Corella, 2022, 46: 7-16

A local scale evaluation of spatial sampling bias in the *Atlas of Australian Birds*

Stephen L. Totterman

Empire Vale, NSW 2478
Email: stephen@totterman.net.au

Received: 26 August 2021
Accepted: 18 January 2022

The consequences of volunteers freely choosing sampling locations in 'citizen science' projects need to be recognised. This study examined local ('patch') scale spatial sampling patterns in the *Atlas of Australian Birds* and then compared reporting rates (*i.e.* the proportion of sampling units in which a given bird species was present) from a sample of atlas points with those from a regular (systematic) sample. Three sites were surveyed between January–May 2017: Killawarra Forest, Victoria, and Coolah Tops National Park and Pilliga Nature Reserve, New South Wales. Sampling bias in the atlas was evident as clusters at tourist areas and dams and as linear patterns along roads and watercourses. Atlas samples overestimated reporting rates for species with distributions that were concordant with those features and *vice versa*. At least two-fold differences in atlas: regular sample reporting rate ratios were identified for between 13–15% of 'non-rare' species (*i.e.* with a reporting rate ≥ 0.08 in either sample). Concerns are raised that spatial sampling bias is common in the atlas and can affect results for a variety of species, that popular sites may not be representative of habitat patches and that many surveys are being filtered out in data analyses.

Keywords*:* sampling bias; bird atlas; convenience sampling.

INTRODUCTION

The analysis of large, volunteer-collected datasets is a growing component of conservation science (*e.g.* Cunningham and Olsen 2009; Szabo *et al.* 2010, 2012). However, the reliability of unstructured surveys for making inferences about the populations of interest has been questioned (Anderson 2001).

Spatial and temporal sampling biases have been identified in the *Atlas of Australian Birds* (hereafter 'the atlas') (Barrett *et al.* 2003; BirdLife Australia 2015). Two frequent causes of sampling bias are 'convenience sampling' and 'subjective' or 'targeted sampling' (Anderson 2001). Convenience sampling is the selection of more accessible locations and/or times (*e.g.* along roadways). Targeted sampling is the selection of locations and/or times where abundance and/or species richness is known to be high (*e.g.* at dams and other special habitat features). Sampling bias can result in overestimation of abundance for species with distributions that are concordant with sampling patterns and *vice versa*.

A previous, regional scale evaluation compared atlas reporting rates (*i.e.* the proportion of sampling units in which a given bird species was present) with those from a structured survey in eucalypt woodlands in the Mount Lofty Ranges, South Australia (hereafter 'the Mount Lofty Ranges evaluation') (Szabo *et al.* 2012). Bivariate regression results showed general agreement in the atlas and structured survey reporting rates (intercept ~ 0 and slope ~ 1). However, that evaluation was not a comparison of two different methods, as the same 20-minute, two-hectare search method was used in both surveys, and so systematic bias (method bias, which is what is estimated by regression analysis) was small relative to variable bias, (*i.e.* differences in spatial and temporal sampling effort and observer effects that can result in different biases for different species).

The Mount Lofty Ranges evaluation reported at least two-fold differences in reporting rates for 17 of the 61 species (28%), but these were disregarded as mostly species using edges and open habitats (Szabo *et al.* 2012). Actually, there were at least two-fold differences for seven of 27 species (26%) that were classified as being dependent on native vegetation, which is practically equal to 10 of 34 species (29%) that were classified as not being dependent on native vegetation. Moreover, the list of species not dependent on native vegetation included the Crimson Rosella *Platycercus elegans* and Superb Fairy-wren *Malurus cyaneus*, which were two of the most common birds (Szabo *et al.* 2011), as well as several other indicator species for eucalypt woodland/forest (as defined by BirdLife Australia 2015). Large sample sizes were a strength of the Mount Lofty Ranges evaluation, with 554 atlas surveys and 3,877 structured surveys, and so a large bias in results for individual species cannot be ascribed to sampling error.

The present study performed a local scale evaluation of spatial sampling bias in the atlas in three eucalypt forests. Atlas data were not requested. Instead, atlas survey points were resurveyed simultaneously with a regular (systematic) sample of points. This approach avoided temporal and observer effects and focused comparisons on spatial sampling bias.

METHODS

Study sites

Suitable study sites were contiguous patches of open, eucalypt forest with at least 100 pre-existing survey points in the atlas from which to sample.

Killawarra Forest (36°13'S, 146°11'E) is a box-ironbark forest remnant in the Ovens-Murray region of Victoria, 18 km north-west of Wangaratta (Fig. 1a). The site is 3,209 ha in area and it is relatively flat, varying from 150–250 m asl. There are several intermittent creeks in the site that were dry during the survey, and several small dams ('water points'), each approximately 100 m^2 in area. Open box, stringybark and ironbark eucalypt forest, with a ground layer of herbs and grasses, grows on the ridge lines. Box woodland with an open mid-storey of wattles (*Acacia* spp.) and a ground layer of herbs and grasses grows on the flats and along creek lines. The site was crisscrossed by many roads and tracks, most of which were rarely used. There was a camp ground in the middle of the forest that had few visitors. Killawarra was surveyed between 28 February and 18 March 2017.

Coolah Tops National Park (31°44'S, 150°01'E) is located on an elevated plateau 1,000–1,200 m asl at the western end of the Liverpool Range, 32 km north-east of Coolah, New South Wales (Fig. 2a). The park's area is 14,097 ha; however, sampling was restricted to 10,113 ha of plateau, mostly above 1,000 m asl, where most of the pre-existing atlas survey points were and to avoid the rugged flanks of the range and drier forest and woodlands of the surrounding Central West Slopes and Plains region. Open stringybark and gum eucalypt forests grow on the plateau, often with a grassy ground layer. There are numerous streams draining the plateau. A dense, shrub mid-storey was common in wetter areas. Most of the roads and tourist facilities are in the west of the forest. Coolah Tops was surveyed between 20 March and 11 April 2017.

Pilliga Nature Reserve (30°53'S, 149°28'E) is at the southern end of the Pilliga Forests in the North-West Slopes and Plains region of New South Wales, 33 km north of Coonabarabran. The study site was defined by drawing a polygon around preexisting atlas survey points (Fig. 3a). The site is 27,098 ha in area and it is essentially flat, extending from 300–500 m asl. Ironbark eucalypt and cypress pine (*Callitris spp.*) grow on the ridge lines. Gum eucalypts grow along creek lines. The mid-storey was often quite dense and contained wattles and other shrubs. Mallee shrubland occurred in the east of the site. The south-western corner of the site had been burnt at some unknown time preceding the survey and showed abundant regrowth. There are several intermittent creeks in the site that were dry during the survey. Borah Creek was exceptional in featuring waterholes and grassy eucalypt woodland along its banks. No dams were found within the site. The Sandstone Caves on the southern boundary and Yaminba Rest Area on the Newell Highway were the only sites frequented by visitors. Pilliga was surveyed between 15 April and 7 May 2017.

Survey method

The sampling unit was the atlas-recommended 20-minute search of a 200 × 100 m (two-ha) area (Barrett *et al.* 2003) by a single observer (the author). Searches were centered on the sampling point coordinates. Points were located and search dimensions were estimated using a handheld GPS receiver (Garmin GPSMAP 62s). All bird species inside the search area were counted, except for those flying over which were recorded as present/absent.

Sampling design

Sample sizes for each study site were 50 atlas points, selected at random, and 50 regular points. Spatial sampling was performed using QGIS version 2.16 (QGIS Development Team 2016) as follows:

1. A base map of the site was made from screenshots of the atlas website (BirdLife Australia 2017; distinct survey points can be seen by zooming in). Any repeated sampling of points was unknown and ignored in this study.
2. The atlas website plotted points on Google Maps (Google 2017). Between 7–12 control points for geo-referencing the base map were obtained from Google Maps.
3. Control points (in latitude and longitude) were projected to Universal Transverse Mercator (UTM), which was selected for local accuracy and ease of navigation, with Cartesian coordinates in metres.
4. The base map was geo-referenced with the UTM control points.
5. Between 9–13 GPS survey points, from precise features like road intersections, were used to check the accuracy of the geo-referenced image. Mean errors were in the range 9–34 m and much smaller than the two-hectare search dimensions and potential inaccuracy in volunteer-recorded coordinates.
6. The boundary of the site was digitised using the Google Maps boundary or a polygon was drawn around pre-existing atlas points.
7. Atlas points inside the site boundary were digitised.
8. A random sample of 50 atlas points was selected, without replacement, saved as a GPX file and copied to the GPS receiver.
9. A regular sample of 50 points inside the site boundary, with random *x* and *y* offsets (*i.e.* a systematic sample with a small amount of random 'jitter'), was selected, saved as a GPX file and copied to the GPS receiver. Regular sampling was used to maximise site coverage and minimise spatial autocorrelation.

Surveying occurred from dawn on each day until bird activity declined, which usually occurred around mid-morning. Surveying was not performed in windy or rainy conditions when it is difficult to detect, identify and count birds. Closely-spaced points less than approximately 400 m apart were surveyed on different days to reduce temporal autocorrelation. Surveying of atlas and regular sample points was haphazardly interspersed both within and among days.

Statistical analysis

The analysis examined the three study sites separately. Atlas spatial sampling patterns were quantified using Clark-Evans tests, where $R = 1$ indicates a random pattern, $R < 1$ an aggregated pattern and $R > 1$ a regular pattern (Clark and Evans 1954). These point patterns were bounded by site boundaries and edge corrections were not applied.

Monitoring sites for Australian Bird Indices are defined as spatial clusters of atlas survey points (Ehmke and Herman 2014; BirdLife Australia 2015). Clusters of atlas points in this study were identified using similar, if not identical, kernel density estimator methods to those used in the atlas (*i.e.* Epanechnikov kernel, 200 m bandwidth, 50 × 50 m cells, 50% or 75% isopleth) and only those clusters with at least four survey points were accepted (Ehmke and Herman 2014).

Reporting rates were used to compare atlas and regular sample observations. Presence-absence data are closely-linked to spatial sampling patterns and Australian Bird Indices are based on reporting rates (BirdLife Australia 2015). Reporting rates were calculated only for diurnal forest birds (*i.e.* excluding any waterbirds, aerial foragers, nocturnal birds and raptors). Overflying birds were also excluded from reporting rate calculations because they were not using the habitat in the search area (Szabo *et al.* 2012).

Comparisons of reporting rates focused on atlas: regular sample reporting rate ratios for individual species. First, large ratios greater than at least two-fold (Szabo *et al.* 2012) for 'non-rare' species (*i.e.* those with at least four presences in either sample [reporting rate ≥ 0.08]) were identified. Ratios of small counts are volatile and then statistical evaluation is futile. Second, reporting rate ratio ('relative risk') confidence intervals were estimated using the unconditional score statistic method (Agresti and Min 2002). A confidence interval that excludes unity identifies a result that warrants further investigation. Third, large ratios were interpreted by reference to distribution maps and habitat observations.

Spatial autocorrelation (*i.e.* where observations from closely spaced locations are often more similar than are those from widely spaced locations) violates the assumption of independent outcomes for the binomial distribution. Spatial autocorrelation was checked using spline correlograms computed for the combined atlas and regular samples (Bjørnstad and Falck 2001). Reporting rate ratio confidence intervals are not reported where the correlogram *y*-intercept (the extrapolated correlation at zero distance) was 0.2 (the theoretical maximum correlation equals one). Nonetheless, a spatially autocorrelated species distribution concordant with the atlas sampling pattern does support positive bias in the atlas reporting rate and identifies a result that warrants further investigation.

Spatial statistical methods could be useful for reducing bias that results from clustered sampling; however, this study was concerned with the direct estimation of bias in the atlas sample relative to the regular sample. The calculation of Australian Bird Indices ignores temporal and spatial autocorrelation (Cunningham and Olsen 2009; BirdLife Australia 2015).

All statistical analyses were performed using the software R version 4.0.4 (R Core Team 2021). Spatial point pattern statistics were computed using the R package *spatstat* version 2.0-1 (Baddeley *et al.* 2015). Spatial clusters were identified using *adehabitatHR* version 0.4.19 (Calenge 2006). Spline correlograms were computed using *ncf* version 1.2-9 (Bjørnstad 2020). Risk ratio confidence intervals were computed using *PropCIs* version 0.3-0 (Scherer 2018). Figures were prepared using *ggplot2* version 3.3.3 (Wickham 2016).

RESULTS

Killawarra

The atlas spatial sampling pattern for Killawarra showed clusters of points at the camp ground and at four of the dams (Fig. 1b) (n = 154, Clark-Evans R = 0.82, P < 0.001). The five clusters were between 13–56 ha in area; they contained between 5–30 points and 64 points in total (42% of 154).

There were 35 non-rare species, 13 of which (37%) had at least two-fold differences in atlas: regular sample survey reporting rate ratios and five of those warranted further investigation (14%), including three with spatially autocorrelated observations (Table 1).

The atlas sample overestimated reporting rates for species that were frequent at the camp ground and/or dams, including the White-plumed Honeyeater *Lichenostomus penicillatus* (ratio = 2.4, CI = NA), Little Friarbird *Philemon citreogularis* (ratio = 2.2, CI = 1.2–4.2), White-browed Babbler *Pomatostomus superciliosus* (ratio = Inf., CI = NA) (a family of babblers was resident at the camp ground) and Mistletoebird *Dicaeum hirundinaceam* (ratio = 2.4, CI = NA) (there were fruiting mistletoes at the camp ground) (Figs 1c–e). The atlas sample underestimated the reporting rate for the Speckled Warbler *Chthonicola sagittata* (ratio = 0.25, CI = 0.06–0.98), which did not frequent those areas (Fig. 1f).

Coolah Tops

The atlas spatial sampling pattern for Coolah Tops showed clusters of points at camp grounds and other tourist areas in the west of the site, relatively few points in the east and a gap in the middle of the forest (Fig. 2b) (n = 116, Clark-Evans R = 0.58, P < 0.001). The six clusters were between 14–66 ha in area; they contained between 4–25 points and 60 points in total (52% of 116).

There were 23 non-rare species, five of which (22%) had at least two-fold differences in atlas: regular sample reporting rate ratios and three of those warranted further investigation (13%), including one with spatially autocorrelated observations (Table 2).

The atlas sample overestimated reporting rates for species that were frequent in more open habitats and camp grounds, including the Australian Magpie *Gymnorhina tibicen* (ratio = 3.7, CI = NA) and Pied Currawong *Strepera graculina* (ratio = 2.2, CI = 0.9–5.2) (Figs 2c–d). The atlas sample underestimated reporting rates for the Red-browed Treecreeper *Climacteris erythrops* (ratio = 0.35, CI = 0.16–0.72), which was more frequent in stringybark forest on ridges, and the Noisy Friarbird *Philemon corniculatus* (ratio = 0.30, CI = 0.09–0.94) (Figs 2e–f).

Pilliga

The atlas spatial sampling pattern for the Pilliga site looked well-dispersed, including lines of regularly spaced points (Fig. 3b). Nonetheless, there were clusters of points at tourist areas and a linear pattern along Borah Creek (n = 108, Clark-Evans R = 0.71, P < 0.001). The three clusters were between 20–32 ha in area; they contained between 4–9 points and 19 points in total (18% of 108).

Table 1

Reporting rate comparisons for Killawarra. Ratios are not reported for rare species (*i.e.* with both reporting rates < 0.08). At least two-fold differences are in bold. Confidence intervals that exclude unity are in bold. Confidence intervals are not reported for species with spatially correlated observations (correlogram *y*-intercept > 0.2). The correlogram *x*-intercept is the distance at which observations are no more similar than that expected by chance. The correlogram *x*-intercept is not reported if the *y*-intercept is negative. Correlogram results are not reported for species with reporting rate ratios less than two-fold. These explanatory notes also apply to Tables 2 and 3.

	Reporting rate			Spatial correlogram	
Species	**Atlas sample**	**Regular sample**	**Ratio (and confidence int.)**	***y*-int.**	***x*-int.**
Common Bronzewing *Phaps chalcoptera*	0.10	0.06	1.7		
Peaceful Dove *Geopelia striata*	0.00	0.02			
Painted Button-quail *Turnix varius*	0.08	0.12	0.67		
Galah *Eolophus roseicapillus*	0.02	0.02			
Sulphur-crested Cockatoo *Cacatua galerita*	0.02	0.00			
Little Lorikeet *Glossopsitta pusilla*	0.04	0.00			
Eastern Rosella *Platycercus eximius*	0.14	0.10	1.4		
Turquoise Parrot *Neophema pulchella*	0.04	0.00			
Horsfield's Bronze-Cuckoo *Chalcites basalis*	0.00	0.02			
Fan-tailed Cuckoo *Cacomantis flabelliformis*	0.02	0.00			
Laughing Kookaburra *Dacelo novaeguineae*	0.00	0.02			
Sacred Kingfisher *Todiramphus sanctus*	0.04	0.00			
Rainbow Bee-eater *Merops ornatus*	0.02	0.02			
White-throated Treecreeper *Cormobates leucophaea*	0.58	0.44	1.3		
Brown Treeereeper *Climacteris picumnus*	0.20	0.22	0.91		
Superb Fairy-wren *Malurus cyaneus*	0.40	0.40	1.0		
Speckled Warbler *Chthonicola sagittata*	0.04	0.16	**0.25 (0.06–0.98)**	0.06	1545
Weebill *Smicrornis brevirostris*	0.18	0.26	0.69		
Western Gerygone *Gerygone fusca*	0.10	0.12	0.83		
Yellow Thornbill *Acanthiza nana*	0.10	0.04	**2.5** (0.59–11)	0.02	1176
Buff-rumped Thornbill *Acanthiza reguloides*	0.32	0.40	0.80		
Brown Thornbill *Acanthiza pusilla*	0.18	0.06	**3.0** (0.94–10)	–0.04	
Striated Pardalote *Pardalotus striatus*	0.30	0.34	0.88		
Eastern Spinebill *Acanthorhynchus tenuirostris*	0.02	0.00			
Yellow-faced Honeyeater *Lichenostomus chrysops*	0.04	0.02			
Yellow-tufted Honeyeater *Lichenostomus melanops*	0.32	0.20	1.6		
Fuscous Honeyeater *Lichenostomus fuscus*	0.52	0.38	1.4		
White-plumed Honeyeater *Lichenostomus penicillatus*	0.44	0.18	**2.4**	0.95	755
Noisy Miner *Manorina melanocephala*	0.16	0.16	1.0		
Red Wattlebird *Anthochaera carunculata*	0.06	0.08	0.75		
Black-chinned Honeyeater *Melithreptus gularis*	0.06	0.00			
Brown-headed Honeyeater *Melithreptus brevirostris*	0.36	0.24	1.5		
Noisy Friarbird *Philemon corniculatus*	0.14	0.08	1.8		
Little Friarbird *Philemon citreogularis*	0.44	0.20	**2.2 (1.2–4.2)**	0.14	891
Painted Honeyeater *Grantiella picta*	0.04	0.06			
White-browed Babbler *Pomatostomus superciliosus*	0.10	0.00	**Inf**	1.99	506
Varied Sittella *Daphoenositta chrysoptera*	0.04	0.10	**0.40** (0.09–1.7)	–0.07	
Black-faced Cuckoo-shrike *Coracina novaehollandiae*	0.04	0.06			
White-bellied Cuckoo-shrike *Coracina papuensis*	0.02	0.00			
Crested Shrike-tit *Falcunculus frontatus*	0.04	0.04			
Golden Whistler *Pachycephala pectoralis*	0.04	0.04			
Rufous Whistler *Pachycephala rufiventris*	0.34	0.50	0.68		
Grey Shrike-thrush *Colluricincla harmonica*	0.24	0.18	1.3		
Olive-backed Oriole *Oriolus sagittatus*	0.04	0.00			
White-browed Woodswallow *Artamus superciliosus*	0.02	0.02			
Dusky Woodswallow *Artamus cyanopterus*	0.04	0.08	**0.50** (0.11–2.2)	–0.06	
Grey Butcherbird *Cracticus torquatus*	0.02	0.04			
Australian Magpie *Cracticus tibicen*	0.10	0.06	1.7		
Grey Fantail *Rhipidura albiscapa*	0.36	0.32	1.1		
Willie Wagtail *Rhipidura leucophrys*	0.26	0.18	1.4		
Satin Flycatcher *Myiagra cyanoleuca*	0.02	0.00			
Restless Flycatcher *Myiagra inquieta*	0.04	0.08	**0.50** (0.11–2.2)	–0.09	
White-winged Chough *Corcorax melanorhamphos*	0.10	0.04	**2.5** (0.59–11)	–0.10	
Jacky Winter *Microeca fascinans*	0.06	0.12	**0.50** (0.14–1.7)	0.04	1076
Red-capped Robin *Petroica goodenovii*	0.06	0.00			
Hooded Robin *Melanodryas cucullata*	0.04	0.00			
Eastern Yellow Robin *Eopsaltria australis*	0.06	0.14	**0.43** (0.13–1.4)	0.08	1015
Silvereye *Zosterops lateralis*	0.12	0.10	1.2		
Mistletoebird *Dicaeum hirundinaceam*	0.38	0.16	**2.4**	0.97	826

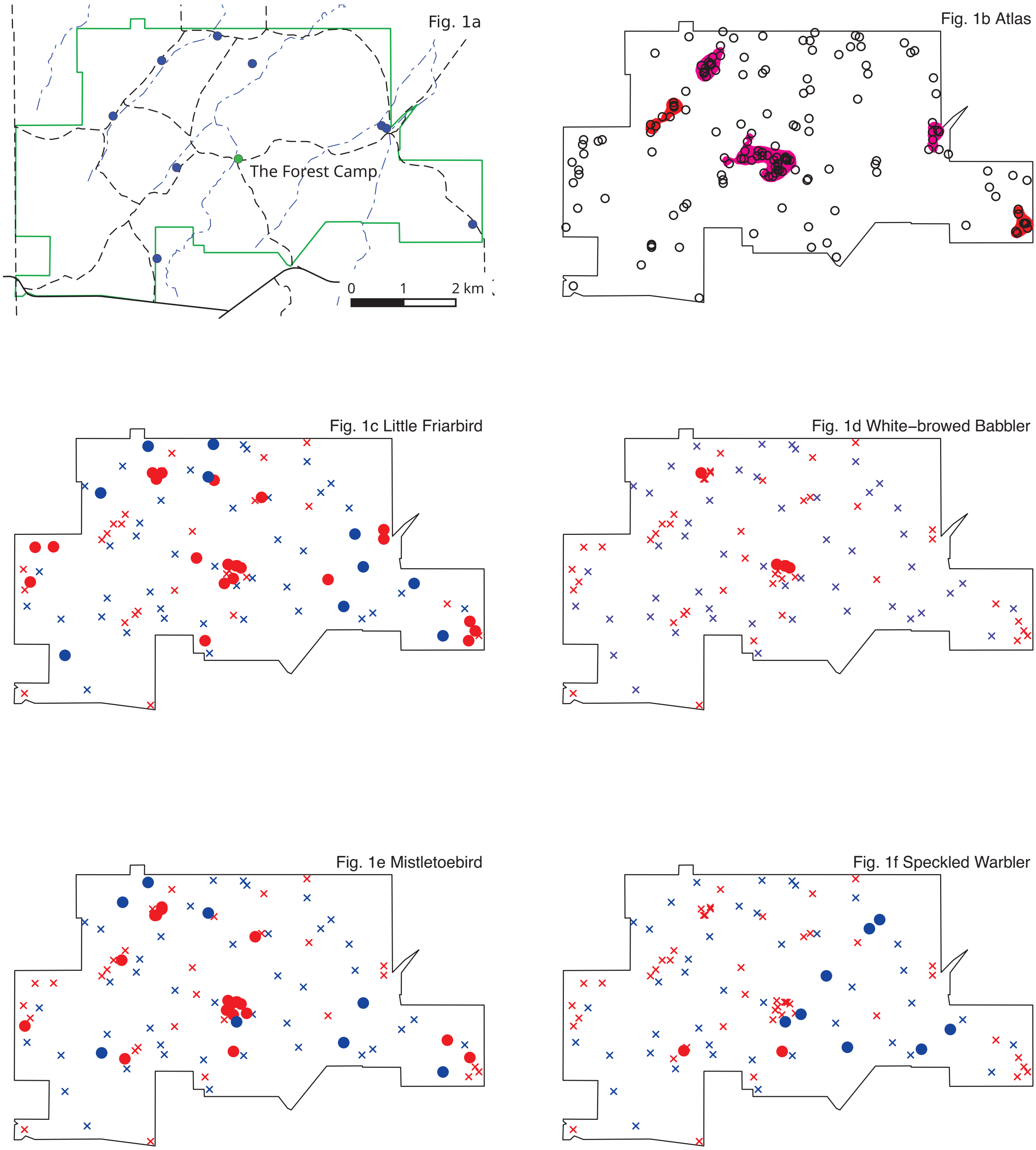

Figure 1. *Killawarra map (a), atlas spatial sampling pattern (n = 154) (b) and species distribution examples (c–f). Solid and dashed black lines in (a) are sealed and unsealed roads, respectively (minor tracks not shown), blue lines are intermittent creek lines and blue circles are dams. Coloured areas in (b) are clusters that were defined using a kernel density and 50% isopleth. Magenta areas correspond to shared sites in the atlas (BirdLife Australia 2021). Red and blue circles in (c–f) are atlas sample and regular sample presences, respectively, and crosses are absences (total n = 50 in each sample).*

Table 2

Reporting rate comparisons for Coolah Tops.

	Reporting rate			Spatial correlogram	
Species	**Atlas sample**	**Reg. sample**	**Ratio (and confidence int.)**	**y-int.**	***x*-int.**
Glossy Black-Cockatoo *Calyptorhynchus lathami*	0.02	0.00			
Yellow-tailed Black-Cockatoo *C. funereus*	0.00	0.02			
Sulphur-crested Cockatoo *Cacatua galerita*	0.32	0.22	1.5		
Musk Lorikeet *Glossopsitta concinna*	0.30	0.28	1.1		
Australian King-Parrot *Alisterus scapularis*	0.04	0.06			
Crimson Rosella *Platycercus elegans*	0.42	0.38	1.1		
Shining Bronze-Cuckoo *Chalcites lucidus*	0.00	0.04			
Fan-tailed Cuckoo *Cacomantis flabelliformis*	0.00	0.02			
Laughing Kookaburra *Dacelo novaeguineae*	0.06	0.08	0.75		
White-throated Treecreeper *Cormobates leucophaea*	0.54	0.48	1.1		
Red-browed Treecreeper *Climacteris erythrops*	0.14	0.40	**0.35 (0.16–0.72)**	0.09	1022
Superb Fairy-wren *Malurus cyaneus*	0.32	0.24	1.3		
White-browed Scrubwren *Sericornis frontalis*	0.56	0.56	1.0		
Speckled Warbler *Chthonicola sagittata*	0.02	0.00			
Striated Thornbill *Acanthiza lineata*	0.56	0.42	1.3		
Buff-rumped Thornbill *Acanthiza reguloides*	0.16	0.20	0.80		
Brown Thornbill *Acanthiza pusilla*	0.48	0.60	0.80		
Spotted Pardalote *Pardalotus punctatus*	0.30	0.24	1.3		
Eastern Spinebill *Acanthorhynchus tenuirostris*	0.16	0.16	1.00		
Yellow-faced Honeyeater *Lichenostomus chrysops*	0.50	0.40	1.3		
White-eared Honeyeater *Lichenostomus leucotis*	0.02	0.06			
Red Wattlebird *Anthochaera carunculata*	0.60	0.52	1.2		
Brown-headed Honeyeater *Melithreptus brevirostris*	0.02	0.00			
White-naped Honeyeater *Melithreptus lunatus*	0.04	0.02			
Noisy Friarbird *Philemon corniculatus*	0.06	0.20	**0.30 (0.09–0.94)**	0.14	2799
Spotted Quail-thrush *Cinclosoma punctatum*	0.00	0.04			
Varied Sittella *Daphoenositta chrysoptera*	0.00	0.02			
Black-faced Cuckoo-shrike *Coracina novaehollandiae*	0.00	0.06			
Golden Whistler *Pachycephala pectoralis*	0.04	0.08	**0.50** (0.11–2.2)	0.03	1430
Rufous Whistler *Pachycephala rufiventris*	0.02	0.06			
Grey Shrike-thrush *Colluricincla harmonica*	0.06	0.08	0.75		
Grey Butcherbird *Cracticus torquatus*	0.02	0.02			
Australian Magpie *Cracticus tibicen*	0.22	0.06	**3.7**	0.34	1223
Pied Currawong *Strepera graculina*	0.26	0.12	**2.2** (0.93–5.2)	−0.08	
Rufous Fantail *Rhipidura rufifrons*	0.02	0.00			
Grey Fantail *Rhipidura albiscapa*	0.56	0.54	1.0		
Willie Wagtail *Rhipidura leucophrys*	0.02	0.02			
Australian Raven *Corvus coronoides*	0.00	0.04			
Satin Flycatcher *Myiagra cyanoleuca*	0.00	0.02			
Eastern Yellow Robin *Eopsaltria australis*	0.10	0.14	0.71		
Silvereye *Zosterops lateralis*	0.06	0.08	0.75		
Mistletoebird *Dicaeum hirundinaceam*	0.00	0.02			

There were 26 non-rare species, seven of which (26%) had at least two-fold differences in atlas: regular sample reporting rate ratios and four of them warranted further investigation (15%), including three with spatially autocorrelated observations (Table 3).

The atlas sample overestimated reporting rates for species that were associated with the grassy woodland habitat along Borah Creek, including the Eastern Rosella *Platycercus eximius* (ratio = Inf., CI = 1.1–Inf.), the Australian Ringneck *Barnardius zonarius* (ratio = Inf., CI = NA), the Noisy Miner *Manorina melanocephala* (ratio = 3.7, CI = NA) (Figs 3c–e) as well as the rare Crested Pigeon *Ocyphaps lophotes* (ratio = Inf., CI = NA) and Blue-faced Honeyeater *Entomyzon cyanotis* (ratio = Inf., CI = NA). The Willie Wagtail *Rhipidura leucophrys* was recorded at five atlas sample points versus zero regular sample points; however, there was no clear spatial pattern in these observations (Fig. 3f).

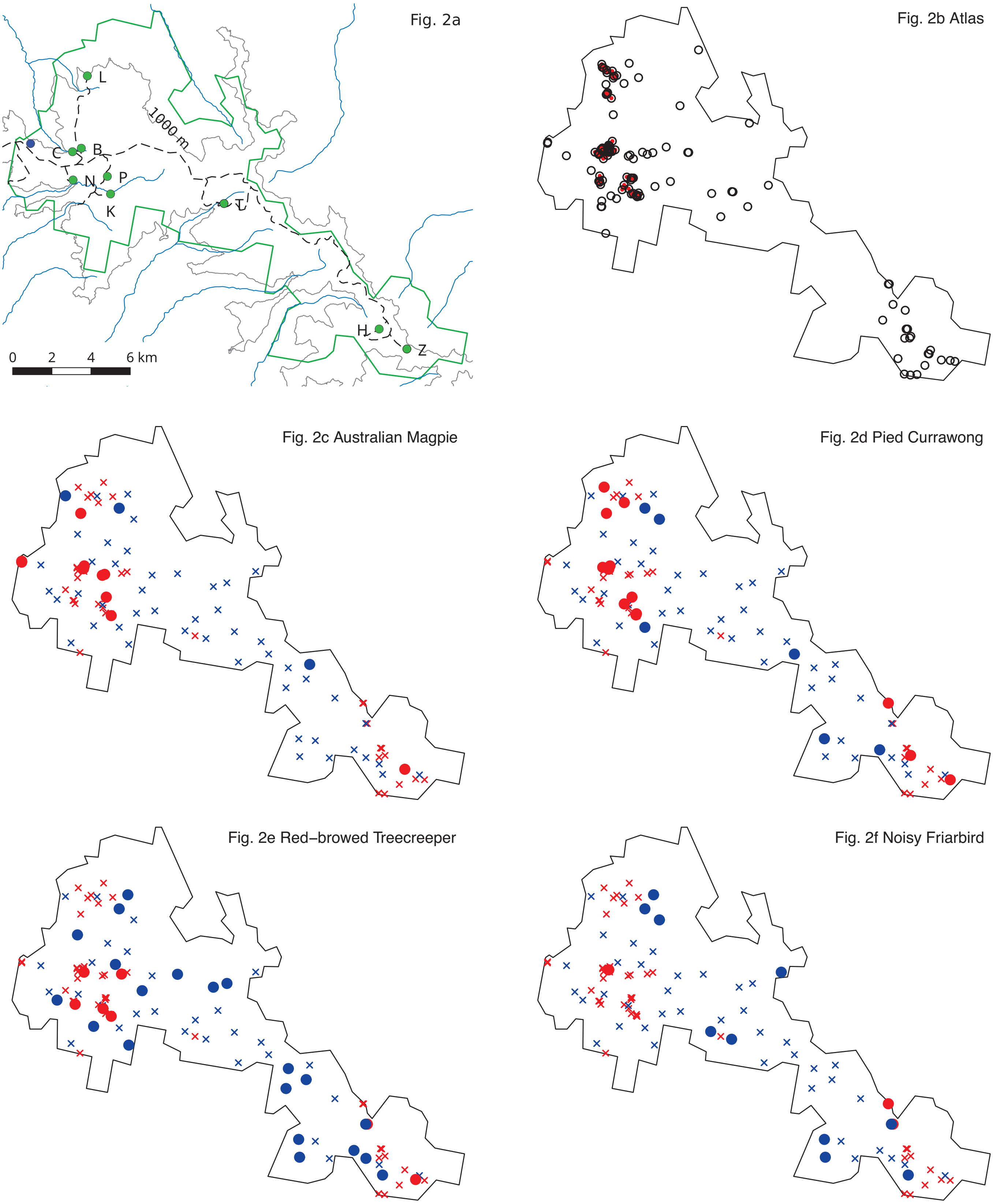

Figure 2. *Coolah Tops map (a), atlas spatial sampling pattern (n = 116) (b) and species distribution examples (c–f). The green line in (a) is the Coolah Tops National Park boundary, the grey line is a 1,000m contour, dashed black lines are unsealed roads (minor tracks and management trails not shown), blue lines are creeks and the blue circle is a dam. Green circles are tourist areas: B = The Barracks Camp, C = Cox's Creek Camp, P = The Pines Camp, H = Cattle Creek Hut, K = Brackens Hut, L = Bundella Lookout, Z = Breeza Lookout, N = Norfolk Falls and T = Talbragar River Falls. Coloured areas in (b) are clusters that were defined using a kernel density and 75% isopleth. There were no shared sites for Coolah Tops in the atlas (BirdLife Australia 2021). Red and blue circles in (c–f) are atlas sample and regular sample presences, respectively, and crosses are absences (total n = 50 in each sample).*

Table 3

Reporting rate comparisons for the Pilliga study site.

Species	Reporting rate			Spatial correlogram	
	Atlas sample	Reg. sample	Ratio (and confidence int.)	y-int.	*x*-int.
Emu *Dromaius novaehollandiae*	0.00	0.04			
Crested Pigeon *Ocyphaps lophotes*	0.04	0.00			
Painted Button-quail *Turnix varius*	0.02	0.08	**0.25** (0.04–1.6)	−0.02	NA
Galah *Eolophus roseicapillus*	0.04	0.02			
Sulphur-crested Cockatoo *Cacatua galerita*	0.02	0.00			
Little Lorikeet *Glossopsitta pusilla*	0.02	0.00			
Australian King-Parrot *Alisterus scapularis*	0.02	0.00			
Eastern Rosella *Platycercus eximius*	0.08	0.00	**Inf (1.1–Inf)**	−0.14	
Australian Ringneck *Barnardius zonarius*	0.16	0.00	**Inf**	0.92	5587
Turquoise Parrot *Neophema pulchella*	0.00	0.02			
Laughing Kookaburra *Dacelo novaeguineae*	0.04	0.00			
White-throated Treecreeper *Cormobates leucophaea*	0.20	0.22	0.91		
Brown Treeereeper *Climacteris picumnus*	0.00	0.02			
Superb Fairy-wren *Malurus cyaneus*	0.06	0.06			
Variegated Fairy-wren *Malurus lamberti*	0.18	0.30	0.60		
Chestnut-rumped Heathwren *Hylacola pyrrhopygia*	0.02	0.02			
Speckled Warbler *Chthonicola sagittata*	0.16	0.12	1.3		
Weebill *Smicrornis brevirostris*	0.40	0.48	0.83		
Yellow Thornbill *Acanthiza nana*	0.40	0.22	1.8		
Chestnut-rumped Thornbill *Acanthiza uropygialis*	0.02	0.00			
Buff-rumped Thornbill *Acanthiza reguloides*	0.18	0.16	1.1		
Inland Thornbill *Acanthiza apicalis*	0.36	0.36	1.0		
Spotted Pardalote *Pardalotus punctatus*	0.42	0.24	1.8		
Striated Pardalote *Pardalotus striatus*	0.02	0.02			
Eastern Spinebill *Acanthorhynchus tenuirostris*	0.02	0.00			
Yellow-faced Honeyeater *Lichenostomus chrysops*	0.46	0.38	1.2		
White-eared Honeyeater *Lichenostomus leucotis*	0.56	0.60	0.93		
White-plumed Honeyeater *Lichenostomus penicillatus*	0.14	0.10	1.4		
Noisy Miner *Manorina melanocephala*	0.22	0.06	**3.7**	1.28	2821
Spiny-cheeked Honeyeater *Acanthagenys rufogularis*	0.12	0.12	1.0		
Brown-headed Honeyeater *Melithreptus brevirostris*	0.08	0.06	1.3		
Blue-faced Honeyeater *Entomyzon cyanotis*	0.04	0.00			
Noisy Friarbird *Philemon corniculatus*	0.06	0.00			
Striped Honeyeater *Plectorhyncha lanceolata*	0.02	0.06			
Grey-crowned Babbler *Pomatostomus temporalis*	0.04	0.02			
Spotted Quail-thrush *Cinclosoma punctatum*	0.06	0.02			
Crested Shrike-tit *Falcunculus frontatus*	0.00	0.04			
Golden Whistler *Pachycephala pectoralis*	0.06	0.10	0.60		
Rufous Whistler *Pachycephala rufiventris*	0.04	0.06			
Grey Shrike-thrush *Colluricincla harmonica*	0.28	0.20	1.4		
Dusky Woodswallow *Artamus cyanopterus*	0.00	0.04			
Grey Butcherbird *Cracticus torquatus*	0.16	0.16	1.0		
Pied Butcherbird *Cracticus nigrogularis*	0.02	0.02			
Australian Magpie *Cracticus tibicen*	0.00	0.02			
Pied Currawong *Strepera graculina*	0.00	0.02			
Grey Fantail *Rhipidura albiscapa*	0.24	0.34	0.71		
Willie Wagtail *Rhipidura leucophrys*	0.10	0.00	**Inf**	0.68	2868
Australian Raven *Corvus coronoides*	0.02	0.00			
Magpie-lark *Grallina cyanoleuca*	0.04	0.00			
Jacky Winter *Microeca fascinans*	0.12	0.10	1.2		
Eastern Yellow Robin *Eopsaltria australis*	0.28	0.40	0.70		
Silvereye *Zosterops lateralis*	0.10	0.02	**5.0** (0.81–32)	−0.01	
Mistletoebird *Dicaeum hirundinaceam*	0.04	0.08	**0.50** (0.11–2.2)	−0.05	
Double-barred Finch *Taeniopygia bichenovii*	0.00	0.02			

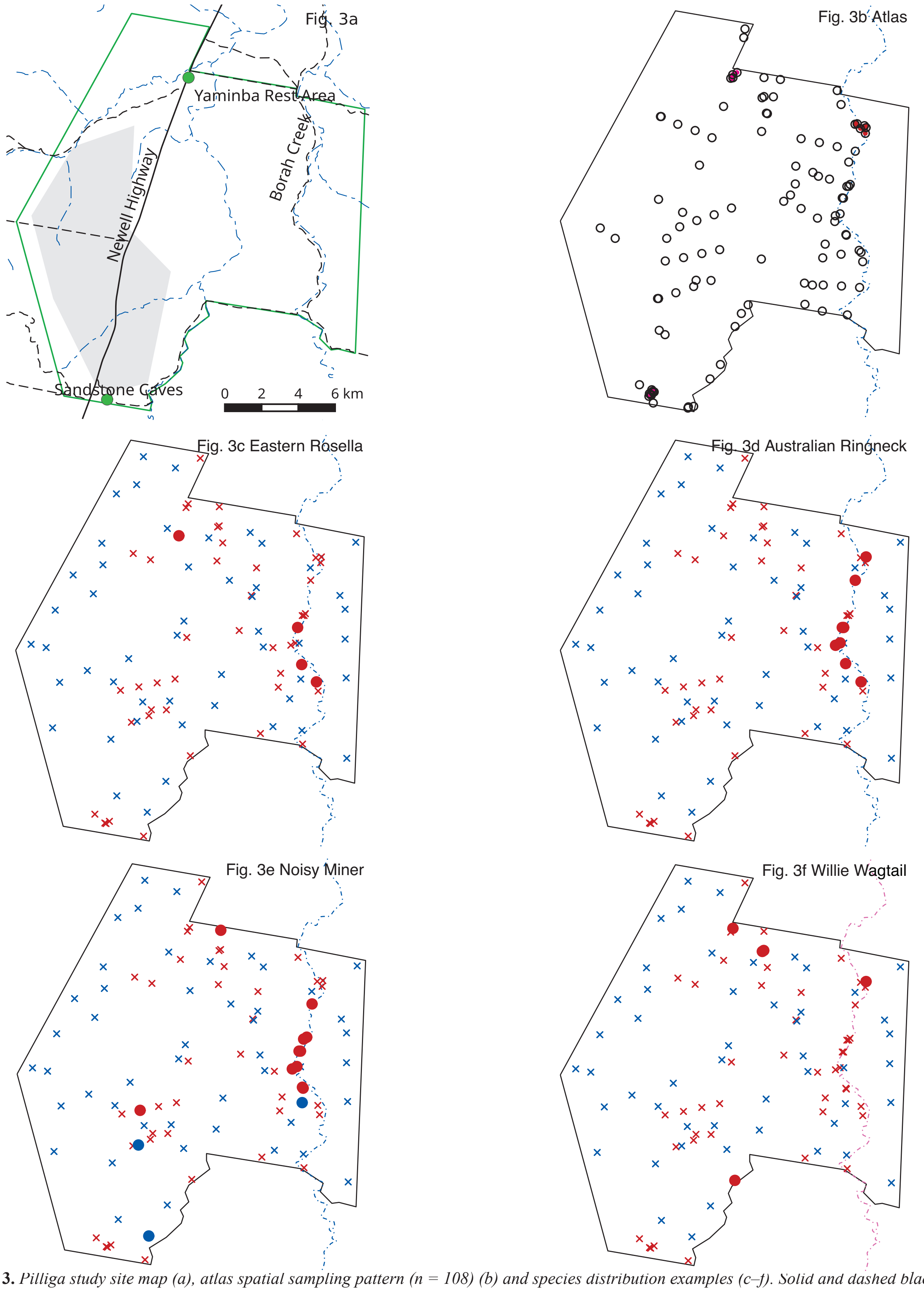

Figure 3. *Pilliga study site map (a), atlas spatial sampling pattern (n = 108) (b) and species distribution examples (c–f). Solid and dashed black lines in (a) are sealed and unsealed roads, respectively (minor tracks not shown), blue lines are intermittent creek lines and green circles are tourist areas. The grey polygon in (a) indicates an area that had been burnt at some unknown time preceding the survey. Coloured areas in (b) are clusters that were defined using a kernel density and 75% isopleth. Magenta areas correspond to shared sites in the atlas (BirdLife Australia 2021). Red and blue circles in (c–f) are atlas sample and regular sample presences, respectively, and crosses are absences (total n = 50 in each sample).*

DISCUSSION

The analysis focused on large reporting rate ratios (effect sizes) and spatial distributions as evidence of spatial sampling bias effects. Statistical comparisons were simply used as a screening tool and not to make pass/fail judgements about the 'significance' of results (Wasserstein 2019). Readers can note that sample sizes of 50 do not allow precise estimation of reporting rates. They are encouraged to study the tables and figures and make their own judgments about the interpretation of the results (Hurlbert *et al.* 2019).

At least two-fold differences in atlas: regular sample reporting rates were found for between 13–15% of non-rare bird species in this study. These percentages are higher than expected by chance at a five percent false discovery rate (*i.e.* the expected proportion of false positive results). More species with large reporting rate differences could have been detected with larger sample sizes (*e.g.* 28% of species in the Mount Lofty Ranges evaluation; Szabo *et al.* 2012). Species with strongly biased atlas reporting rates could not be predicted from habitat associations (they were not all edge and open habitat species) and large sample sizes increase precision but do not reduce bias (*e.g.* Szabo *et al.* 2012).

Between 48–72% of atlas survey points were not within any clusters and may have limited application for Australian Bird Indices. Clusters at Killawarra and Pilliga corresponded with some 'shared sites' that could be used as monitoring sites; however, those shared sites were at a tourist areas and dams and were not representative of the forests in the study sites.

REFERENCES

Agresti, A. and Min, Y. (2002). Unconditional small-sample confidence intervals for the odds ratio. *Biostatistics* **3**: 379–386.

Anderson, D.R. (2001). The need to get the basics right in wildlife field studies. *Wildlife Society Bulletin* **29**: 1294–1297.

Baddeley, A., Rubak, E. and Turner, R. (2015). *Spatial Point Patterns: Methodology and Applications with R*. Chapman and Hall/CRC Press, London, U.K.

Barrett, G., Silcocks, A., Barry, S., Cunningham, R. and Poulter, R. (2003). *The New Atlas of Australian Birds*. Royal Australasian Ornithologists Union, Hawthorn East, Victoria.

BirdLife Australia (2015). *The State of Australia's Birds 2015*. BirdLife Australia, Carlton, Victoria.

BirdLife Australia (2016–2021). *Birdata*. Available at: https://birdata.birdlife.org.au/. Last accessed 2021.

Bjørnstad, O.N. and Falck, W. (2001). Nonparametric spatial covariance functions: estimation and testing. *Environmental and Ecological Statistics* **8**: 53–70.

Bjørnstad, O.N. (2020). *ncf: Spatial Covariance Functions. Version 1.2-9*. R Foundation for Statistical Computing: Vienna, Austria. Available at: https://CRAN.R-project.org/package=ncf. Last accessed 2021.

Calenge, C. (2006). The package adehabitat for the R software: a tool for the analysis of space and habitat use by animals. *Ecological Modelling* **197**: 516–519

Clark, P.J. and Evans, F.C. (1954). Distance to nearest neighbour as a measure of spatial relationships in populations. *Ecology* **35**: 445–453.

Cunningham, R. and Olsen, P. (2009). A statistical methodology for tracking long-term change in reporting rates of birds from volunteer-collected presence-absence data. *Biodiversity Conservation* **18**: 1305–1327.

Ehmke, G. and Herman, K. (2014). Defining sites for State of Australia's Birds and Australian Bird Indices and potentially for an ongoing priority fixed site monitoring network for Australia. Discussion paper, BirdLife Australia, Carlton, Victoria. (unpub.)

Google LLC. (2005–2021). 'Google Maps'. Available at: https://www.google.com.au/maps/. Last accessed 2021.

Hurlbert, S.H., Levine, R.A. and Utts, J. (2019). Coup de grâce for a tough old bull: "statistically significant" expires. *The American Statistician* **73** Supp. 1: 352–357.

QGIS Development Team. (2009–2021). *QGIS Geographic Information System*. Open Source Geospatial Foundation Project: Delaware, U.S.A. Available at: https://qgis.org/. Last accessed 2021.

R Core Team. (2000–2021). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing: Vienna, Austria. Available at: https://www.R-project.org/. Last accessed 2021.

Scherer, R. (2018). *PropCIs: Various Confidence Interval Methods for Proportions*. *Version 0.3-0*. R Foundation for Statistical Computing: Vienna, Austria. Available at: https://CRAN.R-project.org/package=PropCIs. Last accessed 2021.

Szabo, J.K., Vesk, P.A., Baxter, P.W.J. and Possingham, H.P. (2010). Regional avian species declines estimated from volunteer-collected long-term data using List Length Analysis. *Ecological Applications* **20**: 2157–2169.

Szabo, J.K., Vesk, P.A., Baxter, P.W.J. and Possingham, H.P. (2011). Paying the extinction debt: woodland birds in the Mount Lofty Ranges, South Australia. *Emu* **111**: 59–70.

Szabo, J.K., Fuller, R.A. and Possingham, H.P. (2012). A comparison of estimates of relative abundance from a weakly structured mass-participation bird atlas survey and a robustly designed monitoring scheme. *Ibis* **154**: 468–479.

Wasserstein, R.L., Schirm, A.L. and Lazar, N.A. (2019). Moving to a world beyond '*p*< .05.' *The American Statistician* **73** Supp. 1: 1–19.

Wickham, H. (2016). *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag, New York, U.S.A.