiple observers on the transect line would mean that any birds located on the transect line would be less likely to escape detection. Multiple observers would also result in improved sampling coverage of the habitat at each site, increasing the area effectively searched and improving the efficiency and accuracy of the surveys. We recommend that this modification to the current survey protocol be evaluated to determine its suitability for estimating densities of Stubble Quail.

Relatively lower densities of Stubble Quail were estimated in areas with higher proportions of dryland crops compared with pasture and grasslands. Sampling occurred in crop stubble following harvest, which has been previously identified as a highly preferred habitat type due to an abundance of waste grain spilled on the ground following harvest (Toop 1994). Population densities of Stubble Quail exceeding 5 per ha have been reported in recently harvested crop habitat in northern Victoria (Toop 1994); that study also used a strip-transect survey approach. The low densities in crop stubble recorded here, compared with in pasture or seasonal wetland habitats, is somewhat surprising, but may be due to only small amounts of residual grain being present in these stubble habitats at the time when sampling was undertaken. A further explanation for the relatively low density estimates for dryland crop stubble could be that Stubble Quail density was also found to increase with increasing vegetation greenness (NDVI). Since crop stubble has relatively low NDVI, this would have contributed to the low predicted density for this habitat type in our spatial model.

[1] A drive count involves a number of observers walking abreast but evenly spaced at intervals (e.g. 5–20 m) through the survey area and counting all quail that flush. Drive counts are more labour-intensive that single-person line transects, but cover a larger area.

The highest densities of Stubble Quail occurred on the western and northern plains, which were characterised by a mix of habitat types (grazing and cropping). This mosaic of different habitat types may be highly suitable for Stubble Quail by providing foraging and refuge opportunities throughout the annual cropping and grazing cycle. Future analysis should consider recent rainfall patterns as an alternative predictor of abundance, as well as addressing the effects of landscape-scale habitat diversity on abundance.

Our spatial model relied on a relatively simple categorisation of habitat types involving a small number of land-use categories available in existing publicly available land-use data. Refinements in land-use categorisation may provide a more accurate and relevant representation of the habitat types used by Stubble Quail, leading to more accurate and precise estimates of density than the relatively simple categories used here. Improvements in the spatial maps of land-use could be obtained by applying machine-learning methods to satellite imagery collected near-simultaneously with the quail survey data (i.e. Sentinel-2, European Space Agency 2022). By incorporating these classifications of land use with corresponding ground-truthed observations (obtained during sampling), such methods could provide a richer and likely more accurate categorisation of land-use types that may be more useful for predicting Stubble Quail densities.

The precision of the statewide estimate of Stubble Quail abundance was moderate, with a CV of 29%. The precision of the estimates for various regions was variable, ranging from 28% to 66%. This was mostly due to the fact that only 54 of the recommended 80 sites were able to be sampled, due to the difficulty of access to some private properties. Furthermore, some CMAs either had no sites surveyed (East Gippsland and the North East) or very low numbers of sites (see Table 4). Increasing the number of sampled sites for some regions and/or habitat types should result in improved precision in the abundance estimates across the entirety of the study area, as well as in currently undersampled CMAs. Incorporation of other sources of Stubble Quail presence data, obtained through recording of calls or use of citizen science data (e.g. Birdlife Australia monitoring data) may also provide improved abundance estimates, but would require more sophisticated integrated modelling techniques to validly combine the different data types (see, e.g. Farr et al. 2021). However, any increases in sample size or inclusion of other data acquisition methods must be considered in light of any changes to the sampling methodology. Hence, we have not undertaken any investigation into additional sample size requirements until the sampling issues have been considered and suitable trial survey data collected and analysed.

4.1 Recommendations

- Investigate improvements to the distance sampling methods for Stubble Quail that will reduce the chance of birds moving before being detected. One potential modification that should be investigated is to conduct distance sampling with multiple observers (say, 3–5) walking abreast (i.e. a ‘drive count’). Combining drive counts with distance sampling should also result in improvements to the coverage of the habitat at sampled sites, increasing efficiency.
- Investigate improvements to the land-use categorisation by applying machine-learning classification models to recent satellite imagery, to provide more relevant and accurate classification of land-use types (e.g. to distinguish between stubble and standing crops). In addition, investigate the influence of other potential drivers of Stubble Quail abundance (e.g. recent rainfall).
- Revise the number of sites required to be sampled to provide improved precision of statewide and regional abundance estimates. Further sites should be allocated such that currently under-sampled regions of the state are better represented. However, determination of revised sample sizes and selection of additional sites should only be undertaken once the sampling methodology has been satisfactorily refined, as the sample size requirements will depend on the efficiency (i.e. effective area searched) of the improved survey methods.

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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 four covariates are calculated for 2-km radius circles (moving window filter) across the study area (Victoria). For crop, cereal and pasture/grassland cover, the quantity represented is the proportion of the relevant habitat type within a 2-km radius. For the Normalised Difference Vegetation Index (NDVI), the relevant quantity is the mean NDVI value within a 2-km radius.

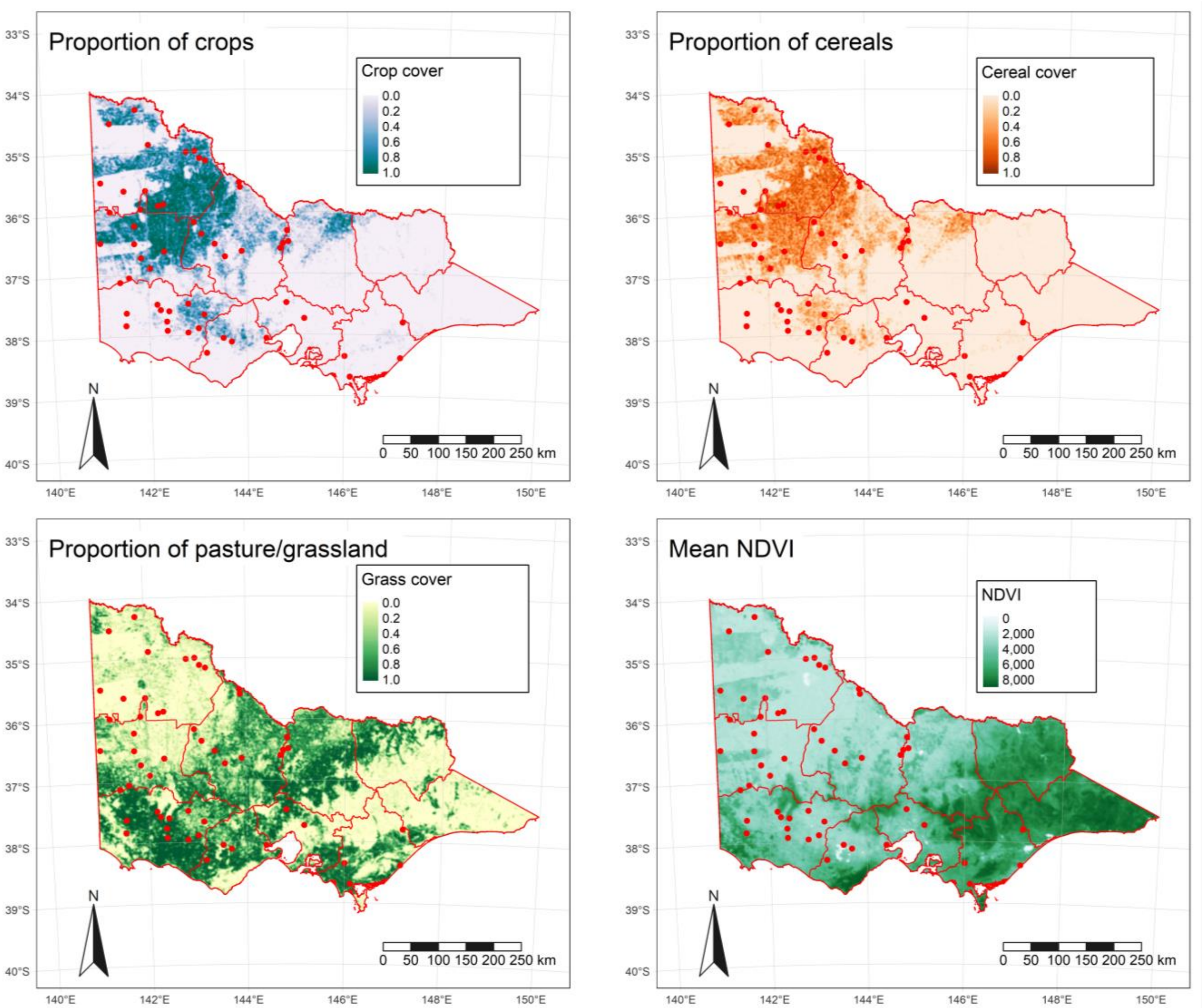

Figure A1. Maps of the three covariates used in the spatial model for Stubble Quail abundance: (i) proportion of All Crops (comprising cereal, legumes and brassicas) within a 2-km radius, (ii) proportion of cereal crops within a 2-km radius, and (iii) proportion of pasture and grassland within a 2-km radius; and (iv) mean normalised difference vegetation index (NDVI) within a 2-km radius. 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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