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

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A R T I C L E I N F O

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A B S T R A C T

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 (r_{SP} 0.225) and wild dog reports (r_{SP} 0.247). The strength of association varied by geographical region and year; the strongest correlations were found in the mid-North Coast region (r_{SP} 0.607 for wild dogs) and in 2016 (r_{SP} 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 vetulus*), crab-eating foxes (*Cerdocyon thous*), and maned wolves (*Chrysocyon brachyurus*) in Southeast Brazil, chilla 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 (Lojkić 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 (Lojkić et al., 2016; Sparkes et al., 2016; McNeill et al.,

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2016). 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 WildDogScan, 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 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 ($0.30\leq r_{SP}<0.50$), or strong ($r_{SP}\geq 0.50$). 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 (1778; 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, 665 (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

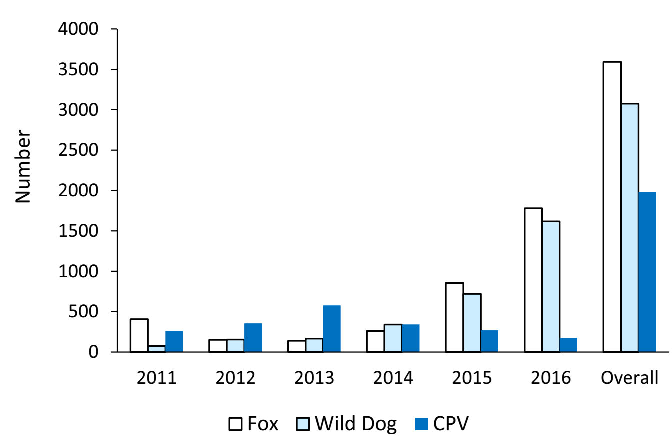

Fig. 1. Number of canine parvovirus (CPV) cases reported to Disease WatchDog, and foxes and wild dogs reported to FeralScan within New South Wales, Australia, between 1 January 2011 and 31 December 2016.

(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_{SP}=0.225) and wild dogs (r_{SP}=0.247) reported between 2011 and 2016. Moderately positive correlations with the number of foxes in 2011 (r_{SP}=0.326) and 2016 (r_{SP}=0.481) were found, and with the number of wild dogs in 2013 (r_{SP}=0.332) and 2014 (r_{SP}=0.307).

Moderately positive and significant ($P < 0.05$) correlations (Table 4) were found between the number of foxes and parvovirus cases in New England (r_{SP}=0.415) and Capital (r_{SP}=0.345) regions. Parvovirus cases were strongly and significantly ($P < 0.01$) correlated with both the number of fox (r_{SP}=0.532) and wild dog (r_{SP}=0.607) reports in the Mid North Coast region.

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 (Lojkić 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 sarcoptic 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 lups*) 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-

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.

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
	Coffs Harbour – Grafton	58	1.614	119	3.870	36	1.815
	Far West & Orana	60	1.670	359	11.675	191	9.627
	Hunter Valley excluding Newcastle	191	5.316	300	9.756	221	11.139
	Illawarra	69	1.920	0	0.000	21	1.058
	Mid North Coast	82	2.282	516	16.780	41	2.067
	Murray	30	0.835	22	0.715	54	2.722
	New England & North West	132	3.674	707	22.992	481	24.244
	Newcastle & Lake Macquarie	46	1.280	11	0.358	30	1.512
	Richmond - Tweed	76	2.115	301	9.789	15	0.756
	Riverina	101	2.811	32	1.041	194	9.778
	Southern Highlands & Shoalhaven	349	9.713	27	0.878	16	0.806
	Sydney	1769	49.235	20	0.650	281	14.163
Remoteness Area	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	–

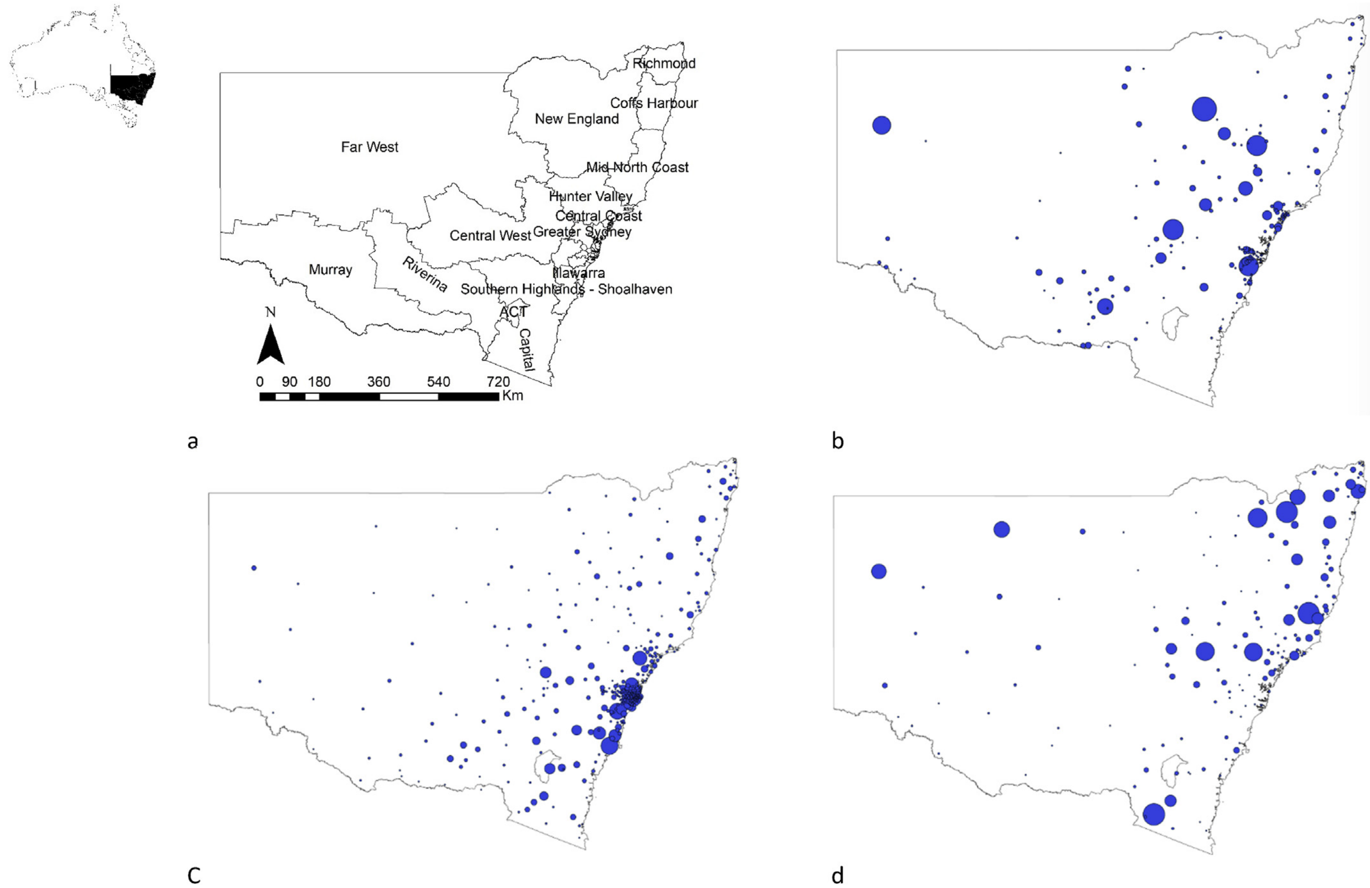

Fig. 2. Map of canine parvovirus cases (b) reported by postcode to Disease WatchDog, and foxes (c) and wild dogs (d) reported to the online monitoring system FeralScan between 1st January 2011 and 31st December 2016 in New South Wales, Australia. Circle size is proportional to the number of cases or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

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

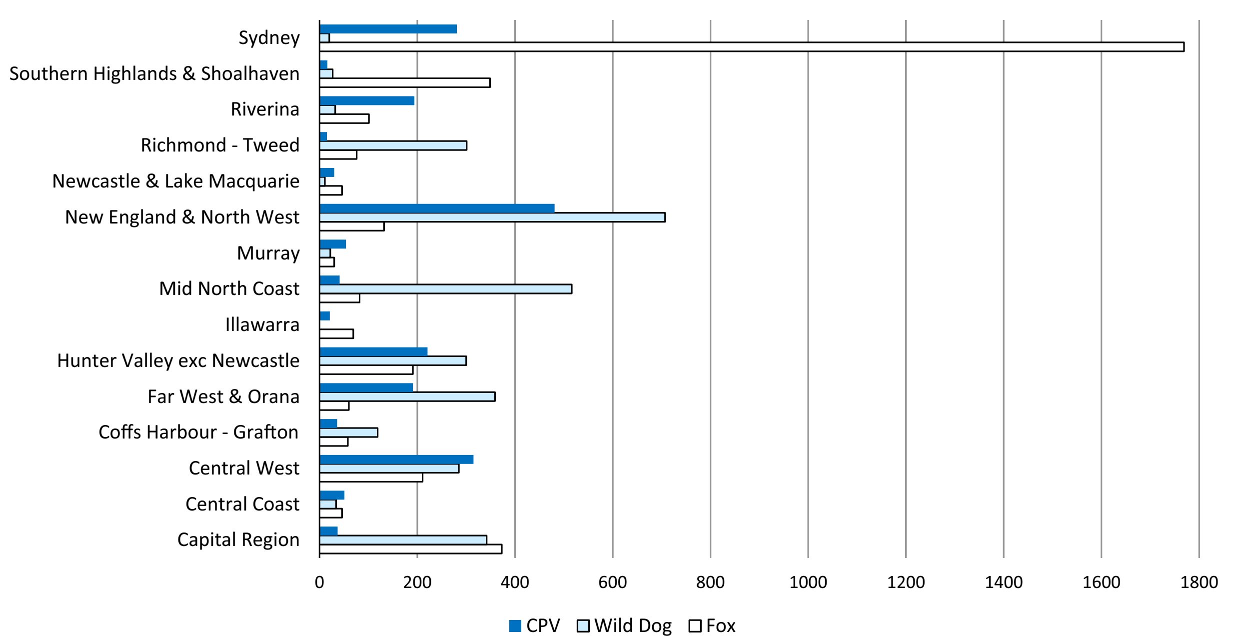

Fig. 3. Number of foxes, wild dogs and canine parvovirus (CPV) cases reported by Statistical Area Level 4 (SA4) region (ABS, 2018) within New South Wales, Australia, between 1st January 2011 and 31st December 2016.

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	χ^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	Present	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				

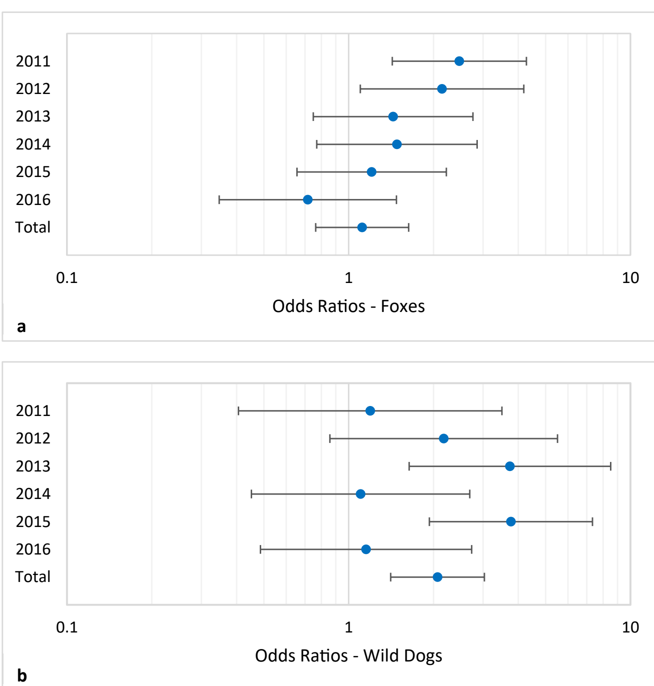

Fig. 4. Odds ratios showing the strength of association between the presence of canine parvovirus reported to Disease WatchDog, and the presence of foxes (a) or wild dogs (b) reported to FeralScan by New South Wales postcode from 1 January 2011 to 31 December 2016. Error bars depict the lower and upper 95% confidence intervals. Odds ratios are depicted with a logarithmic scale.

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, Gabriele-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, respectively (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 km^2, but generally are from 10 to 60 km^2 (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 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	
		r_{SP}	*P*	r_{SP}	*P*
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

Table 4
Spearman's rank correlation analysis by Remoteness Area and Statistical Area Level 4 (SA4) region (ABS, 2018) in New South Wales, Australia, 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. There were no wild dog reports within the Illawarra region between 2011 and 2016.

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 - Grafton	12	0.534	0.074	0.372	0.234
	Far West & Orana	29	0.259	0.175	0.083	0.668
	Hunter Valley exc 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 - Tweed	21	0.251	0.273	0.346	0.125
	Riverina	28	0.368	0.054	0.068	0.732
	Southern Highlands & Shoalhaven	9	0.311	0.415	0.295	0.442
	Sydney	249	-0.048	0.447	0.036	0.567
Remoteness Area	City	304	-0.074	0.198	0.150	0.009
	Regional	280	0.227	$<$0.001	0.143	0.016
	Remote	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.

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 (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. Falsely 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.

Despite the numerous sources of bias present, study results support a role for wild dogs and red foxes in the epidemiology of CPV disease in domestic dogs. Further serological studies and molecular viral diagnosis are required to confirm this apparent association, offering an insight into the direction of transmission. While red foxes are already abundant within major Australian cities, it is expected that pathogen exposure and potential transmission opportunities will increase as wild dogs continue to infiltrate urban Australian areas (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.

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