The relationship between reported domestic canine parvovirus cases and wild canid distribution

Alicia Van Arkel a, Mark Kelman a, Peter West b, c, Michael P. Ward a, *  

a Sydney School of Veterinary Science, The University of Sydney, Camden NSW 2570, Australia  
b New South Wales Department of Primary Industries, Orange NSW 2800, Australia  
c Centre for Invasive Species Solutions, Canberra ACT 2017, Australia

ARTICLE INFO

Keywords:  
Microbiology  
Ecology  
Wildlife ecology  
Viral disease  
Epidemiology  
Animal behavior  
Virology  
canine parvovirus  
Protoparvovirus  
Wild dog  
Fox  
Vulpes vulpes  
Spatial analysis  
Australia

ABSTRACT

Canine parvovirus (CPV) is an important and often fatal pathogen of domestic dogs. It is resistant in the environment and cross-species transmission has been indicated in some canid populations, but never in Australia. The aim of this study was to determine if an association exists between 1. reported CPV cases in domestic dogs, and 2. the wild canid distribution in New South Wales (NSW), Australia. Reported CPV cases, and reports of the presence of wild dogs and the red fox (Vulpes vulpes), were extracted from a voluntary surveillance database and a voluntary pest reporting system, respectively. A total of 1,984 CPV cases in domestic dogs, and 3,593 fox and 3,075 wild dog sightings were reported between 2011 and 2016. Postcodes in which CPV cases were reported were significantly (P = 0.0002) more likely to report wild dogs (odds ratio 2.07, 95% CI 1.41–3.03). Overall, CPV cases were significantly (P < 0.05) correlated with both fox reports (rSP 0.225) and wild dog reports (rSP 0.247). The strength of association varied by geographical region and year; the strongest correlations were found in the mid-North Coast region of New South Wales in 2016 (rSP 0.607 for wild dogs) and in 2016 (rSP 0.481 for foxes). Further serological and virological testing is required to confirm the apparent and plausible association between domestic CPV cases and wild canid distribution found in this study.

1. Introduction

Canine parvovirus (CPV) is one of the most important gastrointestinal pathogens of domestic dogs, responsible for morbidity and mortality worldwide (Clark et al., 2018). In Australia, the annual CPV caseload has been estimated to be approximately 20,000, with an euthanasia rate of 41% and an estimated treatment cost of $A1,500 per patient (Kelman et al., 2019). Although the case-fatality is >40%, it can be reduced to 5–20% with appropriate supportive therapy (Ling et al., 2012). However, such therapy is demanding and requires extensive financial, time and labour commitments; thus CPV prophylaxis is preferable and strongly recommended. Most Australian CPV cases occur in unvaccinated or incompletely vaccinated dogs (Ling et al., 2012; Altman et al., 2017).

Parvoviruses are highly stable in the environment, and CPV can persist in domestic dog populations due to its indirect faeco-oral transmission and circulation in susceptible dogs. As such, spillover transmission from domestic dogs to wild canids – including hoary foxes (Lycalopex culpaeus), crab-eating foxes (Cerdocyon thous), and maned wolves (Chrysocyon brachyurus) in Southeast Brazil, chilli foxes (Lycalopex griseus) and culpeo foxes (Lycalopex culpaeus) in the Coquimbo region of Chile and African wild dogs (Lycaon pictus) in Kenya – is considered likely (de Almeida Curi et al., 2010; Acosta-Jamett et al., 2015; Woodroffe et al., 2012). Conversely, wild canids – including urban red foxes (Vulpes vulpes) – are likely to act as reservoirs of CPV infection for domestic canine populations (Lojkic et al., 2016; Truyen et al., 1998; de Almeida Curi et al., 2010; Sobrino et al., 2008).

Within Australia, the term ‘wild dog’ is applied to wild and feral dogs, dingoes and their hybrids (Canis familiaris; Jackson et al., 2017). The only other wild canid species present is the red fox, Vulpes vulpes. Disease surveillance of Australian wild canids is rarely undertaken, and most published cases involve diseases with zoonotic potential. To date, CPV antibodies have been identified in serum of a single red fox from Camden, New South Wales in 1980 (Mulley et al., 1981), and one dingo parvovirus case has been reported (Zourkas et al., 2015). With extensive overlap of domestic and wild dog home range, and the increasingly urban distribution of red foxes and wild dogs in Australia, there is potential for transmission of CPV between and within the wild and domestic canid populations (Lojkic et al., 2016; Sparkes et al., 2016; McNeill et al., 2015).

* Corresponding author.
E-mail address: michael.ward@sydney.edu.au (M.P. Ward).

https://doi.org/10.1016/j.heliyon.2019.e02511
Received 5 June 2019; Received in revised form 8 August 2019; Accepted 19 September 2019
2405-8440/© 2019 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
The aim of the current study was to determine if an association exists between reports of domestic CPV cases and wild canid distributions, by integrating reported disease and pest species data from New South Wales. Identification of such an association would guide disease prevention strategies in regions of increased pathogen exposure, and direct future wild canid disease surveillance.

2. Materials and methods

2.1. Data source

Canine parvovirus (CPV) case data was obtained from Disease WatchDog, a surveillance tool used by veterinary clinicians and nurses. CPV cases reported within NSW with a case date between 1 January 2011 and 31 December 2016 were extracted for analysis. The minimum inclusion criteria for a CPV enteritis diagnosis was veterinary reported cases supported by at least one positive CPV diagnostic test result (ELISA, PCR, antigen; other) and clinical signs suggestive of CPV infection.

Red fox and wild dog data were supplied by FoxScan and WatchDogScan, respectively, as part of the FeralScan program funded by the Australian Government, New South Wales Department of Primary Industries and Australian Wool Innovation through the Centre for Invasive Species Solutions. FeralScan is an online community mapping program that allows individuals within Australia to record invasive animal species sightings, deaths, damage sites and other evidence such as scats, tracks and vocalisations. Each report was allocated a unique record identification number and the following data fields were extracted: latitude, longitude, inspection date, and the presence of the invasive species (red fox, wild dog). The data did not distinguish between the type of report (sighting, dead animal or damage). Reports occurring between 1 January 2011 and 31 December 2016 were extracted for analysis to match the CPV data available.

2.2. Data management

Duplicate CPV case reports and cases with a non-logical date progression were removed. Multiple parvovirus infections occurring within a single litter were assumed to be caused by a single parvovirus event. Reported fox and wild dog sighting latitude and longitude coordinates were joined in ArcMap v. 10.5 (ESRI, Redlands CA) to a polygon of NSW postcodes (2006), summed for each NSW postcode, and then joined with the sum of CPV cases reported for each NSW postcode for analysis. Postcodes were assigned to a NSW region (15) and remoteness area (major city, regional or remote) based on the Australian Bureau of Statistics (ABS) 2011 Statistical Area Level 4 (SA4), and 2011 Remoteness Area postcode indexes, respectively.

2.3. Analysis

To characterise the CPV case population, age, sex and breed distribution was described. Descriptive tables were produced for CPV patient characteristics, and to report the number of foxes, wild dogs and parvovirus cases reported by year, SA4 region and remoteness area. Proportional distribution maps were generated (ArcGIS v10.5) to display the number of CPV cases and fox and wild dogs reported by postcode.

The association between the presence or absence of domestic CPV cases, and the presence or absence of fox or wild dog sightings was assessed using a Chi-squared test of independence (Statistix v10. Analytical Software, Tallahassee FL). Odds ratios and 95% confidence intervals were also calculated for each reporting year to determine the strength of association.

Spearman’s Rank correlation analysis was performed between the number of reported CPV cases, and the number of fox or wild dog reports per postcode (SPSS Statistics v. 24). Correlation statistics and P values were reported by year for those postcodes that had confirmed parvovirus reports, and additionally by SA4 region and remoteness area for all postcodes. Correlations were considered weak ($r_{SP} < 0.30$), moderate ($0.30 < r_{SP} < 0.50$), or strong ($r_{SP} > 0.50$). A level of significance of 0.05 was used.

3. Results

3.1. CPV patient characteristics

A total of 2,523 canine parvovirus (CPV) cases were reported within NSW between 1 January 2011 and 31 December 2016. Eighty-six (3.4%) entries were removed following data cleaning, and of the remaining 2,437 cases, 453 (18.6%) failed to meet the minimum diagnostic inclusion criteria. The remaining 1,984 cases accounted for 2,605 individual CPV infections reported from 131 NSW clinics and 184 postcodes.

Most (1,778; 89.6%) reported cases involved an individual patient. Cases were predominantly young dogs (median 5.25 months); of the 1,167 cases for which age was recorded 622 (53.3%) patients were less than 6 months of age. Most cases were male; of the 1,077 non-litter cases for which sex was recorded, 594 (55.2%) were male (37 [40.7%] for litter cases). Of the 1,165 cases for which breed was reported, 605 (57.1%) were pedigree breeds, including 219 (32.9%) working dogs. One reported case involved a dingo. Most cases (687; 58.8%) were unvaccinated. For the 1,077 non-litter cases with a reported outcome, 538 (50.0%) cases recovered, and 315 (29.2%) were euthanased and 121 (11.2%) dogs died. Most cases occurred during spring (683 cases; 34.4%), followed by summer and autumn (542 cases each; 27.3%), and then winter (217 cases; 10.9%). Most CPV cases were reported in 2013 (578 cases; 29.1%) (Fig. 1).

3.2. Dingo and dingo-dog hybrid CPV reports

CPV was reported in a litter of three 6-month old dingo puppies from a wildlife park, and in a single 22-week-old dingo-dog hybrid (reported as dingo mix) in 2013. Diagnosis was confirmed with a parvovirus rapid antigen test kit for the litter case, and with an ELISA Snap Test and clinical presentation for the dingo-dog hybrid. Both the litter case and hybrid dog were previously unvaccinated.

3.3. Wild dog and fox reports

There was a total of 3,593 fox reports from 421 postcodes, and 3,075 wild dog reports from 153 postcodes between 1 January 2011 and 31 December 2016. For the postcodes that reported fox activity, the median (minimum–maximum) number of reports were 4 (1–155). Most of the fox reports occurred in 2016 (1,780 reports; 49.5%) (Fig. 1). For the postcodes that reported wild dog activity, the median...
(minimum–maximum) number of reports were 4 (1–243). Most of the wild dog reports occurred in 2016 (1,618 reports; 52.6%) (Fig. 1).

3.4. Spatial distribution of CPV, wild dog and fox reports

Most CPV reports occurred in regional New South Wales (1,504 cases; 75.8%; Table 1) and CPV cases were reported in all 15 SA4 regions (Fig. 2). A mean and median of 132.3 and 51 cases, respectively, were reported per region (Fig. 3). Fox reports occurred from city (1,833 reports; 51.0%) and regional (1,735 reports; 48.3%) New South Wales similarly, whereas most wild dog reports occurred within regional New South Wales (2,820 reports; 91.7%) (Table 1). Fox reports occurred in all 15 SA4 regions, and wild dog reports occurred in all regions except for the Illawarra (Fig. 2). There was a mean of 239.5 fox reports and 205 wild dog reports per region.

3.5. Association analysis

The presence and absence of wild dogs versus the presence or absence of domestic CPV cases by postcode for the period 2011 to 2016 were significantly associated (P = 0.0002); a significant association was also found for 2013 (P = 0.0008) and 2015 (P < 0.0001) data (Table 2). Between 2011 and 2016, postcodes with confirmed wild dog reports were 2.07 times more likely to have reported CPV cases than postcodes in which wild dogs were not reported. The presence and absence of foxes versus the presence or absence of domestic CPV cases was significantly associated by postcode in 2011 (P = 0.0009) and 2012 (P = 0.0225) (Fig. 4).

3.6. Correlation analysis

CPV cases per postcode were significantly (P < 0.01) correlated (Table 3) with the number of foxes (r_s = 0.225) and wild dogs (r_s = 0.247) reported between 2011 and 2016. Moderately positive correlations with the number of foxes in 2011 (r_s = 0.326) and 2016 (r_s = 0.481) were found, and with the number of wild dogs in 2013 (r_s = 0.332) and 2014 (r_s = 0.307).

Table 1
Number of foxes, wild dogs and canine parvovirus (CPV) cases reported by Remoteness Area and Statistical Area Level 4 (SA4) region (ABS, 2018) within New South Wales, Australia, between 1 January 2011 and 31 December 2016.

### Table 1

| Variable       | Category         | Fox          | Wild Dog       | CPV           |
|----------------|------------------|--------------|----------------|---------------|
|                |                  | Reports (%)  | Reports (%)    | Cases (%)     |
| SA4 Region     |                  |              |                |               |
| Capital Region |                  | 373          | 10.381         | 342           | 11.122        | 37            | 1.865         |
| Central Coast  |                  | 46           | 1.280          | 34            | 1.106         | 51            | 2.571         |
| Central West   |                  | 211          | 5.873          | 285           | 9.268         | 315           | 15.877        |
| Goffs Harbour  |                  | 58           | 1.614          | 119           | 3.870         | 36            | 1.815         |
| New England    |                  | 60           | 1.670          | 359           | 11.675        | 191           | 9.627         |
| Illawarra      |                  | 191          | 5.316          | 300           | 9.756         | 221           | 11.139        |
| North Coast    |                  | 69           | 1.920          | 0             | 0.000         | 21            | 1.058         |
| Murray         |                  | 82           | 2.282          | 516           | 16.780        | 41            | 2.067         |
| New England    |                  | 30           | 0.835          | 22            | 0.715         | 54            | 2.722         |
| North West     |                  | 132          | 3.674          | 707           | 22.992        | 481           | 24.244        |
| Newcastle      |                  | 46           | 1.280          | 11            | 0.358         | 30            | 1.512         |
| Richmond       |                  | 76           | 2.115          | 301           | 9.789         | 15            | 0.756         |
| Riverina       |                  | 101          | 2.811          | 32            | 1.041         | 194           | 9.778         |
| Southern       |                  | 349          | 9.713          | 27            | 0.878         | 16            | 0.806         |
| Sydney         |                  | 1769         | 49.235         | 20            | 0.650         | 281           | 14.163        |
| City           |                  | 1833         | 51.016         | 81            | 2.634         | 439           | 22.127        |
| Regional       |                  | 1735         | 48.288         | 2820          | 91.707        | 1504          | 75.806        |
| Remote         |                  | 25           | 0.696          | 174           | 5.659         | 41            | 2.067         |
| Overall        |                  | 3593         |                | 3075          |                | 1984          |                |

4. Discussion

This study contributes evidence that wild canids have a potential role in the epidemiology of canine parvovirus (CPV) within domestic dog populations, and is the first such study conducted in Australia. However, associations varied by year, geographical region and remoteness.

CPV infection in Australia’s red fox population is poorly understood (Mulley et al., 1982), however serological evidence has been detected in most species of the Vulpes and Lycalopex genera overseas, including red foxes (de Almeida Curi et al., 2010; Acosta-Jamett et al., 2015; Truyen et al., 1998; Gese et al., 2004; Allison et al., 2014). Parvovirus sequence data (Ljokić et al., 2016) suggests that bi-directional, cross-species transmission can occur between red fox and domestic dog populations (Sobrino et al., 2008). Within Australia, red foxes have also been linked to the direct or indirect transmission of parvovirus mange, hydatid tapeworms, canine adenovirus, canine heartworm and many bacterial infections to domestic animals (Saunders et al., 1995; Cooper et al., 2012; Kaewmongkol et al., 2011; Robinson et al., 2005; Marks and Bloomfield, 1998). Transmission of CPV is likely even more efficient due to its prolonged environmental stability, massive viral shedding and indirect transmission via the faeco-oral route (de Almeida Curi et al., 2010).

Similar correlations were detected between the presence of CPV cases and wild dog reports over the study period (2011–2016), and in 2013 and 2015. CPV has previously been identified (albeit with limited detail) in at least one dingo within Australia, and in dingo puppies housed in Germany between 1980 and 1984 (Zourkas et al., 2015; Steinel et al., 2001). The prevalence and pathogenesis of CPV within Australia’s wild dogs is otherwise largely undocumented. With the confirmation (via diagnostic testing) of CPV in three owned dingoes within a litter, and one dingo-dog hybrid animal in this study, it is therefore reasonable to propose that wild dogs can also be infected with CPV. Transmission of CPV between domestic and wild dogs is also plausible when considering the extensive spatial overlap of these populations within New South Wales and their likely contact (Sparkes et al., 2016). Overseas, CPV seroprevalence estimates in red fox populations in general have been observed to be much lower than those observed in wild dogs or closer relatives of domestic dogs – including African Wild Dogs (Lycaon pictus), grey wolves (Canis lupus) and coyotes (Canis latrans) (Woodroffe et al., 2012; Almberg et al., 2009; Belsare et al., 2014) — suggesting that foxes might be less important as a source of infection for other canids (Sobrino et al., 2008). Almost 5 times as many foxes were reported from the Sydney region as any other New South Wales region. Despite this high density, the correlation with CPV domestic dog reports was negative and non-significant.
significant. However, CPV reports were strongly correlated with fox reports in the Capital, Mid North Coast and New England & North West regions. This suggests that a link – if it exists – between CPV in domestic dogs and foxes might be variable. For example, increased confinement of domestic dogs within houses or backyards in urban regions, or greater domestic dog herd immunity in the Sydney region (Brady et al., 2012) might make foxes as a CPV reservoir irrelevant in such regions. Wild dog reports were strongly correlated with reported CPV cases in the Mid

![Map of canine parvovirus cases (b) reported by postcode to Disease WatchDog, and foxes (c) and wild dogs (d) reported to the online monitoring system FeralScan between 1st January 2011 and 31st December 2016 in New South Wales, Australia. Circle size is proportional to the number of cases or wild canid reports. Statistical Area Level 4 (SA4) region locations are shown for reference (a).]

![Number of foxes, wild dogs and canine parvovirus (CPV) cases reported by Statistical Area Level 4 (SA4) region (ABS, 2018) within New South Wales, Australia, between 1st January 2011 and 31st December 2016.]

Fig. 2. Map of canine parvovirus cases (b) reported by postcode to Disease WatchDog, and foxes (c) and wild dogs (d) reported to the online monitoring system FeralScan between 1st January 2011 and 31st December 2016 in New South Wales, Australia. Circle size is proportional to the number of cases or wild canid reports. Statistical Area Level 4 (SA4) region locations are shown for reference (a).

Fig. 3. Number of foxes, wild dogs and canine parvovirus (CPV) cases reported by Statistical Area Level 4 (SA4) region (ABS, 2018) within New South Wales, Australia, between 1st January 2011 and 31st December 2016.
North Coast region. In this region there is a high density of wild dog reports. A clear link between pathogen exposure and canid density has been observed overseas (Woodroffe et al., 2012) and wild dog density might be a predictor of domestic dog CPV cases. Therefore, the spatially-variable correlations observed in this study might be due to how domestic dogs are managed – promoting exposure – or due to regional differences in size and density of the wild dog and fox populations. Similarly, temporal correlations are more likely due to variations in wild canid populations, or the dynamics of vaccination and herd immunity within the domestic dog populations. There has been limited research undertaken in Australia on the home range and seasonal breeding of dingoes and wild dogs. In a recent scoping review, Gabrielle-Rivet et al. (2019) identified 24 and 14 articles on these topics, respectively. Of these, only 6 and 2 were conducted in New South Wales (Catling, 1978; Claridge et al., 2009; Harden, 1985; McBride, 2007; McLlroy et al., 1986; Purcell, 2008). Estimated home ranges are highly variable, 2.2–227 km², but generally are from 10 to 60 km² (which potentially contrasts with smaller home ranges for the red fox [Carter et al., 2012]). It has been noted that dingoes exhibit two types of movement, searching and exploratory (Harden, 1985). Long distance movements of 20 km have been reported. These estimates are consistent with likely contacts – either direct, or via contaminated environments – between domestic dogs and dingoes, wild dogs and foxes. In the present study, most CPV cases were reported in spring. In the above scoping review and publications identified conducted in New South Wales, the breeding season of dingoes has been reported as typically April to May.

Table 2
Association between the presence of canine parvovirus (CPV) cases reported to Disease WatchDog and the presence of foxes or wild dogs reported to FeralScan by New South Wales postcode between 1st January 2011 and 31st December 2016.

| Year | Variable | Category | CPV present | CPV absent | $\chi^2$ | P       | Odds ratio | 95% CI   |
|------|----------|----------|-------------|------------|---------|---------|------------|---------|
| 2011 | Fox Reports | Present | 28          | 150        | 10.98   | 0.0009  | 2.47       | 1.43–4.27|
|      |           | Absent   | 30          | 397        |         |         |            |         |
|      | Wild Dog Reports | Present | 4           | 32         | 0.10    | 0.7487  | 1.19       | 0.41–3.50|
|      |           | Absent   | 54          | 515        |         |         |            |         |
| 2012 | Fox Reports | Present | 13          | 61         | 5.21    | 0.0225  | 2.14       | 1.10–4.18|
|      |           | Absent   | 48          | 483        |         |         |            |         |
|      | Wild Dog Reports | Present | 6           | 26         | 2.80    | 0.0943  | 2.17       | 0.86–5.51|
|      |           | Absent   | 55          | 518        |         |         |            |         |
| 2013 | Fox Reports | Present | 13          | 52         | 1.20    | 0.2735  | 1.44       | 0.75–2.76|
|      |           | Absent   | 80          | 460        |         |         |            |         |
|      | Wild Dog Reports | Present | 10          | 16         | 11.13   | 0.0008  | 3.73       | 1.64–8.51|
|      |           | Absent   | 83          | 496        |         |         |            |         |
| 2014 | Fox Reports | Present | 13          | 84         | 1.40    | 0.2361  | 1.48       | 0.77–2.86|
|      |           | Absent   | 48          | 460        |         |         |            |         |
|      | Wild Dog Reports | Present | 6           | 49         | 0.05    | 0.8309  | 1.10       | 0.45–2.69|
|      |           | Absent   | 55          | 495        |         |         |            |         |
| 2015 | Fox Reports | Present | 18          | 185        | 0.36    | 0.5462  | 1.21       | 0.66–2.22|
|      |           | Absent   | 30          | 372        |         |         |            |         |
|      | Wild Dog Reports | Present | 15          | 60         | 17.06   | <0.0001 | 3.77       | 1.93–7.33|
|      |           | Absent   | 33          | 497        |         |         |            |         |
| 2016 | Fox Reports | Present | 13          | 280        | 0.82    | 0.3640  | 0.72       | 0.35–1.48|
|      |           | Absent   | 19          | 293        |         |         |            |         |
|      | Wild Dog Reports | Present | 7           | 112        | 0.10    | 0.7471  | 1.15       | 0.49–2.73|
|      |           | Absent   | 25          | 461        |         |         |            |         |
|      | Overall   | Fox Reports | 131        | 290        | 0.32    | 0.5696  | 1.17       | 0.76–1.63|
|      |           | Absent   | 53          | 131        |         |         |            |         |
|      | Wild Dog Reports | Present | 65          | 88         | 14.10   | 0.0002  | 2.07       | 1.41–3.03|
|      |           | Absent   | 119         | 333        |         |         |            |         |

Table 3
Spearman’s rank correlation analysis for New South Wales postcodes reporting canine parvovirus cases between 1 January 2011 and 31 December 2016. Coefficients and P values were calculated between the number of fox or wild dog reports, and the number of reported canine parvovirus cases per NSW postcode.

| Year | n | Fox | Wild Dog |
|------|---|-----|----------|
| 2011 | 58 | 0.326 | 0.013 | 0.296 | 0.024 |
| 2012 | 61 | 0.190 | 0.143 | 0.236 | 0.068 |
| 2013 | 93 | 0.061 | 0.562 | 0.332 | 0.001 |
| 2014 | 61 | 0.229 | 0.076 | 0.307 | 0.016 |
| 2015 | 48 | 0.238 | 0.103 | 0.171 | 0.246 |
| 2016 | 32 | 0.481 | 0.005 | 0.156 | 0.392 |
| Total | 184 | 0.225 | 0.002 | 0.247 | 0.001 |

Fig. 4. Odds ratios showing the strength of association between the presence of canine parvovirus reported to Disease WatchDog, and the presence of foxes (a) or wild dogs (b) reported to FeralScan by New South Wales postcode from 1 January 2011 to 31 December 2016. Error bars depict the lower and upper 95% confidence intervals. Odds ratios are depicted with a logarithmic scale.
While the term placed on landholders, community, industry and government users. Disease WatchDog or regularly reported CPV cases. FeralScan infected with CPV and acting as a reservoir of infection for domestic dog compounded by the presence of wild canid populations potentially likely explains increased risk of CPV cases. This situation might be partially wild canid population control. We have previously investigated vaccination and CPV case reports in rural versus urban areas of NSW potentially environmental pathogen exposure should also be considered; these include restriction of extensive domestic dog movements, reducing environmental faecal contamination by wild and domestic canids, and potentially wild canid population control. We have previously investigated vaccination and CPV case reports in rural versus urban areas of NSW (Zourkas et al., 2015). Lower levels of vaccination in rural populations likely explains increased risk of CPV cases. This situation might be compounded by the presence of wild canid populations potentially infected with CPV and acting as a reservoir of infection for domestic dog populations.

The main limitation of this study is the use of data collected by passive surveillance systems. Both Disease WatchDog and FeralScan systems relied on voluntary reporting. Not all veterinary practices were registered users of Disease WatchDog or regularly reported CPV cases. FeralScan largely involves reports by the general public, however an emphasis is placed on landholders, community, industry and government users. While the term ‘wild dog’ in this study applies to wild dogs, feral dogs, dingoes and their hybrids, reporting was at the discretion of the users of FeralScan. Fox and wild dog records are also likely to be biased towards certain locations where FeralScan community and media campaigns occurred. Underreporting, incomplete reporting and reporting bias is therefore likely within both systems (Moore and Lund, 2009). Also, this study was based on correlations between confirmed CPV cases in domestic dogs and reported wild dog and fox sightings, so are prone to ecological fallacy; sampling of wild dogs and foxes, and phylogenetic analysis and sequencing – which we are currently undertaking – would provide stronger evidence of a causal association. CPV cases in domestic dogs were confirmed using diagnostic testing and were reported by veterinarians. False diagnosed cases are very unlikely based on clinical signs and diagnostic test confirmation, and any diagnostic errors made are likely to be non-differential with respect to location (and therefore wild canid sightings). Finally, study results need to be put into the context of previous studies which demonstrated the importance of vaccination and the role of living in rural and lower socioeconomic areas on the risk of CPV (Brady et al., 2012; Zourkas et al., 2015). Vaccination, location and wild dog populations likely act within a multicausal web in which CPV occurs.

This study suggests that targeted prophylaxis is indicated in domestic dogs living in areas which support wild dog and red fox populations. Routine CPV vaccination is already recommended for dogs within New South Wales, however most cases reported in this study occurred in unvaccinated animals. Alternative methods aimed at reducing environmental pathogen exposure should also be considered; these include restriction of extensive domestic dog movements, reducing environmental faecal contamination by wild and domestic canids, and potentially wild canid population control. We have previously investigated vaccination and CPV case reports in rural versus urban areas of NSW (Jenkins et al., 2008). A centralised national disease surveillance system could therefore be beneficial in supporting future investigations of Australian pest canids and their potential influence on CPV prevalence and other diseases of domestic animals and wildlife.

Declarations

Author contribution statement

Alicia Van Arkel: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Mark Kelman, Peter West: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Michael Ward: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

The Disease WatchDog database was created by Virbac Animal Health in 2010 and gifted to the VetCompass group when it was closed in 2017; the authors wish to thank the many veterinary clinic contributors of case reports, without whom this research would not have been possible. Fox and wild dog distribution data was supplied by the FeralScan program that has been funded by the Australian Government, NSW Department of Primary Industries and Australian Wool Innovation, through the Centre for Invasive Species Solutions. The lead author completed this study as a third year Doctor of Veterinary Medicine student professionally-focused

| Variable | Category | n   | Fox    | Wild Dog | r_Sp | p  | r_Sp | p  |
|----------|----------|-----|--------|----------|------|----|------|----|
| SA4 Region | Capital Region | 36  | 0.345 | 0.039 | -0.015 | 0.93 |
|          | Central Coast | 10  | 0.42  | 0.227 | 0.338 | 0.34 |
|          | Central West | 42  | 0.284 | 0.069 | 0.295 | 0.057 |
|          | Coffs Harbour | 12  | 0.534 | 0.074 | 0.372 | 0.234 |
|          | Grafton | 29  | 0.259 | 0.175 | 0.083 | 0.668 |
|          | Far West & Orana | 29  | 0.259 | 0.175 | 0.083 | 0.668 |
|          | Hunter Valley excl Newcastle | 25  | 0.139 | 0.508 | 0.178 | 0.394 |
|          | Illawarra | 18  | -0.167 | 0.507 | – | – |
|          | Mid North Coast | 23  | 0.532 | 0.009 | 0.607 | 0.002 |
|          | Murray | 29  | -0.164 | 0.394 | 0.078 | 0.686 |
|          | New England & North West | 43  | 0.415 | 0.006 | -0.37 | 0.812 |
|          | Newcastle & Lake Macquarie | 31  | -0.0072 | 0.701 | -0.066 | 0.723 |
|          | Richmond | 21  | 0.251 | 0.273 | 0.346 | 0.125 |
|          | Tweed | 28  | 0.369 | 0.054 | 0.068 | 0.732 |
|          | Southern | 9  | 0.311 | 0.415 | 0.295 | 0.442 |
|          | Highlands & Shoalhaven | 249 | -0.048 | 0.447 | 0.036 | 0.567 |
| Remoteness Area | Sydney | 304 | -0.074 | 0.198 | 0.150 | 0.009 |
|          | City | 280 | 0.227 | <0.001 | 0.143 | 0.016 |
|          | Regional | 21  | 0.278 | 0.222 | 0.103 | 0.658 |

(autumn), with litters born between June and August (winter) (Catling et al., 1992; Purcell, 2008). In New South Wales, for red foxes these periods have been reported as June to July and August to September, respectively (McIlroy et al., 2001). Thus, the dispersal of dingo and fox puppies in spring might contribute to CPV case load at this time of the year. More detailed field studies are needed to provide evidence regarding to potential transmission of CPV between domestic dogs and dingoes and wild dogs.

The authors declare no conflict of interest.
project at the Sydney School of Veterinary Science.

References

Acosta-Jamett, G., Cunningham, A.A., Bronsvoot, B.M.d., Cleaveland, S., 2015. Serosurvey of canine distemper virus and canine parvovirus in wild canids and domestic dogs at the rural interface in the Coquimbo Region, Chile. Eur. J. Wildl. Res. 61, 329–332.

Allison, A.B., Kohler, D.J., Ortega, A., et al., 2014. Host-specific parvovirus evolution in nature is recapitulated by in vitro adaptation to different carnivore species. PLoS Pathog. 10, e1004475.

Almberg, E.S., Mesch, L.D., Smith, D.W., Sheldon, J.W., Crabtree, R.L., 2009. A serological survey of infectious disease in Yellowstone National Park’s canid community. PLoS One 4, e7042.

Altman, K.D., Kelman, M., Ward, M.P., 2017. Are vaccine strain, type or administration protocol risk factors for canine parvovirus vaccine failure? Vet. Microbiol. 210, 8–16.

Australian Bureau of Statistics, 2011. Socio-economic Advantage and Disadvantage. http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/by_Subject/2071.0–2016–Main Features–Socio-Economic_A dvantage_and_Disadvantage–123. (Accessed September 2018).

Belsare, A.V., Vanak, A.T., Gompper, M.E., 2014. Epidemiology of viral pathogens of free-ranging dogs and Indian foxes in a human-dominated landscape in central India. Transboundary Emerg. Dis. 61 (Suppl 1), 78–86.

Brady, S., Norris, J.M., Kelman, M., Ward, M.P., 2012. Canine parvovirus in Australia: the role of socio-economic factors in disease clusters. Vet. J. 193, 522–528.

Carter, A., Luck, G.W., McDonald, S.P., 2012. Ecology of the red fox (Vulpes vulpes) in an agricultural landscape. 2. Home range and movements. Aust. Mammal. 34, 175–187.

Catling, P.C., 1978. Dingo movements in South-eastern New South Wales. In: Working Papers of the Australian Vertebrate Pest Control Conference, Canberra, pp. 40–42.

Catling, P.C., Corbett, L.K., Newsome, A.E., 1992. Reproduction in captive and wild dingoes (Canis familiaris dingo) in temperate and arid environments of Australia. Wildl. Res. 19, 195–209.

Claridge, A.W., Mills, D.J., Hunt, R., Jenkins, D.J., Bean, J., 2009. Satellite tracking of wild dogs in south-eastern mainland Australia: implications for management of a problematic top-order carnivore. For. Ecol. Manag. 258, 614–622.

Clark, N.J., Seddon, J.M., Kyaw-Tanner, M., et al., 2018. Emergence of canine parvovirus subtype 2b (CPV-2b) infections in Australian dogs. Infect. Genet. Evol. 50, 50–55.

Cooper, A., Goullet, M., Mitchell, J., Ketheesan, N., Govan, B., 2012. Wild canids, domestic dogs and their pathogens in Southeast Brazil: disease threats for canid conservation. Biodivers. Conserv. 19, 3513–3524.

Gabrielle-Bivet, V., Arsenault, J., Wilhelm, B., Newsome, T., Ward, M.P., Brookes, V.J., 2019. A scoping review of dingo and wild-living dog ecology and biology in Australia to inform parameterisation for disease spread. Front. Vet. Sci. 6, 47.

Gee, E.M., Karki, S.M., Klavetter, M.L., Schauster, E.R., Kitchen, A.M., 2004. Serologic survey for canine infectious diseases among sympatric swift foxes (Vulpes velox) and coyotes (Canis latrans) in southeastern Colorado. J. Wildl. Dis. 40, 741–748.

Harden, R.H., 1985. The ecology of the dingo in north-eastern New South Wales. I. Movements and home range. Aust. Wildl. Res. 12, 25–37.

Jackson, S.M., Groves, C.P., Fleming, P.J.S., Aplin, K.P., Eldridge, M.D.B., 2017. The wayward dog: is the Australian native dog or dingo a distinct species? Zootaxa 4317, 201–224.

Jenkins, D.J., Allen, L., Goullet, M., 2008. Encroachment of Echinococcus granulosus into urban areas in eastern Queensland, Australia. Aust. Vet. J. 86, 294–300.

Kaewmongkol, G., Kaewmongkol, S., Fleming, P.A., et al., 2011. Zoonotic Bartonella species in fleas and blood from red foxes in Australia. Vector Borne Zoonotic Dis. 11, 1549–1553.

Kelman, M., Ward, M.P., Barrs, V.R., Norris, J.M., 2019. The geographic distribution and financial impact of canine parvovirus in Australia. Transboundary Emerg. Dis. 66, 299–311.

Ling, M., Norris, J.M., Kelman, M., Ward, M.P., 2012. Risk factors for death from canine parvoviral-related disease in Australia. Vet. Microbiol. 158, 280–290.

Lojkic, I., Bidin, M., Prpic, J., et al., 2016. Faecal virome of red foxes from peri-urban areas. Comparative Immunol. Microbiol. 45, 10–15.

McBride, G., 2007. An Exploratory Analysis of Landscape-Level Effects on Wild Dog home Ranges and Core Areas: A Case Study at Kosciuszko National Park, and Bago and Maragle State Forest. Master of Environmental Science thesis. Australian National University, Canberra.

McIroy, J.C., Copper, R.J., Gifford, E.J., Green, B.F., Newgrain, K.W., 1986. The effect on wild dogs Canis familiaris familiaris of 1080 poisoning campaigns in Kosciuszko national park New South Wales Australia. Aust. Wildl. Res. 3, 535–544.

McIroy, J., Saunders, G., Hinds, L.A., 2001. The reproductive performance of female red foxes, Vulpes vulpes, in central-western New South Wales during and after a drought. Can. J. Zool. 59, 545–553.

McVeil, A.T., Leung, L.K.P., Goullet, M.S., Gentile, M.N., Allen, B.L., 2016. Dingoes at the doorstep: home range sizes and activity patterns of dingoes and other wild dogs around urban areas of North-Eastern Australia. Animals 6, 48.

Marks, C.A., Bloomfield, T.E., 1998. Canine heartworm (Dirofilaria immitis) detected in red foxes (Vulpes vulpes) in urban Melbourne. Vet. Parasitol. 78, 147–154.

Moore, G.E., Lund, E., 2009. Disease reporting and surveillance: where do companion animal diseases fit in? Vet. Clin. North Am. - Small Anim. 39, 225–240.

Mulley, R.C., Claxton, P.D., Feilen, C.P., 1981. A serological survey of some infectious diseases in the red fox (Vulpes vulpes) in New South Wales. In: Proceedings of 4th International Conference of the Wildlife. Diseases Association, Sydney, Australia, pp. 44–46.

Purcell, B.V., 2008. Intraspecific variations in spatial organisation, movement and activity. In: Order in the Pack: Ecology of Canis lupus Dingo in the Southern Greater Blue Mountains World Heritage Area. University of Western Sydney, Hawkesbury, pp. 176–237. PhD thesis.

Robinson, A.J., Cerrar, S.K., Sharma, N.W., Muller, W.J., Bradley, M.P., 2005. Prevalence of serum antibodies to canine adenovirus and canine herpesvirus in the European red fox (Vulpes vulpes) in Australia. Aust. Vet. J. 83, 356–361.

Saunders, G., Coman, B., Kinnej, J., Braysher, M., 1995. Managing Vertebrate Pests: Foxes. Australian Government Publishing Service, Canberra.

Sobrino, R., Arnal, M.C., Luso, D.F., Gortazar, C., 2008. Prevalence of antibodies against canine distemper virus and canine parvovirus among foxes and wolves from Spain. Vet. Microbiol. 126, 251–256.

Sparkes, J., Ballard, G., Fleming, P.J.S., van de Ven, R., Kortner, G., 2016. Contact rates of wild-living and domestic dog populations in Australia: a new approach. Oecologia 182, 1007–1018.

Steelin, A., Parrish, C.R., Bloom, M.E., Truyen, U., 2001. Parvovirus infections in wild carnivores. J. Wildl. Dis. 37, 594–607.

Truyen, U., Müller, T., Heidrich, R., Tackmann, K., Carmichael, L.E., 1998. Survey on viral pathogens in wild red foxes (Vulpes vulpes) in Germany with emphasis on paroviruses and analysis of a DNA sequence from a red fox parovirus. Epidemiol. Infect. 121, 433–440.

Woodroffe, R., Prager, K.C., Munson, L., et al., 2012. Contact with domestic dogs increases pathogen exposure in endangered African wild dogs (Lycaon pictus). PLoS One 7, e30099.

Zourkas, E., Ward, M.P., Kelman, M., 2015. Canine parvovirus in Australia: a comparative study of reported rural and urban cases. Vet. Microbiol. 181, 198–203.