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Dogs on livestock farms: A cross-sectional study investigating potential roles in zoonotic pathogen transmission

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Summary

Dogs are often present on livestock farms, where they serve important management and companion roles, yet may be involved in zoonotic pathogen transmission. Numerous factors can potentially alter the risk of exposure to zoonotic pathogens, such as the dog's access to livestock, close dog–human contact and an increasing immunocompromised human population. The objective of this study was to quantify and qualify dog ownership among livestock owners, their dog husbandry and biosecurity practices, the dogs' access to livestock and potential risks for zoonotic pathogen transmission. A questionnaire was developed and mailed to 2,000 presumed Ohio livestock owners. Data were collected on demographics, dog husbandry practices, attitudes surrounding zoonotic diseases and attachment to and preventive veterinary care for the dogs. There were 446 responders who met the study inclusion criteria as an Ohio livestock farm owner, with 297 (67%) also owning dogs. Approximately 52% of dog-owning households included at least one individual at higher disease risk (i.e., <5 years, ≥65 years, diagnosed with an immunocompromising condition). Most respondents had little/no concern for disease transmission from livestock to dogs (90%), from dogs to livestock (87%) and from dogs to people (94%). Dogs were allowed access to livestock by 70% of respondents and nearly all (96%; 198) indicated at least one higher risk dog–livestock management practice. In addition, many reported never leashing or fencing their dog (61%) and rarely to never picking up dog faeces (76%). Households with higher risk members reported similar husbandry, biosecurity and concern levels as households without those members (all $p > .05$). Numerous opportunities for zoonotic pathogen transmission and low level of zoonotic disease concern suggest a need for improved education and outreach for the livestock dog-owning community, particularly for higher risk households.

KEYWORDS
biosecurity, farm dog, immunocompromised, raw diet

1 | INTRODUCTION

Dogs have been associated with livestock management since the early days of agriculture, creating a bond between dogs and humans based on shared activities and reciprocal benefits that promote the well-being of both parties (often referred to as the human–animal bond) (Russow, 2002). The human health benefits associated with the human–animal bond have been documented in numerous studies, identifying both physical and psychological benefits. Pet ownership has been shown to decrease loneliness, social isolation and stress responses such as anxiety (Friedmann & Son, 2009). Children raised in a home with pets tend to have higher self-esteem and are more autonomous than children in homes without pets (Van Houtte & Jarvis, 1995). These benefits do come with risk of pathogen transmission from the animal and its environment to the owners. People can be exposed to zoonotic organisms through animal bites or scratches, direct or indirect contact with animal blood, urine, faeces or other bodily secretions, inhalation of contaminated particles and invertebrate vectors such as arthropods (Mani & Maguire, 2009). Although the burden of zoonotic diseases attributable to pet ownership has not yet been well quantified (Whitfield & Smith, 2014), pathogen transmission does occur and awareness of the potential risk is needed for effective disease prevention (Stull, Peregrine, Sargeant, & Weese, 2012).

Having a dog on a livestock farm presents a unique opportunity for zoonotic pathogens to travel among livestock, their environment and the dog, and then potentially to the humans who likely come in close contact with the dog. Management practices that seek to limit pathogen introduction onto and from farms and any pathogen spread within the premises, typically referred to in agricultural settings as biosecurity (USDA, 2016), may not address the dog's movements or access to livestock. Numerous zoonotic pathogens, such as *Salmonella*, enterohemorrhagic *Escherichia coli*, *Leptospira* and intestinal parasites, are frequently identified in livestock populations (LeJeune & Hancock, 2001). The transmission of a number of zoonotic pathogens between dogs and livestock has been documented, including *Salmonella* (Caldow & Graham, 1998), *Echinococcus granulosus* (Bristow, Lee, Shafir, & Sorvillo, 2012) and *Brucella abortus* (Wareth et al., 2016). In situations when a specific pathogen appears to have been shared among livestock, dogs and humans, the exact transmission pathways have not been proven; at times, dogs are suggested to be involved in transmission (Hogg et al., 2009; Mateus et al., 2008). Due to limitations in animal and human health surveillance and minimal efforts dedicated to this topic, the full scope of zoonotic pathogen transmission among humans, dogs and livestock is poorly understood.

The interplay of dogs, humans and livestock is a public health concern, especially among vulnerable populations such as young children, elderly adults and immunocompromised individuals who live or work on livestock farms. The mean age of US farm principal operators has been increasing over the last three decades and is currently 58 years, with 33% aged 65 years or older (United States National Agricultural Statistics Service, 2014), placing them at higher risk for acquiring a zoonotic infection. Zoonotic pathogens can also be disseminated beyond the farm borders via human hosts. In two separate outbreaks of salmonellosis among newborns in hospital nurseries, the pathogens were traced back to outbreaks in animals on dairy farms where the mothers of the index cases lived (Bezanson, Khakhria, & Bollegraaf, 1983; Lyons, 1980).

As little is known about the potential health risks posed by dogs on livestock farms, we designed a cross-sectional descriptive study to determine general characteristics of dog–person–livestock farm interactions, specifically to quantify and qualify dog ownership among Ohio livestock owners, their biosecurity and husbandry practices, and their level of concern for zoonotic disease and potential risks for zoonotic disease transmission.

Impacts

- Dogs are often present on livestock farms and have frequent access to people, wildlife and many species of domestic animals.
- There is a low level of awareness and concern among livestock owners for transmission of zoonotic pathogens among dogs, livestock and people.
- Relaxed biosecurity and dog husbandry practices are commonplace and increase the risk of zoonotic pathogen transmission among dogs, livestock and people.

2 | MATERIALS AND METHODS

The region chosen for the study was Ohio, USA, which contains over 30,000 livestock farms of varying sizes and livestock species (United States National Agricultural Statistics Service, 2014). The population of interest was livestock farm operators, defined here as individuals owning any number of livestock. A 10-min, self-administered, written questionnaire was developed with guidance from veterinary epidemiologists, veterinarians and zoonotic disease experts (questionnaire can be obtained from the corresponding author). Using primarily closed-ended questions with multiple options or variations on the Likert scale (e.g., strongly agree, agree), the survey captured information on human, dog and farm demographics, husbandry and hygiene practices, and attachment level to and preventive veterinary care for the dogs. Skips were incorporated into the survey to streamline responses. To address the issue of multiple dog ownership, respondents were asked to answer questions for all or any of their dogs (depending on the question). The survey was pilot tested on 15 members of the public who had an agricultural background. All materials mailed to the livestock owners were approved by The Ohio State University Institutional Review Board. No incentives were offered in return for participating in the survey.

The mailing list for the survey came from the Progressive Farmer magazine with approximately 50,000 mailing subscriptions in Ohio. Sample size was based on an expected questionnaire response of 40%, with 50% dog ownership in responding households, providing a final sample size large enough to estimate a factor with a 50% prevalence and 95% confidence interval ±5%. A random sample of 2,000 presumed livestock owners was drawn using a random number generator, removing duplicate entries based on mailing address and name. In August 2014, study packets were mailed to prospective study participants. All materials were written in English and were addressed to "Farm Operator" to assist with anonymity and to encourage the same person at each farm to complete the survey. The mailed packet included a cover letter, consent letter, 10-page survey and a postage-paid return envelope. Each survey had a unique identifier for tracking purposes. The Tailored Design Method (Dillman, Smyth, Christian, & Dillman, 2009) was used to maximize response. Pre-survey postcards were mailed a few days prior to the survey packet, and reminder postcards were mailed to non-responders approximately 2 weeks after initial survey mailing. A final reminder letter and copy of the survey was mailed to non-responders in mid-October, and the study was closed in early December 2014.

2.1 | Study measures

The criteria for a survey respondent to be included in the study were ownership or management of livestock species (e.g., cattle, swine, sheep, poultry, horses) by an individual with an Ohio address. Demographic information and reported medical history information were used to categorize households into "higher risk" (at least one individual that was under the age of 5 years, greater than or equal to 65 years of age or had been reportedly diagnosed with an immunocompromising condition such as cancer, diabetes, organ transplant or HIV/AIDS) or "lower risk" (all members were between 5 and 64 years of age and a negative reporting of a diagnosed immunocompromising condition). If the household had only members between 5 and 64 years of age but immunologic status was not reported, their data were not included in either risk group and not included in related analyses, but were included in the overall data. "Higher risk feeding practices" were defined as feeding the dog deli meats, home killed meat, raw meat, raw eggs, raw milk or raw animal product treats (e.g., pig's ears, rawhides, bully sticks) (see Table 2). Respondents who indicated their dog had no access to livestock (hereafter referred to as "no access" group) or did not answer that question were excluded from the dog–livestock interaction management analysis. The remaining respondents allowed at least one dog to have some livestock contact (minimum of roaming the pastures *and* drinking from a lake or stream on the farm) and thus comprised the "access" group. When analysing the dog–livestock interactions, "higher risk management practices" were defined as reporting one or more of the following: allowing the dog to roam the pastures, access the livestock stalls or pens, sick or isolation pens, or livestock bedding, have immediate access to new livestock or eating by-products such as placentas or testicles (see Table 4). Level of veterinary care for the dog was divided into two categories based on the responses to the following three questions: "Do all the dogs get an annual examination by a veterinarian?" "Do you take the dogs to a veterinarian's office to be examined?" and "Does the farm veterinarian examine or treat the dogs?" If a respondent answered yes to at least one of the questions, they were included in the "established veterinary care category." If a respondent answered no to all three questions, they were included in the "no established veterinary care" category.

2.2 | Data analysis

Data were entered into an ACCESS 2013 database (Microsoft Corp., Redmond, WA, USA) and analysed using OPENEPI 3.03a (Dean, Sullivan, & Soe, 2015). Farm and household demographic information was analysed for all reported livestock farm operators. Animal species that respondents listed under the "other" category were excluded from analysis. Respondents who did not also own dogs were excluded from further analysis.

Data were combined for several questions that used categorical scales due to low numbers of responses in some categories. The "always/usually" and "sometimes" responses were combined and compared to the "rarely/never" responses. For the questions regarding frequency of a behaviour, "daily" and "several times per week" were combined and "less than one time per week" and "never" were combined and then compared to each other. For questions about how concerned the respondent was, "very concerned," "concerned" and "somewhat concerned" were combined as were "minimally concerned" and "not at all concerned."

Descriptive statistics were calculated for all variables. Comparison of variables between "higher risk" and "lower risk" households and "access" versus "no access" households were performed using chi-square analysis or Fisher's exact test when the cell expected minimum frequencies were not met (Rosner, 2011). "Do not know" and "Do not know/Not applicable" answers were excluded from analysis. Association between sex and neutered/spayed status was the only comparison made with the dog demographical data. Statistical significance was based on a p value < .05.

3 | RESULTS

3.1 | General characteristics of respondents

Completed surveys were returned by 446 current livestock farm operators (Figure 1), with responses from 82 of Ohio's 88 counties. Numerous livestock species and various farm sizes were represented. The median age for all livestock farm operators was 59 years (range 24–93) with a majority (80%) of male respondents. The predominant ethnicity was white (99.9%). A farming-related occupation, either full or part-time, was listed by 70% (312) of respondents. Livestock farm operators who had dogs (67%; 297) were more likely to be raising livestock primarily for personal/family use than non-dog owners (36% [106] versus 19% [28]; p = .008) and 83% (247) lived on the same property as the livestock.

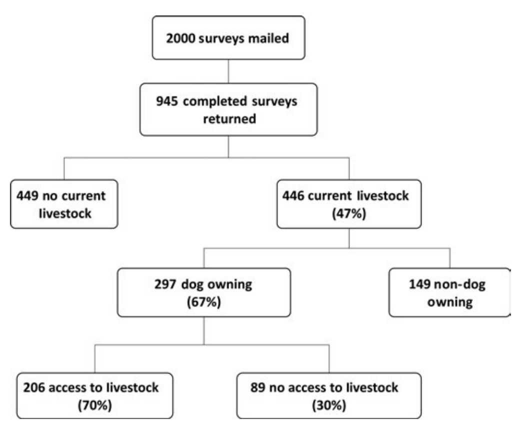

FIGURE 1 Flow diagram of returned surveys and subsets for analysis

3.2 | Characteristics of dog-owning livestock operators

For the remaining results, only those respondents that owned dogs (297) were included unless otherwise noted. Of those households, 7% (20) had a child younger than 5 years of age and 32% (94) had a person 65 years of age or older. Thirty-two per cent (92) reported one or more household members had ever been diagnosed with an immunocompromising condition (e.g., diabetes, cancer, HIV/AIDS; not answered by 5%). Thus, the majority of dog-owning livestock operators (52%; 153) lived in a household classified as "higher risk" for zoonotic diseases based on member ages and reported disease/immune status. For all respondents ($N = 446$), dog ownership was not associated with higher/lower household risk (Table 1; $p = .096$).

The majority of dog-owning respondents had cattle (79%; 235), with 52% (154) having pre-weaned calves. Horses were reported by 24% (70) of respondents, 20% (61) reported having chickens and 20% (58) reported having swine. The other livestock categories (sheep, goats, llamas/alpacas, rabbits, ducks/turkeys) were reported by fewer than 10% of respondents. Cats were listed for 69% (205) of households with 63% (188) reporting barn cats.

TABLE 1 Household zoonotic disease risk status for dog and non-dog-owning livestock farm operators in Ohio ($N = 446$)

	N	Higher risk households[c]		Lower risk households[c]		Unable to determine[d]	
All livestock owners	446	244	55%	192	43%	10	2%
Livestock only owners[a]	149	91	61%	57	38%	1	0.7%
Livestock and dog owners[a]	297	153	52%	135	46%	9	3%
Access to livestock[b]	206	109	53%	91	44%	6	3%
No access[b]	89	41	46%	44	49%	4	4%

[a]Frequency of higher risk status did not differ between dog and non-dog-owning households (X^2, $p = .096$).
[b]Frequency of higher risk status did not differ between households where at least one dog had access to livestock and those where no dog had access to livestock (X^2, $p = .332$).
[c]Demographic information and reported medical history information were used to categorize households into "higher risk" (at least one individual that was under the age of 5 years, greater than or equal to 65 years of age or had been diagnosed with an immunocompromising condition such as cancer, diabetes, organ transplant or HIV/AIDS) or "lower risk" (all members were between 5 and 64 years of age and a negative reporting of a diagnosed immunocompromising condition).
[d]The household had only members between 5 and 64 years of age, but immunologic status was not reported. Data were not included in either risk group and were excluded from analysis.

3.3 | Dog husbandry and attachment

Respondents reported a total of 525 dogs from 297 households. Most households (52%; 156) had only one dog. Multidog households had a median of two dogs (range 2–7 dogs). Dog–dog contact occurred in 78% (108) of multidog households. Male and female dogs were equally represented, although spay/neuter was more likely for females than males (80% versus 64%; $p < .001$). The most frequent sources reported for how dogs were obtained were breeders (40%; 119) and family or friends (41%; 121), although 14% (41) of respondents had acquired a dog as a stray.

The majority of livestock operators (70%; 206) allowed their dogs to have at least some level of livestock contact, either indirect (e.g., roaming the pastures *and* drinking from a lake or stream on the farm) or greater access. Nearly all of those respondents (96%; 198) indicated they allowed at least one higher risk dog–livestock management practice. Respondents reporting dogs that had livestock contact were more likely to live on the same property as the livestock, compared to the dog-owning respondents that did not allow access to livestock (91% [187] versus 66% [59]; $p < .001$). They were also more likely to have three or more species on the property, excluding dogs (44% [90] versus 25% [22]; $p = .002$), more likely to own horses (28% [57] versus 15% [13]; $p = .015$) and less likely to own swine (16% [32] versus 29% [26]; $p = .007$) than those without access.

A high level of emotional attachment of livestock operators to their dogs was reported with 96% (283) of respondents stating they were at least somewhat attached emotionally to their dogs and 62% (182) stating they were very attached. A small minority (3%; 9) viewed at least one dog as a working dog only, although 25% (72) used a dog to herd livestock. The majority (63%; 183) of respondents considered at least one dog as a family pet only; respondents who allowed their dogs access to livestock were less likely to consider at least one dog a family pet only (56%; 113) as compared to respondents who did not allow dogs access to livestock (78%; 69) ($p < .001$).

Dogs were reportedly fed at least one higher risk food, such as raw meat, raw eggs, raw milk, deli meats, raw animal product treats or home killed meat, by 24% (71) of respondents (Table 2). More specifically, raw meat and/or raw eggs were fed by 11% (33) of respondents. These feeding practices did not significantly vary between "higher risk" and "lower risk" households (all $p > .05$). Overall, households where dogs had access to livestock were significantly more likely to feed higher risk foods than those that did not (30% [62] versus 10% [9]; $p < .001$). Dairy cattle were owned or managed by 81% (13) of the respondents who fed their dog raw milk. Dogs were fed in the kitchen by 23% (68) of respondents, and this was more common in households where the dog did not have access to livestock compared to those that did have access (31% [27] versus 20% [41]; $p = .046$).

Dogs were allowed free access to the house for sleeping at night by 24% (71) of respondents, with 13% (39) reporting the dog slept on a family member's bed. These practices did not significantly vary between "higher risk" and "lower risk" households (both $p > .05$). Dogs with livestock access were more likely to live outdoors only (58% [119] versus 39% [35]; $p = .003$), sleep in the barn overnight (38% [77] versus 13% [11]; $p < .001$) and never be leashed or fenced (61% [124] versus 36% [32]; $p < .001$) compared to dogs without access to livestock. Dogs were reported to defecate primarily in the household yard by 64% (186) of respondents and 72% (146) of respondents with dogs that had livestock access indicated the dogs defecated in the fields. When asked how frequently respondents or household members

TABLE 2 Food items reportedly fed to dogs on livestock farms in Ohio by household risk status and access to livestock

	Total[b] *N* = 296		Higher risk households[b] *N* = 152		Lower risk households[b] *N* = 134		*p* Value[c]	Access to livestock[b] *N* = 206		No access[b] *N* = 89		*p* Value[c]
Commercial dog food (dry or canned)	296	100%	152	100%	134	100%		206	100%	89	100%	
Home cooked dog food	2	0.7%	1	0.7%	1	0.7%		1	<1%	1	<1%	
Home cooked human food (table scraps)	146	49%	71	47%	70	52%	.35	112	54%	33	37%	.006
Deli meats[a]	16	5%	7	5%	9	7%	.44	14	7%	2	2%	.11
Home killed meat[a]	18	6%	10	7%	8	6%	.83	17	8%	1	<1%	.019
Raw meat[a]	21	7%	11	7%	10	8%	.94	20	10%	1	<1%	.008
Raw eggs[a]	19	6%	9	6%	9	7%	.78	17	8%	2	2%	.053
Raw animal product treats (such as pig's ears, rawhides or bully sticks)[a]	33	11%	19	12%	12	9%	.34	28	14%	5	5.6%	.046
Commercial processed pet treats	89	31%	49	32%	35	26%	.26	63	31%	25	28%	.67
Raw/unpasteurized milk[a]	16	5%	11	7%	5	4%	.20	15	7%	1	1%	.045
At least one higher risk feeding practice	71	24%	40	26%	28	21%	.28	62	30%	9	10%	<.001

[a]Denotes higher risk feeding practice.
[b]Column totals may exceed 100% as respondents could choose multiple items.
[c]Chi-square or Fisher's exact test used to compare higher versus lower risk households and access to livestock versus no access.

TABLE 3 Reported veterinary preventative care for dogs of Ohio livestock farm operators

	Total (*N* = 297)		Established veterinary care[a] (*N* = 244)		No established veterinary care[a] (*N* = 40)		*p* Value[b]
Current rabies vaccination	248	85%	225	93%	20	50%	<.001
Have had other vaccines in the last 3 years	232	80%	213	88%	15	38%	<.001
Annual heartworm prevention	212	73%	197	81%	11	28%	<.001
Flea/tick prevention programme	249	86%	215	88%	27	68%	<.001
Intestinal parasite prevention programme	205	71%	186	77%	15	38%	<.001

[a]Level of veterinary care for the dog was divided into two categories based on the responses to the following three questions: "Do all the dogs get an annual examination by a veterinarian?" "Do you take the dogs to a veterinarian's office to be examined?" and "Does the farm veterinarian examine or treat the dogs?" If a respondent answered yes to at least one of the questions, they were included in the "established veterinary care category." If a respondent answered no to all three questions, they were included in the "no established veterinary care" category.
[b]Chi-square test comparing respondents with established veterinary care to those with no established veterinary care.

picked up the dogs' faeces, 76% (156) of respondents with dogs that had livestock access noted rarely to never, compared to 64% (54) of respondents with dogs without access to livestock ($p = .024$).

3.4 | Veterinary care and biosecurity

Various levels of veterinary and preventive care of the dogs were reported. Based on answers regarding veterinary visits, 85% (244) of respondents were categorized as having an established veterinary–client–patient relationship (VCPR) involving their dog, 14% (40) were deemed not to have established veterinary care, and 1% (4) could not be determined. The presence of a VCPR positively affected all measures of preventive care for the dog (Table 3), while the respondent's desire for less expensive veterinary care was negatively associated with rabies vaccination (78% [62] versus 90% [172]; $p = .011$) and heartworm prevention (62% [49] versus 79% [150]; $p = .004$). Dogs reportedly receiving an annual veterinary examination was the only significant difference between dogs with livestock access and those without livestock access (55% [109] versus 68% [59]; $p = .022$). No difference in the presence of a veterinary relationship was noted

TABLE 4 Reported hygiene and husbandry practices of Ohio livestock farm operators

	Total (*N* = 297)			Established veterinary care[a] (*N* = 244)			No established veterinary care[a] (*N* = 40)			
	n	Yes	%	*n*	Yes	%	*n*	Yes	%	*p* Value[b]
Self-reported handwashing at least some of the time after touching dog	293	242	83%	241	200	83%	40	31	78%	.40
Fed dog at least one higher risk food	296	71	24%	244	55	22%	40	10	25%	.73
Dogs with access to livestock	206			168			28			
Dogs roam on the pastures	199	158	79%	161	128	80%	28	21	75%	.59
Dogs get into the stalls/pens with the livestock	197	140	71%	159	116	73%	28	18	64%	.35
Have sick/isolation pen on the farm	198	87	44%	161	75	47%	28	7	25%	.03
Dogs get into the sick/isolation pen	85	34	40%	73	29	40%	7	2	29%	.56
Dogs get into the livestock's bedding	190	139	73%	156	116	74%	24	14	58%	.10
Dogs eat by-products such as placentas, testicles	197	54	27%	160	39	24%	27	11	40%	.08
Dogs have immediate access to new livestock	199	91	46%	163	74	45%	28	14	50%	.65

[a]Level of veterinary care for the dog was divided into two categories based on the responses to the following three questions: "Do all the dogs get an annual examination by a veterinarian?" "Do you take the dogs to a veterinarian's office to be examined?" and "Does the farm veterinarian examine or treat the dogs?" If a respondent answered yes to at least one of the questions, they were included in the "established veterinary care category." If a respondent answered no to all three questions, they were included in the "no established veterinary care" category.
[b]Chi-square or Fisher's exact test used to compare practices of respondents that had established veterinary care versus those that did not.

between "higher risk" and "lower risk" households. The level of veterinary care did not correspond to a significant difference in the frequency of higher risk management factors or in the feeding of higher risk foods (Table 4).

Movement of dogs on and off farms was not well controlled; 52% (151) of respondents allowed other dogs, belonging to visitors, onto their farm and 12% (35) took their dog on visits to other farms. These practices were more common among livestock operators that allowed their dog access to livestock than those that did not. Dogs with access to livestock had more known contact with wildlife (61% [123] versus 18% [16]; $p < .001$) and had eaten wildlife or wildlife carcasses (31% [63] versus 6% [5]; $p < .001$) in the past 12 months compared to dogs without access.

There was minimal to no concern for disease transmission from livestock to dogs (90%; 263), from dogs to livestock (87%; 256) and from dogs to people (94%; 274). Less than 1% (3) of respondents had knowledge of anyone in the household ever becoming infected with a pathogen from the dog and none knew of a household member transmitting a disease to the dog. The lack of awareness or concern for zoonotic disease transmission was also demonstrated by the households with higher risk members reporting similar husbandry, biosecurity and concern levels to those with lower risk household members (all $p > .05$).

4 | DISCUSSION

This study addressed the movement of dogs on the farm and within the home, its interactions with livestock as well as people and the level of preventive veterinary care the dogs received. We identified several high-risk behaviours for potential zoonotic pathogen transmission among dog-owning livestock operators. For instance, 24% of respondents fed a higher risk food to their dog, including raw meat, raw eggs or raw milk. Such practices are a concern as raw food diets, even those available commercially, are frequently contaminated with *Salmonella* spp. and pose a health risk to the public (Finley et al., 2007). Another concern is cross-contamination of food preparation surfaces, as many respondents reported feeding a dog in the kitchen. Many of the higher risk feeding practices were positively associated with dogs having access to livestock.

We identified several opportunities for potential pathogen transmission due to minimal restrictions on the dogs' movements within the home and around livestock. Prolonged close dog–human contact was reported by the 13% of respondents who had dogs that slept on a family member's bed, which is similar to non-farming households where 26% had dogs that slept on a child's bed (Stull, Peregrine, Sargeant, & Weese, 2013) and 18% in an adult's bed (Chomel & Sun, 2011). Farms that did have biosecurity infrastructure in place, such as sick or isolation pens for livestock, allowed the dog access to the pens, thus undermining its infection control function. An accepted biosecurity practice of quarantining new livestock arrivals to the farm was not strictly practised as almost half of respondents allowed their dog to have immediate access to new livestock and presumable contact thereafter with existing animals on the farm and people. Further, these transmission risks may go beyond the farms as many respondents reported taking a dog off the farm, potentially exposing that dog to other dogs, other people and other environments and allowing for the spread of pathogens beyond the farm borders to naïve populations.

Altering these factors or changing behaviours to reduce associated risks is likely to present a challenge. For example, it may be difficult to eliminate raw foods as part of a dog's diet due to many owners' ideological beliefs regarding the benefits of a raw diet, regardless of the scientific evidence to the contrary (Lenz, Zhang, LeJeune, Joffe, & Kauffman, 2009). It appears that further efforts aimed at preventing the consumption of raw milk (Peterson, 2003) would have minimal impact in reducing the number of dogs fed raw milk, as most respondents who did this also owned dairy cattle. In most cases, the presence of established veterinary care for the dog was not associated with a reported reduced occurrence of higher risk practices. This is concerning as it suggests veterinarians are not discussing or recommending changes to these practices and/or farmers are not willing to make changes. Livestock farm operators may be resistant to making biosecurity changes as they reported a very low level of concern regarding zoonotic disease potentially affecting themselves or their livestock. This may be partially attributed to the fact that the respondents had frequent interaction with animals with few known related zoonotic disease events and thus low perceived risk. This is similar to the finding of low levels of concern for pet-associated disease in pet owning households in the general population (Stull et al., 2012) and with those having higher risk family members (Stull et al., 2014).

The risk of acquiring a zoonotic disease is in part affected by an individual's immune status (Mani & Maguire, 2009). Higher risk households, those with a member <5 years of age, ≥65 years of age or immunocompromised, made up 52% of our dog-owning study population. This is comparable to other studies where 52% of the general dog-owning household population were categorized as higher risk (Stull et al., 2013). Given an ageing farming population, this proportion of higher risk households may increase over time. Increased biosecurity or concern levels within this group and corresponding changes to husbandry practices are encouraged to counterbalance the rise in vulnerable farming household members. Over half of US primary farm operators list their primary occupation as "other than farming" (United States National Agricultural Statistics Service, 2014) because they are employed off the farm, extending the concern for zoonotic pathogen transmission to non-farming-related populations.

Although a number of potential zoonotic risks were evident in our study, several preventive measures to reduce zoonotic disease transmission were also reported. Most owners had spayed or neutered dogs, which eliminates sexual reproduction and reduces the risk of pathogens transmitted through the reproductive tract or birthing process. The most frequent preventive measure reported was the use of flea and tick prevention, which can be purchased over the counter. Ticks can play a role in the spread of various zoonotic pathogens in the farm environment, including *Coxiella burnetii* for which having dogs on a farm has been identified as an added risk (Cantas, Muwonge, Sareyyupoglu, Yardimci, & Skjerve, 2011). The effectiveness of flea and tick preventatives is easy to appreciate and therefore perhaps in part responsible for the high reported use. Most other preventive measures result in the absence of oftentimes otherwise uncommon or rarely noticed disease and may therefore be discounted as unimportant for the health of the dog.

Predicting the specific disease risk of the reported practices in this study is difficult. Currently, there is limited information regarding the burden of non-foodborne zoonotic disease attributable to livestock, with similar information gaps for dogs and transmission between dogs, humans and livestock species. Barriers include accurate disease diagnoses from physicians and veterinarians and determining which of several exposure routes may have led to the infection. Even if properly diagnosed, not all zoonotic diseases are reportable and disease reporting systems for humans and animals are generally separate (Day et al., 2012). Efforts are being taken by some entities to better harmonize animal and human disease reporting systems, but overall these systems are poorly integrated (Ehnert et al., 2015). Further work in this area is needed to determine the actual risk dogs on livestock farms pose. More rigorous studies that include pathogen testing of humans, livestock and companion animals with temporal and spatial determinants to evaluate likely zoonotic pathogen transmission among these groups are strongly needed.

5 | LIMITATIONS

Ohio has one of the largest Amish populations in the United States, and it is unknown if the study included any Amish participants. Although the materials were written in English, 99% of Ohio principal farm operators identify as white/non-Hispanic or Latino (United States National Agricultural Statistics Service, 2014). The number of respondents feeding higher risk foods may actually be greater than reported if respondents did not review all the food options listed when marking their answer or are unknowingly feeding a raw food or treat item. It was challenging to capture dog-level data, and some variability within a multidog household may have been missed. Non-response from non-dog owners or from dog owners with less attachment to or concern for their dog may have biased the data towards dog owners with greater attachment for their dog.

6 | CONCLUSIONS

This study described dog–livestock–human interaction on farms and pathways for potential zoonotic pathogen transmission. Based on our findings, a dog owned by a livestock operator with access to livestock is viewed and treated similar to a dog without livestock access, yet this dog has a higher potential risk of acquiring or transmitting zoonotic pathogens to household members. Outreach efforts to raise awareness of this concern should be directed towards both human and animal healthcare providers as well as the farming community. Further studies to determine the actual risks to humans involved with companion animals on livestock farms are needed.

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