

# Using citizen-collected wildlife sightings to predict traffic strike hot spots for threatened species: a case study on the southern cassowary

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## Summary

1. Assessing the causal factors underpinning the distribution and abundance of wildlife road-induced mortality can be challenging. This is particularly ubiquitous for rare or elusive species, because traffic strikes occur infrequently for these populations and information about localized abundance, distribution and movements are generally lacking. Here, we assessed whether citizen-collected sightings data may serve as a low cost and efficient means of gathering long-term animal roadside presence and road-crossing information, which could then be used to assess the causative factors and direct mitigation actions aimed at reducing wildlife traffic strike frequency.

2. We explored this principle using two decades of traffic strike records and citizen-collected sightings of the southern cassowary *Casuarius casuarius johnsonii*. Roads have bisected the cassowaries' rain forest habitat and despite considerable investment into mitigation strategies for this species, road-induced mortality is considered one of the primary threatening processes affecting the population.

3. Using a Bayesian approach and controlling for spatial autocorrelation with conditional autoregressive models, we demonstrate that traffic strikes are primarily a density-dependent process in the southern cassowary. That is, traffic strike clusters occurred along stretches of road where cassowaries were most frequently sighted. There were, however, road stretches where traffic strike frequency was greater than predicted by the number of roadside sightings, illustrating when and where density-independent processes increased the mortality potential for a road-crossing cassowary.

4. *Synthesis and applications.* This is the first time that citizen-collected sightings data have been used to systematically inform upon the abundance and distribution of wildlife traffic strike. The technique not only predicts where incidents are likely to occur but also helps us to understand the factors responsible for strike clustering. While not a replacement for systematic surveys, we highlight citizen-collected sightings data as a low-cost option when assessing contributing factors to vehicle-induced mortality. Accounting for density-dependent and density-independent processes will ensure the most effective allocation of resources when implementing wildlife traffic strike mitigation.

**Key-words:** citizen science, conservation, ratite, roads, southern cassowary *Casuarius casuarius johnsonii*, urban ecology, wildlife mortality

## Introduction

Roads are a major cause of environmental degradation and biodiversity loss (Laurance, Goosem & Laurance 2009; Laurance & Balmford 2013). In addition to habitat

loss, fragmentation and disturbance, roads and traffic are a direct source of wildlife mortality through vehicle collisions. Premature mortality due to traffic strike has been shown to affect a broad range of taxa (e.g. Fahrig *et al.* 1995; Reijnen *et al.* 1995; Gibbs & Shriver 2002; Taylor *et al.* 2002; Rao & Girish 2007; Fahrig & Rytwinski 2009; Kociolek *et al.* 2011; Coelho *et al.* 2012). In some cases,

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mortality was sufficiently high for the viability of the localized population to be jeopardized. The number and extent of road networks are predicted to expand dramatically this century, with a significant proportion projected to occur in developing countries (Fahrig & Rytwinski 2009; Laurance & Balmford 2013). It is therefore a valuable scientific endeavour to research and develop low-cost strategies for identifying the location and causation of wildlife traffic strike. In this manner, traffic strike hot spots can be identified and acted upon before the impact to the localized animal populations is irreparable.

Generally, the spatial distributions of mortality through traffic strike are non-random, with incidences clustered along particular stretches of road (Clevenger, Chruszcz & Gunson 2003; Saeki & Macdonald 2004). The reasons for traffic strike clustering have been attributed to the following: (i) a localized high density of the species (Fahrig *et al.* 1995; Barrientos & de Dios Miranda 2012), (ii) road stretches intersecting a population's thoroughfare to resources (Grilo *et al.* 2011; Coelho *et al.* 2012; Beyer *et al.* 2013) and (iii) road or roadside features such as high speed limits, large traffic volume, topography and features that impede the driver's visual distance (Fahrig *et al.* 1995; Trombulak & Frissell 2000; Laurance, Goosem & Laurance 2009). Teasing out which of these factors are responsible for the observed traffic strike clustering can be challenging, but critical for selecting appropriate mitigation actions. For example, wildlife overpasses and underpasses are expensive to construct and effective only over a very limited focal area. Consequently, they should be spared for localities where the highest frequencies of wildlife road crossings occur. In areas where wildlife road crossings are of a lower density and are more dispersed, alternative cheaper actions such as road signage, speed limits and maintenance of verge vegetation could be a more cost-effective approach. Moreover, the potential for a vehicle driver to hit a road-crossing animal may be locally increased due to environmental or topographical features (e.g. a blind corner or hill crest), requiring a different mitigation approach. There are seldom sufficient funds to instigate every mitigation action, and understanding the interaction between the distribution and abundance of wildlife road crossings and traffic strikes will aid in optimizing the allocation of limited resources.

It is challenging, however, to assess the causal factors of wildlife traffic strike clustering from the incidence of traffic strike alone. Clustering may be complicated by variations in animal behaviour associated with seasonal conditions, breeding patterns, climatic events and spatial heterogeneity in habitat types. Sparse information on population abundance and distribution can make it difficult to compare traffic strike potential across areas and timeframes (Erritzoe, Mazgajski & Rejt 2003; Kociolek *et al.* 2011; van der Ree *et al.* 2011). Furthermore, the spatial clustering of traffic strikes and naturally low densities of threatened species can lead to statistical difficulties, such as excess zeros and spatial autocorrelation (Lord, Wash-

ington & Ivan 2005; Lord 2006). Here we assess whether long-term and broad-scale information on the abundance and distribution of wildlife road crossings could provide the analytical power to determine which factors drive the abundance and distribution of traffic strike in the endangered southern cassowary *Casuarius casuarius johnsonii*.

The southern cassowary is a large flightless bird that inhabits the wet tropical rain forest regions of north-east Australia. Roads have bisected the cassowaries' rain forest habitat and despite considerable investment into strategies to reduce road mortality, traffic strike is considered one of the primary threatening processes affecting the long-term viability of the population (Queensland Parks and Wildlife Services 2001; Gibbs & Shriver 2002; Latch 2007; Goosem *et al.* 2011). Due to this predicament, local community groups have collected cassowary sightings data over 254 km of road since 1999, and the local management authorities have maintained detailed records about the location of cassowary traffic strikes going back 20 years. These data offered the opportunity to determine whether citizen-collected sightings data could provide a low-cost means of predicting long-term spatiotemporal trends in traffic strike frequency and used to highlight areas, periods and life-history stages that require more focused investment and mitigation. We hypothesized that there would be a positive correlation between the distribution of cassowary roadside sightings and the incidence of traffic strike (i.e. cassowaries would be hit more frequently by vehicles along road stretches where they were sighted more frequently). Deviations above or below this correlation would imply that other localized factors (environmental, topographical or social) were influencing the probability that a road-crossing cassowary would collide with a moving vehicle. This study is the first to use citizen-collected wildlife sightings for assessing the spatiotemporal distribution of wildlife traffic strikes and develops a probabilistic Bayesian approach to negate much of the biases associated with citizen-collected data.

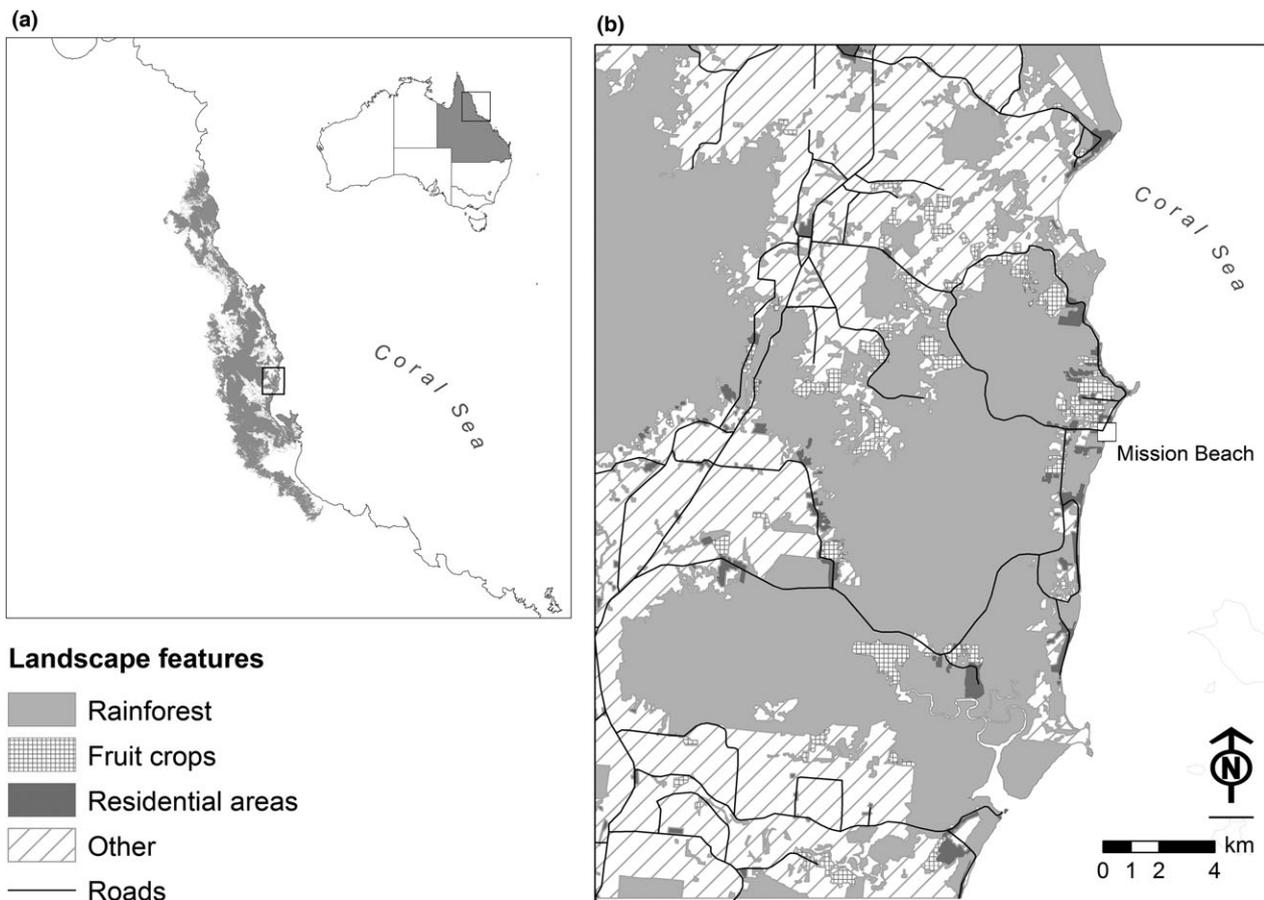
## Materials and methods

### STUDY LOCATION

The study was conducted in the area surrounding Mission Beach, Queensland, Australia, 145-045 °E 17-878 °S (Fig. 1). The area consists of a mosaic of remnant rain forest, agricultural and urban areas and contains a significant proportion of Australia's southern cassowary population (Crome & Moore 1990; Moore 2007).

### TRAFFIC STRIKE DATA

Hard copy memorandums containing fatal and non-fatal injuries to cassowaries were sourced from the Queensland Department of Environment and Heritage Protection archives. These memorandums were recorded between 1992 and 2012 by Queensland Parks and Wildlife Services



**Fig. 1.** (a) Predicted distribution of southern cassowary *Casuarius casuarius johnsonii* habitat in the Wet Tropics region of Queensland, Australia. Grey shaded area represents predicted cassowary habitat. (b) Map of the study area showing the locations of roads and landscape features.

staff and contained the date of entry, geographical location (coordinates, street address or without a location), animal age (adult, subadult and juvenile), sex and cause of injury and whether or not it was fatal. Memorandums were manually searched for both fatal and non-fatal records that occurred on roads as a result of traffic strike.

#### SIGHTINGS DATA

To ascertain the distribution and abundance of cassowary road crossings, a sightings data base was obtained from a local community conservation group [Community for Coastal and Cassowary Conservation – (C4)]. This data base was compiled from sightings of cassowaries recorded by members of the public as they moved throughout the area between 1999 and 2012. To maximize the ease by which local residents and visitors to Mission Beach could attribute a cassowary sighting to a particular geographical location, contributors were asked to record sightings on a map of the area composed of 1-km<sup>2</sup> grid cells (rows = 31, columns = 22). This resolution was chosen, as it was a simple method of location finding for non-trained observers, thereby reducing the opportunity for location error. It also represented the approximate area of a cassowary home

range (Campbell *et al.* 2012). Along with the grid cell ID, contributors were also asked to record the date and time of the sighting, and the animal's age.

For the temporal analysis, complete traffic strike and sighting records were summed across grid cells and allocated to a particular season and year. To ensure that seasons were aligned, years were classed according to the seasonal midpoint; the dates 19 November 2011 and 21 February 2012 would both be classed as Wet 2012. For the spatial analysis, records were summed across years and compiled into a raster object in ArcGIS 10 (ESRI, Redlands, CA, USA), using the same resolution, extent and cell identifiers as the C4 sightings data base.

#### ROADS AND THEIR FEATURES

Data regarding road placement were sourced from the DNRM via the Queensland Government Spatial Catalogue (Baseline roads and tracks Queensland © State of Queensland, Department of Natural Resources and Mines 2014), and the length of road features occurring within grid cells extracted using ArcGIS. Comparison between archival maps of the Mission Beach area and a visual inspection along the study roads in 2013 suggested no

major deviations from the DNRM roads layer during the study period. As the focus of our study was that of traffic-related mortalities, we restricted our analyses to only those grid cells intersecting roads (road length = 254 km;  $n = 293$  cells). Grid cells that were not bisected by roads, or fell beyond the extent where cassowaries were observed in both memorandums and the sightings data base, were eliminated from our analysis.

To assess which road features were associated with the locations of cassowary traffic strikes, roads within a 10-km radius of Mission Beach township (road length = 57 km) were divided into 1-km segments, and the number of traffic strikes per segment extracted using ArcGIS. At the centroid of each 1-km segment, the following features were recorded in the field: visual distance (m), road width (m), distance of concealing vegetation to road edge (m), speed limit ( $\text{km h}^{-1}$ ) and cassowary warning sign presence. A hand-held GPS (Garmin Oregon 550t, Olathe, KS, USA) was used to confirm position and a laser distance meter (Bushnell Yardage Pro Sport 450, Overland Park, KS, USA) used to measure distance. At the centroid of each road segment, sightings frequency was also extracted using ArcGIS.

#### HABITAT VARIABLES

Land-use data were obtained as a spatial layer (.SHP) from the Department of Natural Resources and Mines via the Queensland Government Spatial Catalogue (Land-use mapping – Queensland current © State of Queensland, Department of Science, Information Technology, Innovation and the Arts 2014). These data were classified into four land-use types: conservation and natural environments (= rain forest), irrigated perennial horticulture (= fruit crops), residential and intensive use areas (= residential) and other types (= other; Fig. 1). This 'other' land-use category included mostly non-fruiting agricultural land, pasture and wetland habitat. Land-use maps were accurate as of 1999, a midpoint of the study period; comparison with archival satellite imagery and communications with parks officials/local residents and a visual inspection along the study road in 2013 confirmed these land-use types were consistent throughout the study period. The land-use data were overlaid with a grid of the same resolution and extent as the sightings data base, and the distance from the grid centroid to each land-use type, and the proportion of each land-use types within grid cells were extracted in ArcGIS.

#### STATISTICAL ANALYSIS

First, to determine whether any temporal patterns existed within the sightings data base or the traffic strike data base, four separate generalized linear models (GLMs) were constructed. The first GLM tested whether the frequency of traffic strikes exhibited a significant annual or season trend. Here, the response variable was the total number of

traffic strikes recorded throughout the study region during that period, and the independent variables were season (dry: May to October; wet: November to April) and year (1992–2012) with a two-way interaction between these variables. The second GLM tested whether the frequency of cassowary sightings exhibited a significant annual or seasonal trend. Here, the response variable was the total number of cassowary sightings recorded during that period and the independent variables were season, year (2000–2012) and the two-way interaction between these variables. After a series of model checks, a negative binomial GLM with a logarithmic link function was selected for both the traffic strikes and the sightings data sets as it provided the best model fit whilst accommodating overdispersion. We also investigated whether traffic strike frequency throughout the study region was greater in years in which there were more sightings. These models were run separately for dry and wet season data, with traffic strike frequency (strikes per year) as the response variable and sightings frequency (sightings per year) as the independent variables.

Secondly, to evaluate which environmental factors contributed to the frequency of traffic strikes, a series of spatially explicit models were constructed. In these models, the number of traffic strikes per 1-km<sup>2</sup> grid cell was the response variable and the independent variables were natural log-transformed sightings frequency per 1-km<sup>2</sup> grid cell, the distance to fruit plantations or residential housing and the area of rain forest habitat within a grid cell. As the frequency of strikes or sightings increased with the length of road within a grid cell, road length was included in our model as an offset term. Despite limiting our sample to only those grid cells intersecting roads, the distribution of cassowary traffic strikes per cell was heavily skewed towards extra zeros (84% of cells held no records of traffic strikes). To predict the distribution of traffic strikes, we considered Poisson models both with and without a zero-inflated component (Zuur, Saveliev & Ieno 2012). This statistical framework is frequently applied in the modelling of motor vehicle crash data (Lord, Washington & Ivan 2005; Lord 2006). For the zero-inflated models, the complete distribution of the estimated counts (including zeros) was represented by two separate components. The count component was a count process modelled by a Poisson distribution, which accounted for the true zeros (i.e. a traffic strike did not occur in a grid cell) and nonzero counts given a set of parameters. The zero component was a binomial process, which modelled the probability that a false zero was observed (i.e. a traffic strike did occur but was not reported) given the same set of model parameters. For the count component, the probability that observation  $i$  of the response variable  $E(\text{Strikes})$  is a zero equals the probability that it is a false zero plus the probability that it is not a false zero times the probability of sampling a true zero in the count process. In the zero component, the probability that observation  $i$  of the response variable is a false zero is binomially distributed with probability  $\pi_i$ .

A Moran  $I$  test and the shape of the semi-variogram for the residuals of models showed traffic strike data among neighbouring grid cells to be spatially auto-correlated (Moran's  $I = 0.053$ ;  $P < 0.001$ ). That is grid cells in close proximity were more similar in traffic strike frequency, but this effect declined with increasing distance between cells. While spatial clustering is a common feature in the traffic strike literature (Lord, Washington & Ivan 2005; Lord 2006), spatial autocorrelation violates our assumption of sample independence and could lead to spurious cross correlations due to local dynamics, rather than the ecological processes of direct interest (Hanski & Woiwod 1993). In order to capture the small-scale spatially correlated patterns between adjoining cells, conditional auto-regressive (CAR) correlation structure was implemented into the model residuals following a Bayesian approach (Dormann *et al.* 2007; Zuur, Saveliev & Ieno 2012). Bayesian methods extend naturally to allow the inclusion of area-level covariates, thus enabling us to incorporate residual spatial correlation at each grid cell into our models as a function of the residual score at neighbouring cells (i.e. those sharing a common border). To illustrate how this correlation structure was implemented into our models, the equation for the zero-inflated Poisson model with CAR correlation structure (ZIP CAR) for the 1-km grid cells is given below:

$$\text{Strikes}_i \sim \text{ZIP}(\mu_i, \pi_i)$$

$$E(\text{Strikes}_i) = \mu_i \times (1 - \pi_i) \text{ and } \text{var}(\text{Strikes}_i) \\ = (1 - \pi_i) \times (\mu_i + \pi_i \times \mu_i^2)$$

$$\log(\mu_i) = \beta_0 + \beta_1 \times \ln(1 + \text{Sightings}_i) \\ + \beta_2 \times D_{\text{fruit}_i} + \beta_3 \times D_{\text{resident}_i} \\ + \beta_4 \times P_{\text{rainforest}_i} + \text{offset}(L_{\text{road}_i}) + \varepsilon_i$$

$$\text{logit}(\pi_i) = \gamma_0 + \gamma_1 \times \ln(1 + \text{Sightings}_i) \\ + \gamma_2 \times D_{\text{fruit}_i} + \gamma_3 \times D_{\text{resident}_i} \\ + \gamma_4 \times P_{\text{rainforest}_i} + \xi_i$$

where  $\mu$  is the mean,  $\pi$  is the probability of false zeros,  $E(\text{Strikes}_i)$  is the expected value of traffic strike in cell  $i$ ,  $\text{var}(\text{Strikes}_i)$  is the variance of traffic strike in cell  $i$ , and  $\alpha$  is the intercept. In the zero-inflated models, CAR correlation structure in cell  $i$  was included in both the count ( $\varepsilon$ ) and zero ( $\xi$ ) components of our model. For the count component, the residual CAR correlation  $\varepsilon_i$  at site  $i$  is modelled as a function of residuals at neighbouring sites.

$$E(\varepsilon_i) = \rho \times \sum_{j \neq i} c_{ij} \times \varepsilon_{ij}$$

Here,  $c_{ij}$  is the weighting function that depends on the distance between neighbouring sites, and  $\rho$  is the strength of the spatial correlation parameter. Models were run with and without sightings frequency to investigate how the inclusion of this term affected our conclusions.

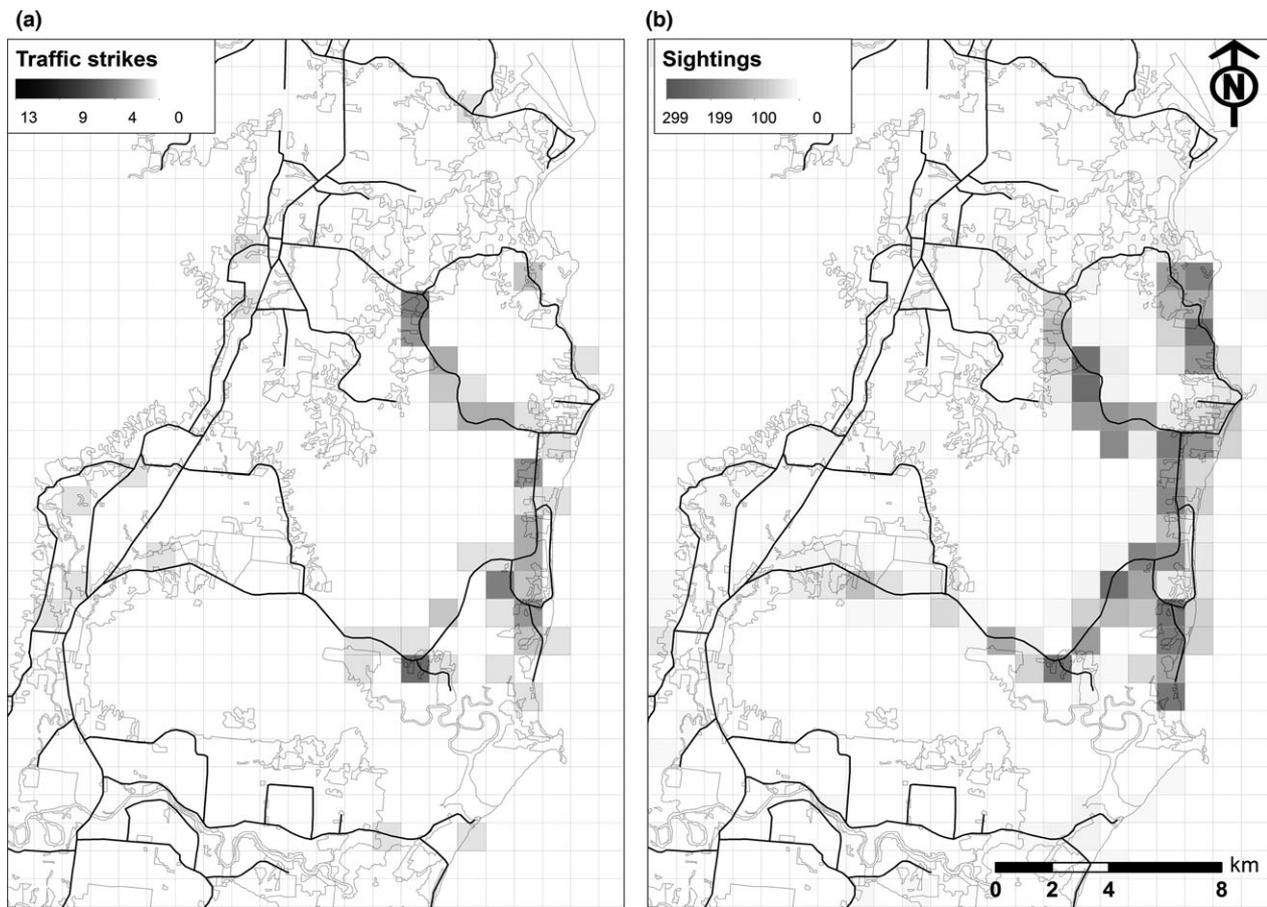
Thirdly, to investigate which road features were associated with the locations of traffic strikes, a final series of models were constructed using traffic strike frequency per 1-km road segment (rather than 1-km<sup>2</sup> grid cells) as the sampling unit. Here, the frequency of traffic strikes within a road segment was the response variable, and natural log-transformed sightings frequency, visual distance (m), road width (m), distance of concealing vegetation to road edge (m), speed limit (km h<sup>-1</sup>; factorial) and the presence of a cassowary warning sign (true/false) were used as the independent variables. Poisson GLMs were considered both with and without a zero-inflated component. As the distribution of cassowary traffic strikes along road segments produced evidence of residual spatial correlation (Moran's  $I = 0.04$ ;  $P = 0.028$ ), CAR correlation structure was implemented into the model residuals.

All statistical tests and analysis were performed using the R programming language (R Core Team 2014). Spatial autocorrelation was assessed using the 'gstat' package to generate a sample variogram of the Pearson residuals (Pebesma 2004), and the 'ape' R package to calculate the Moran's  $I$  value (Paradis, Claude & Strimmer 2004). Bayesian models were executed using the WinBUGS software (version 1.4, Imperial College and MRC, UK) and implemented in the 'R2WinBUGS' R package (Sturtz, Ligges & Gelman 2005). To account for the absence of prior information about our model parameters, we chose diffuse (non-informative) priors for all independent variables (given as a Gaussian distribution with mean = 0 and standard deviation = 1000). Posterior distributions of model parameters were obtained using Markov chain Monte Carlo (MCMC) methods. Three chains were used in the MCMC process with 1 000 000 iterations each. A burn-in of 50 000 iterations was used and the remainder thinned by 1 in 1000 draws to obtain 2850 observations for the posterior distributions. This led to acceptable convergence for all structural parameters in our Bayesian models, according to the Gelman–Rubin statistic ( $R < 1.002$ ; Gelman 1996). Following Zuur, Saveliev & Ieno (2012), estimates and 95% credibility intervals (CRI) were extracted from all parameters in both the count and zero components of the models. Those parameters containing zero in the 95% CRI were considered unimportant in predicting strike frequency. Bayesian models were selected according to the Deviance Information Criterion (DIC), where models with a small DIC were preferred.

## Results

### TEMPORAL DISTRIBUTION OF TRAFFIC STRIKES

Between 1992 and 2012, a total of 88 cassowary traffic strikes were recorded in the area surrounding Mission Beach (Fig. 2). Adult birds were the most frequent victims of traffic strike ( $n = 42$ ; 47.7% of total), followed by sub-adult ( $n = 30$ ; 34.1%) and juvenile birds ( $n = 15$ ; 17.0%).



**Fig. 2.** Frequency of cassowary traffic strikes (a) and sightings (b) in the Mission Beach area. The degree of fill within each 1-km<sup>2</sup> cell indicates an increase in strike frequency (a) or sighting (b). Figures also show the location of public roads and land-use type within the study area grid. Only those cells containing roads were included in the statistical analyses.

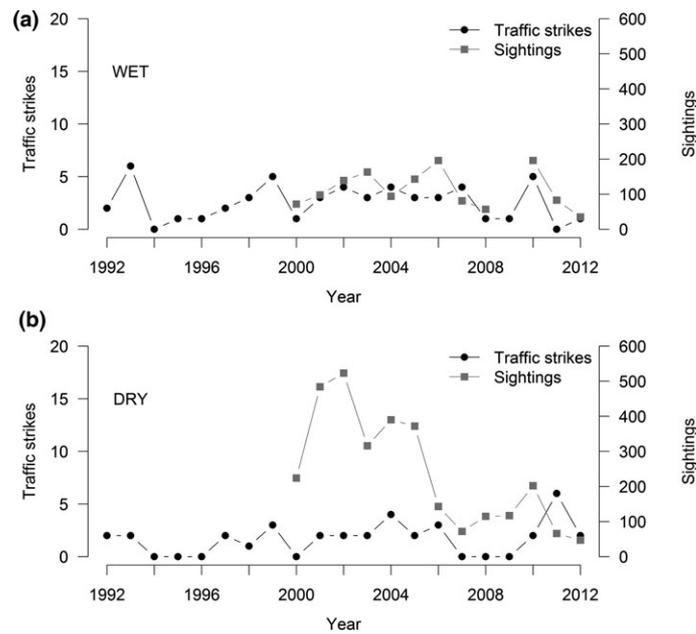
Only one individual was of unknown age class. Of the 88 birds struck by traffic, 21.6% were female, 27.3% were male, and 51.1% were of unknown sex. The mean ( $\pm$  SD) number of traffic strikes reported per year was marginally greater in the wet season (2.65 strikes  $\pm$  1.66) compared to the dry season (1.75 strikes  $\pm$  1.55). However, our GLM provided no evidence to suggest any annual ( $\chi_1^2 = 0.09$ ,  $P = 0.865$ ; Fig. 3) or seasonal ( $\chi_1^2 = 0.93$ ,  $P = 0.335$ ) trends in the frequency of traffic strikes occurring between 1992 and 2012. The interaction effect was also non-significant ( $\chi_1^2 = 1.60$ ,  $P = 0.205$ ). The frequency of traffic strikes was greatest in the dry season following a major cyclone event (Severe Tropical Cyclone Yasi), which made landfall in the Mission Beach area in February 2011.

Between 1999 and 2012, 4427 cassowary sightings were recorded along public roads in the study area (Fig. 2). This was comprised of 2438 sightings of adult birds (56.1%), 600 subadults (13.6%) and 1344 juveniles (30.3%) (~90% of the records in the sightings data base were submitted by visitors to the area). A significant interaction was found between season and survey year ( $\chi_1^2 = 7.69$ ,  $P = 0.006$ ), indicating that more sightings were recorded during the dry season earlier in the study

(Fig. 3). Less temporal variation was evident during the wet season. Traffic strike frequency was positively related to the frequency of cassowary sightings during the wet season ( $\chi_1^2 = 3.95$ ,  $P = 0.046$ ); however, there was no evidence of a significant trend in data collected during the dry season ( $\chi_1^2 = 0.13$ ,  $P = 0.718$ ).

#### CONTRIBUTION OF ENVIRONMENTAL FACTORS TO TRAFFIC STRIKE FREQUENCY

Of the models constructed to assess the contribution of environmental factors to traffic strike frequency, the Poisson CAR GLM showed the best model fit (Poisson CAR: pD = 30.54; DIC = 247.43; ZIP CAR: pD = 72.80; DIC = 274.43). The estimated posteriors for the parameters in the zero components of the ZIP CAR models were large and negative. In this scenario, the probability of a false zero converges to zero and a Poisson CAR GLM is preferred (Zuur, Saveliev & Ieno 2012). In all models, the samples for the posterior of the spatial correlation parameters did not include zero, validating our choice to incorporate CAR correlation structure (Table 1). In our Poisson CAR GLM, the 95% CRI for cassowary sightings was given as [0.48, 1.21]; there was at least a 95%



**Fig. 3.** Temporal distribution of cassowary traffic strikes and reported sightings in (a) the wet season (Oct–Apr) and (b) the dry season (May–Sep) in the Mission Beach area.

chance that cassowary sightings were positively related to traffic strike frequency (Fig. 4). There was one grid cell (grid cell = O23) where the frequency of traffic strikes ( $n = 13$ ) was considerably greater than those predicted by sightings frequency; however, the inclusion of this data point had no effect on our model outcomes (Table S1, Supporting Information). Cells containing a greater area of rain forest habitat also had a higher frequency of traffic strikes, regardless of whether sightings data was included in our model (Table 1). Distance to fruit plantations and distance to residential areas were poor predictors of traffic strike frequency.

CONTRIBUTION OF ROAD FEATURES TO TRAFFIC STRIKE FREQUENCY

Of the models constructed to assess the contribution of road features to traffic strike frequency, the Poisson CAR GLM again exhibited the best model fit (Poisson CAR:  $pD = 24.4$ ,  $DIC = 143.8$ ; ZIP CAR:  $pD = 597.8$ ,  $DIC = 1289.6$ ). The posterior distribution of the cas-

sowary sightings variable in the Poisson CAR GLM had a 95% CRI of [0.00, 1.36] and a mean of 0.67, suggesting a positive relationship existed between sightings frequency and traffic strikes (Table 2). The relationship between road features and strike frequency was weak (the CRI of the posterior distribution contained zero for all parameters), even when sightings data were excluded from the model. The samples for the posterior of the spatial correlation parameters did not include zero, again supporting the incorporation of spatially correlated patterns between neighbouring cells into our model.

Discussion

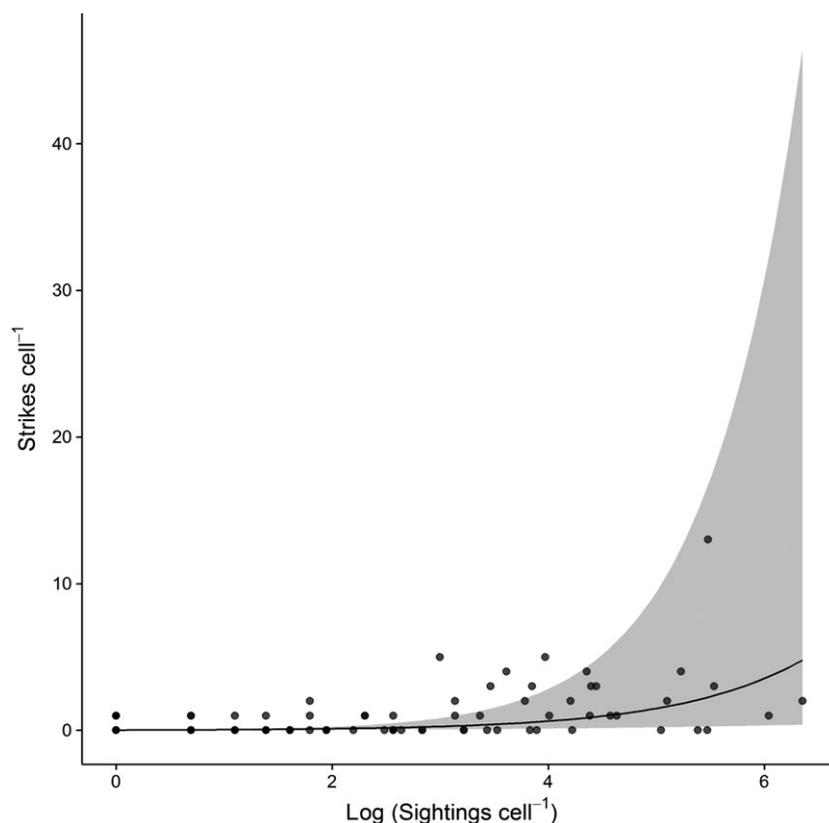
Global road construction is projected to rise by 6-fold over the next 50 years (Laurance & Balmford 2013). Many of these new roads will be constructed in developing countries within, or adjacent to, wilderness areas (Laurance, Goosem & Laurance 2009), necessitating the development of low-cost measures to reduce road-induced mortality in local wildlife populations. Our study demonstrates that citizen-collected wildlife sightings data, which can be collected at a low financial cost, can be a reliable predictor of where and when traffic strike hot spots are likely to occur. Furthermore, modelling this relationship allowed us to identify areas, time periods and life-history stages where traffic strike frequency was elevated due to density-independent processes. This information is particularly useful when deciding upon appropriate mitigation actions to reduce road-induced mortality in wildlife.

**Table 1.** Parameter estimates for the Poisson conditional autoregressive GLM fitted to traffic strikes per 1 km<sup>2</sup> cell. Estimates are based on summaries of the marginal posterior distributions (mean, SD, 2.5% and 97.5% percentiles) obtained from 1 000 000 iterations of the model. Significant effects are *italicized*

	Post. mean	Post. SD	95% credibility intervals	
Intercept	-3.793	0.3301	-4.511	-3.191
Sightings	<i>0.844</i>	<i>0.187</i>	<i>0.480</i>	<i>1.213</i>
Distance to fruit crops	-0.171	0.188	-0.530	0.206
Distance to residential	-0.082	0.176	-0.416	0.286
Area of rain forest	<i>0.492</i>	<i>0.220</i>	<i>0.049</i>	<i>0.919</i>
Spatial correlation	<i>0.523</i>	<i>0.290</i>	<i>0.029</i>	<i>0.981</i>

SPECIES-SPECIFIC FINDINGS

Of the 88 cassowary traffic strikes recorded in the Mission Beach area, the majority were adult birds. The proportion of adult birds involved in vehicle collisions closely



**Fig. 4.** Relationship between traffic strike frequency and citizen-collected sightings of cassowaries within 1-km<sup>2</sup> grid cells. The solid line is the mean of the posterior predictions from the Poisson conditional autoregressive GLM model, and the shaded area represents the 95% credible intervals. The outlier had no effect on the finding that traffic strikes were positively related to cassowary sightings.

**Table 2.** Parameter estimates from the Poisson conditional autoregressive GLM for 1-km<sup>2</sup> road segment data, based on summaries of the marginal posterior distributions [mean, SD, 2.5% and 97.5% percentiles (95% CRI)]. Significant effects are *italicized*

	Post. mean	Post. SD	95% CRI	
Intercept	-2.223	1.229	-4.612	0.007
Sightings	<i>0.670</i>	<i>0.328</i>	<i>0.003</i>	<i>1.358</i>
Visual distance	-0.122	0.289	-0.682	0.464
Road width	-0.428	0.248	-0.960	0.037
Distance to cover	0.231	0.371	-0.507	0.981
50 km h <sup>-1</sup> limit	1.085	1.733	-1.708	5.166
80 km h <sup>-1</sup> limit	2.236	1.647	-0.605	6.094
Sign presence	-0.493	0.521	-1.556	0.562
Spatial correlation	<i>0.538</i>	<i>0.274</i>	<i>0.037</i>	<i>0.965</i>

matched the frequency this age class was sighted and reported. Subadults on the other hand made up a greater proportion of traffic strike victims than expected from road-sighting frequency. This may have occurred due to observer error (i.e. subadults identified as adult birds), but could also be attributed to behavioural differences between adult and subadult birds when out from under the rain forest canopy (e.g. on road verges or crossing roads). There was no sexual bias in traffic strike frequency. This was surprising given female cassowaries typically occupy larger territories than males (Campbell *et al.* 2012), which has previously been shown to increase an animal's encounter rate with a given road network (Carr & Fahrig 2001; Fahrig & Rytwinski 2009). The roadside

sightings data cannot shed any light on this anomaly, as bird sex was not recorded in contributions to the sightings data base (to the untrained eye, male and female adult cassowaries look very similar). An absence of seasonal patterns in traffic strike frequency was also contrary to many other species that incur a high traffic-induced mortality (Coelho *et al.* 2012; Beyer *et al.* 2013). This may be explained by the highly territorial behaviour exhibited by this species (Campbell *et al.* 2012), but also by predictable sources of food located within an animal's territory. This aspect of their ecology and how variation in movement strategies might increase ranging behaviour and road encounter rate requires further investigation.

Cassowaries are long lived with a low reproductive rate, and therefore, the current rate of premature mortality is of concern (Latch 2007; Goosem *et al.* 2011). Using the citizen-collected road sightings, we were able to demonstrate that the incidence of wildlife traffic strike was driven by the frequency of road crossings, with the greatest incidence of traffic strike occurring in those areas and years where individuals were sighted most frequently. However, traffic strike and sightings records exhibited no significant temporal trends in frequency over the past two decades, suggesting that the local cassowary population is not in decline. A sustained population size despite the high occurrence of premature mortality could be the result of high fledgling success, or increased recruitment from the surrounding area. At its worst, the area may be functioning as an ecological sink for surrounding

cassowary populations. In this scenario, birds are enticed into the area by improved feeding opportunities; however, the mortality potential of this area may be elevated due to a busy road network.

Cassowaries play a significant role in attracting tourists to the area. A reduction in the incidences of traffic strike is therefore a profitable investment for local authorities. The data presented demonstrates where higher frequencies of cassowary road crossings occur and where the mortality potential is increased due to localized factors. This information should be used to decide upon which mitigation actions are appropriate, and where best to implement them. As of 2013, there were 45 cassowary-themed traffic-calming signs placed along 57 km of road in the immediate Mission Beach area. The spatial arrangement of the signage appears to be random, with many occurring along stretches of road where few or no cassowary traffic strikes have been recorded and where sightings were low or non-existent. It has been demonstrated that high levels of signage can result in sign habituation, where repeated exposure results in diminishing influence over the viewer (Wogalter & Laughery 1996). Cassowaries continue to be regular victims of traffic strike in the Mission Beach area, and a targeted approach based on robust scientific data may be a more successful strategy.

#### ASSESSING WILDLIFE TRAFFIC STRIKE FROM SIGHTINGS DATA

Citizen science initiatives are growing rapidly in popularity as low-cost alternatives to gathering species abundance and distribution data over large spatial and temporal scales (Bonney *et al.* 2014). The eBird project, for example, collects more than five million bird observations every month by engaging the global bird-watching community. The potential for error and bias in these large longitudinal data sets is poorly understood, but they are a valuable resource that is complementary to professional scientific research (Dickinson, Zuckerberg & Bonter 2010). For the current study, we discuss the spatial and temporal biases within the citizen-collected sightings data set and demonstrate how these interacted with our assessment of traffic strike clustering.

As the majority of sightings records came from visitors to the area, temporal variation in visitor numbers would have influenced survey effort. Visitor numbers in the Mission Beach area are greater in the dry season than in the wet season, and the interaction in our GLM between season and year for cassowary sightings likely reflects this increase in survey effort during the dry season. However, it would be expected that more traffic on the road during the dry season would have increased the potential for cassowary traffic strike. This was not observed in the data, and there was no significant difference in traffic strike between the wet and dry seasons. This suggests that other factors, such as driver reaction times or cassowary

biology, were inflating cassowary traffic strikes during the wet season. Studies looking to use citizen-collected sightings data to extract temporal trends must in some form control for this sampling bias.

The ability of a person within a moving vehicle to visually detect a cassowary at the roadside may also have been reduced on road stretches bordered by rain forest, compared to road stretches intersecting open grassland or urban areas. This was evident in that grid cells containing a greater area of rain forest habitat held a higher frequency of traffic strikes beyond the numbers predicted by sighting frequency. Although distance of concealing vegetation to road edge (a feature known to increase strike frequency) was not significant in our model, it does suggest that spatial variation in detection probability can be a source of sampling bias even for large-bodied and readily identifiable species such as the southern cassowary.

In the field of road ecology, authors have stressed that missing information about population densities makes it difficult to compare rates of mortality in different areas (Erritzoe, Mazgajski & Rejt 2003; Barrientos & de Dios Miranda 2012). Moreover, inaccurate estimates of vehicle-induced mortality can result if carcasses are studied in the absence of species abundance data (Kociolek *et al.* 2011). Despite the flaws inherent to citizen-collected data, this study demonstrates that it can provide an accurate predictor of when and where wildlife traffic strike clustering is likely to occur, and reveals whether clusters are a consequence of density-dependent or density-independent processes. This is because there is an intrinsic link between sighting an animal from a moving vehicle and not hitting it, and not sighting an animal from a moving vehicle and hitting it. Subsequently, biases in the distribution and abundance of wildlife traffic strike are the same as wildlife roadside sightings.

The tapping of volunteers to collect information pertaining to wildlife roadside activity is a low-cost means to gather data over broad spatial and temporal scales and can complement hypothesis-driven research into road ecology. Our approach is the first to detail how these data can be applied statistically to better understand the processes responsible for wildlife traffic strike clustering. These techniques are low cost and transferable to a wide variety of species and systems. We forecast that these methods will be particularly valuable in developing countries, where the majority of road expansion is predicted to occur (Laurance & Balmford 2013).

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## Data accessibility

The raw data, processed data and R scripts used for the analyses can be found in Dryad Digital Repository doi:10.5061/dryad.k8h4t (Dwyer *et al.* 2016).

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## Supporting Information

Additional Supporting Information may be found in the online version of this article.

**Table S1.** Poisson CAR GLM with the removal of outliers.