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Pathways for avian influenza virus spread: GPS reveals wild waterfowl in commercial livestock facilities and connectivity with the natural wetland landscape

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Abstract

Zoonotic diseases are of considerable concern to the human population and viruses such as avian influenza (AIV) threaten food security, wildlife conservation and human health. Wild waterfowl and the natural wetlands they use are known AIV reservoirs, with birds capable of virus transmission to domestic poultry populations. While infection risk models have linked migration routes and AIV outbreaks, there is a limited understanding of wild waterfowl presence on commercial livestock facilities, and movement patterns linked to natural wetlands. We documented 11 wild waterfowl (three Anatidae species) in or near eight commercial livestock facilities in Washington and California with GPS telemetry data. Wild ducks used dairy and beef cattle feed lots and facility retention ponds during both day and night suggesting use for roosting and foraging. Two individuals (single locations) were observed inside poultry facility boundaries while using nearby wetlands. Ducks demonstrated high site fidelity, returning to the same areas of habitats (at livestock facilities and nearby wetlands), across months or years, showed strong connectivity with surrounding wetlands, and arrived from wetlands up to 1251 km away in the week prior. Telemetry data provides substantial advantages over observational data, allowing assessment of individual movement behaviour and wetland connectivity that has significant implications for outbreak management. Telemetry improves our understanding of risk factors for waterfowl–livestock virus transmission and helps identify factors associated with coincident space use at the wild waterfowl–domestic livestock interface. Our research suggests that even relatively small or isolated natural and artificial water or food sources in/near facilities increases the likelihood of attracting waterfowl, which has important consequences for managers attempting to minimize or prevent AIV outbreaks. Use and interpretation of telemetry data, especially in near-real-time, could provide key information for reducing virus transmission risk between waterfowl and livestock, improving protective barriers between wild and domestic species, and abating outbreaks.

KEYWORDS
AIV, domestic poultry, GPS telemetry, migration, surrogate habitat, wild birds, wild-domestic interface, zoonotic diseases

1 | INTRODUCTION

Zoonotic diseases, such as avian influenza virus (AIV), pose serious domestic livestock and human health threats with outbreaks causing deaths and substantial economic damage (Dargatz et al., 2016; Häsler et al., 2012; Rahman et al., 2020). AIV is a national and global health concern that threatens food security, wildlife conservation and human health (Ferguson et al., 2004; Jones et al., 2008; Li et al., 2004). In response, the Center for Disease Control's (CDC) One Health Program recognizes the threat of interspecies AIV dispersal and infection and investigates the interface among animals, humans and the environment for zoonotic disease transmission risk (McCarthy, 2014; U.S. Department of Health & Human Services, 2021). Experts work locally, regionally, nationally and globally to prioritize, prevent, detect and respond to zoonotic diseases of greatest concern such as influenza viruses.

Commercial poultry are highly susceptible to AIV, with large outbreaks causing substantial losses (Li et al., 2018; Yu et al., 2018), and transmission to other farmed animals including cattle has been demonstrated (Kalthoff et al., 2008; Lopez & Woods, 1984). Outbreaks have been linked to coincident movements of wild birds, including waterfowl (Gaidet et al., 2010; Prosser et al., 2009, 2011), in which AIV has been detected (Bevins et al., 2016; Munster et al., 2007; Newman et al., 2012). Wild ducks, especially dabbling ducks such as mallard (*Anas platyrhynchos*), are known to be a principal reservoir of Low Pathogenic Avian Influenza (LPAI; Olsen et al., 2006), and migratory species demonstrate an elevated prevalence and are a primary vector (Bodewes & Kuiken, 2018; Garamszegi & Møller, 2007). Often asymptomatic (Gaidet et al., 2010) and possessing a natural resistance to Highly Pathogenic Avian Influenza (HPAI) (Evseev & Magor, 2019; Ramey et al., 2018), wild ducks can be competent virus vectors (Bergervoet et al., 2019; Koehler et al., 2008; Munster et al., 2007).

Rapid, long-distance dispersal of migratory waterfowl contributes to intercontinental virus spread (Bahl et al., 2016; Lee et al., 2015; Prosser et al., 2011) and wild ducks may transmit viruses to domestic livestock at overlap hotspots (Cappelle et al., 2014; Gaidet et al., 2010). Migratory waterfowl were hypothesized to be the cause of the 2014–15 outbreak in which AIV spread globally from Asia and caused the loss of ~ 50 million poultry across 21 states of the United States (Dargatz et al., 2016; Lee et al., 2015). The US Geological Survey (USGS) has genetically linked Asian and North American populations (Koehler et al., 2008; Ramey et al., 2016; Ramey et al., 2018) and we tracked at least one northern pintail (*A. acuta*) performing an intercontinental migration to Russia (see Figure 8). While the mechanism of virus transmission is still uncertain, indirect transmission could be facilitated at the livestock/waterfowl interface, for example via high faecal concentrations that allow effective transmission through drinking water supplies for livestock (Webster et al., 1992) and support for the "livestock–waterfowl interface hypothesis" is increasing.

Recent studies have documented sympatric habitat use between wild waterfowl and free-ranging livestock and the correspondence between waterfowl migration routes and AIV outbreaks in poultry. Mallard and northern pintail have been documented using rice fields in China where free-grazing juvenile ducks are intensively farmed (Cappelle et al., 2014), and free-range cattle ponds in north Texas (Mason et al., 2013). Farm-scale and farm-specific studies using on-site camera or infrared traps and banding records have recorded various avian species (although few waterfowl) on free-range poultry farm areas and dams in Australia (East et al., 2008; Elbers & Gonzales, 2020; Scott et al., 2018). Additionally, disease distribution modelling studies have suggested links between wild waterfowl migration routes and AIV outbreaks (Belkhiria et al., 2018; Newman et al., 2012; van Toor et al., 2018), and telemetry tracking studies have shown geographic overlap of wild bird migratory routes and commercial livestock facilities (e.g. Humphreys et al., 2020; Prosser et al., 2009, 2011; Prosser et al., 2013).

To date, an understanding of waterfowl use of the landscape surrounding livestock facilities, and the spatio-temporal connectivity between facilities and wetlands where AIV naturally persists, is lacking. Waterfowl movement between these habitats may facilitate virus transmission to domestic livestock. This may have significant management implications for disease spread if habitat near farms attracts waterfowl and consequently encourages waterfowl to use facilities, particularly if movement between habitats and facilities occurs in a relevant timeframe to the average AIV incubation period (3–5 days; Food & Agriculture Organization of the United Nations, 2021). Western states of the USA and California's Central Valley host millions of residents and wintering migratory waterfowl, a unique landscape with a large extent of wetlands available in flooded agricultural fields (e.g. rice) and hundreds of duck hunting clubs that manage seasonal wetlands. This vastly expands the available wetland habitat for waterfowl in this region where numerous commercial livestock facilities including poultry, cattle and swine, occur (U.S. Department of Agriculture, 2021a, 2021b). This juxtaposition, which presents a high likelihood of geographic overlap between waterfowl AIV hosts and domestic livestock including poultry, is of great concern in western states that are among the major milk and egg-producing areas of the United States (USDA; U.S. Department of Agriculture, 2021a). Moreover, high-risk areas for AIV outbreaks in California have been identified through modelling (Belkhiria et al., 2018), and LPAI and HPAI have been detected in live and hunter-harvested waterfowl sampled at locations near commercial (poultry and cattle) facilities (Ferro et al., 2010; Hill et al., 2010; U.S. Department of Agriculture, 2006).

Identification of an AIV transmission pathway to livestock continues to elude animal health and disease research. Despite the geographic correspondence between AIV detections in wild waterfowl populations and outbreaks in poultry, waterfowl's potential as an AIV vector to commercial livestock (either from direct contact or indirectly from faecal contamination of food or water supplies), has received relatively little consideration by the disease literature. Therefore, we aimed to improve understanding of AIV transmission pathways by leveraging our large, highly accurate GPS tracking dataset to ascertain whether wild waterfowl of the Pacific Flyway visit commercial livestock facilities (specifically, poultry, cattle and dairy) in the western United States and to understand habitat-use and movement connectivity between facilities and the surrounding landscape and wetlands. We used our GPS data to assess the interface between wild ducks and livestock facilities as a hypothetical mechanism for transmission of AIV or other diseases by identifying time spent in/near facilities, the types of habitat used when nearby, the life history stage, philopatry and connectivity with the surrounding landscape.

2 | MATERIALS AND METHODS

2.1 | Study area and data collection

This study was conducted in California's Central Valley during spring, summer and fall between January 2015 and March 2020 with 688 individuals of three species of Pacific Flyway waterfowl. Mallard (n = 213), northern pintail (n = 247) and cinnamon teal (*Spatula cyanoptera*; n = 228) were captured with rocket nets, handheld dip nets and baited funnel traps (Drewien & Clegg, 1992; McDuie et al., 2019; Schemnitz et al., 2009) at Grizzly Island State Wildlife Area (SWA; 38.138°, −121.978°), private properties within Suisun Marsh, and at Howard Slough unit of the Upper Butte Wildlife Area (39.467°, −121.877°). Female mallard and cinnamon teal were found on Grizzly Island SWA nesting fields during summer breeding using standard nest dragging techniques (McLandress et al., 1996). Breeding and molting cinnamon teal were also captured at various locations within Oregon, Idaho, Colorado, Nevada, Washington and Utah (Mackell et al., 2021). To ensure only adults of appropriate size received GPS transmitters (transmitter weight varied by species from <1% to <5% of body weight, as recommended for birds (Barron et al., 2010; Kenward, 2001)), each individual was assessed for body mass and aged based on feather and molt plumage (Carney, 1992). Each duck received individually numbered aluminium US Geological Survey Bird Banding Lab leg bands, and all were released at the location of capture after a handling time of < 30 min.

2.2 | Electronic tracking

To identify the interaction between wild waterfowl and commercial livestock facilities along the Pacific Flyway, we deployed high resolution solar-powered, remotely programmable GPS–GSM electronic transmitters (~5 m location accuracy), which use Global Positioning System (GPS) satellites to record GPS coordinates and the Global System for Mobile Communications (GSM) to transmit location data. We used species-appropriate transmitter models and sizes including Ornitela® (Ornitela, Vilnius, Lithuania) Ornitrack-15 (58 × 25 × 14 mm; 15 g) and Ornitrack-10 (47 × 18 × 12 mm; 10 g for the smaller teal), Ecotone® (Ecotone Telemetry, Gdynia Poland) SAKER L series (58 × 27 × 18 mm; 17 g) and CREX-XS (36 × 25 × 19 mm; 14 g for cinnamon teal). Transmitters were fitted with a 3 mm foam base pad attached to back-mounted body harnesses constructed of 9.5 mm automotive elastic, which is less likely to wick water to down feathers than other materials and added 1.25 (teal)—2 g to the deployment weight. Transmitters were fastened to elastic with crimps (early deployments) or knotted and fixed in place with cyanoacrylic glue. Total deployment weights were 17–19 g for mallard and northern pintail and 11.25–15.25 g for cinnamon teal. Duck behaviour (sheltering in vegetation) and inclement weather can negatively affect the ability of the solar panels to recharge the GPS batteries. As a result, location data intervals varied from 15 min at highest battery power level to 6 hr at the lowest, with occasional larger data gaps when battery levels were insufficient for the GPS to acquire locations. GPS transmitted location (latitude/longitude), date, and time data via cellular GSM text message when in network range. When out of range, data were stored on devices and backfilled on servers once within network range. Data utilized in the analyses are available from the US Geological Survey (McDuie et al., 2021).

2.3 | Movement behaviour

Once downloaded, each telemetry location was attributed with local time, and whether it occurred during the day or night (defined by sunrise and sunset). To identify on-ground habitats used by ducks, we conservatively eliminated all movements that could potentially be flighted. We calculated the speed and distance moved from each location to the subsequent location (step length) and classified all with speeds greater than 5 km/hr as flight (McDuie et al., 2019; Usherwood et al., 2008), with the adehabitatLT package (Calenge, 2015) in R (R Core Team, 2019).

2.4 | Habitat and livestock facility use

To classify the types of habitat used by ducks we mapped non-flighted duck telemetry locations and cattle or poultry facilities across areas where clusters of locations occurred in or adjacent to agricultural regions in California, Oregon and Washington, with ArcGIS® 10.8 for desktop, ArcMap™ software (Esri, Redlands, CA, USA) and Google Earth™ software. Habitats were assessed with high-resolution satellite imagery and, to determine if they were public or private we used the Protected Areas Database of the United States (U.S. Geological Survey, 2018), an inventory of public lands. We visually identified commercial poultry and cattle facilities. Poultry facilities are identifiable by long barns that have attached or adjacent feed silos and/or fans; dairy farms have barns with adjacent paddocks and ponds, and cattle production facilities have large feed lots surrounded by effluent ponds. We are unable to pinpoint specific facility locations due to biosecurity restrictions and privacy concerns. We created 2 km buffers (based on average daily forage-roost movement distances for these species; McDuie et al., 2019) around classified commercial livestock facilities and identified all instances in which tracked ducks were detected within the buffer or the facility. We created another buffer of 10 km (based on daily movement distances; McDuie et al., 2019) to classify the type of habitats being used when birds were traveling back and forth between commercial facilities and surrounding areas, specifically agricultural farmlands, private wetlands and National Wildlife Refuges (NWRs). To better understand broader habitat usage and transmission potential from natural wetlands, which can be AIV reservoirs (Ramey et al., 2020), we also noted sequential locations further afield and measured the maximum distance a bird travelled in the week prior to arriving at/near a facility, encompassing the minimum 3-5 day AIV incubation period (Food & Agriculture Organization of the United Nations, 2021).

3 | RESULTS

Our high-resolution GPS–GSM allowed us to detect 11 individual wild ducks of three Pacific Flyway Anatidae species (two northern pintail, three mallard and six cinnamon teal), tracked to or near (within 10 km) eight commercial poultry, dairy and cattle production facilities across California and Washington state. Seven individuals were observed within the boundaries of six facilities (Table 1). All individuals used wetlands, NWRs and agricultural farmlands within 10 km (often much nearer) of the nearest facility (Table 1). We report each facility separately often with multiple ducks accessing a facility. Except for Facility 1, we were able to identify the type of facility (cattle production, dairy farm or poultry). Eight instances occurred in California and two in Washington State (Table 1).

3.1 | Facility 1: Waterfowl in and near small-scale California farm

A female mallard (WATE15) frequently visited an area in California with a small-scale farming operation (likely cattle) surrounded by other farms and ranches with ponds and various protected wetlands during the day (n = 1282) and night (n = 1178; Figure 1a). During winter and spring of 2016 (26 February—11 May) and 2017 (1—20 March; Table 1, Figure 1b), the mallard repeatedly visited the small-scale farm primarily during the day, with locations mostly concentrated on or near a pond adjacent to farm buildings (within 200 m), unenclosed paddocks and with several locations very close to or possibly within farm buildings (2016: day n = 337, night n = 28, and 2017: day n = 114, night n = 7; Figure 1b). The bird also spent the day and nighttime in nearby farm or ranch ponds as close as ∼1 km and generally within 4 km of the farm, and protected wetlands slightly farther afield (∼10 km; Figure 1a). In evaluating wetland connectivity via movement, this individual used wetlands a maximum of 19 km away in the week prior to each visit. Location data intervals were at 30-min to hourly intervals (except for some larger gaps and missing days).

3.2 | Facility 2: Waterfowl near densely concentrated poultry and dairy facilities in California

In California, two ducks were observed using an area of extensive commercial poultry and dairy production surrounded by unfarmed fields with ponds, channels and surface water, with eight dairy and three poultry facilities within a 10 km radius. A female mallard (WATE45) arrived in this area on 23 December 2015 (day n = 1; Table 1; Figure 2), having flown from Suisun Marsh (377 km) in the week prior. Due to irregular, low-frequency data (∼ 1/day), only a single day location indicated its presence within 2.3 km of the nearest poultry and dairy facilities. The previous location (22 hr prior) showed this bird to be 332 km north and 2 hr later the bird was once again 18 km to the north and on to wetlands and conservation easements over the subsequent∼3 weeks. It was last seen ∼197 km away. Almost 3 years later (15 and 16 June 2018) a female cinnamon teal (DRIB53; n locations = 23; Table 1) visited fields/ponds in the area for 2 days (Figure 2). This bird arrived from northern wetlands 348 km away the week prior to spend nights within 900 m of the nearest dairy and days within 1.7 km of the nearest poultry facility. It was in cropland before sunrise (n = 1), spent the day (n = 14) in unfarmed land with waterbodies (ponds and channels) and returned to the same crop field during the night (n = 6), where it remained until relocating at 0100 hr on 16 June 2018 to a canal ∼18 km south, the final location acquired.

3.3 | Facilities 3, 4, 5 and 6: Waterfowl near densely concentrated California dairy and poultry facilities

Three female regional migrant cinnamon teal were observed in a region of California with many poultry and dairy facilities. One individual (TEAL #191534; n locations = 7375; Table 1) migrated three times to the region during spring (11 February–15 April) and fall (7 September–27 November) of 2020 and returned in spring of 2021 (23 February and 11–15 April; Figure 3). The teal was first tracked in the region when it arrived from 10 km away at a private conservation easement wetland, between 11 February and 11 March 2020 (with a subsequent single location 23 February 2021) which was 5.9 km to the nearest (Facility 3) of three dairies (all within 7.5 km; n locations = 2819; Figure 3). The bird then moved ∼8 km to an NWR ∼9.5 km from a poultry facility to the north (Facility 4) where it remained until 2 April 2020 (n locations = 2074; Figure 3).

When the teal returned to the region in the fall of 2020, it arrived in an agricultural area with seven poultry facilities within 10 km, on 7 September from wetlands 668 km to the north. The bird divided its time between a nearby river ∼4.3 km from the nearest (Facility 5; Figure 5b) of three poultry facilities where it was primarily tracked during daytime (day n = 176; night n = 11), and in wet-

TABLE 1 GPS tracking data for 11 individual dabbling ducks of three species (8 facilities) in or near private farm, dairy, poultry or cattle production facilities in California (CA) and Washington (WA), USA since 2015

Facility number and type	Individual ID	Species	Sex	State	Dates ducks entered/neared facility	Total locations in facility (day/night)	Total locations within 10 km of facility	Max. distance in 7 days prior to facility	Location interval	Migrant/ Resident	*Location marked
1: un-identified	WATE15	Mallard	F	CA	26 Feb-11 May 2016 and 1-20 Mar 2017	460/38	2460	19 km	30 min-12hr	migrant	Suisun
								10 km			
2: many dairy and poultry	WATE45	Mallard	F	CA	23-Dec-15	0/0	1	377 km	NA	resident	Suisun
	DRIB53	Cinnamon teal	F	CA	15-16 Jun 2018	0/0	23	348 km	1hr	resident	Suisun
3: dairy	191534	Cinnamon teal	F	CA	11 Feb–11 Mar 2020 and 23-Feb-21	0/0	2819	53 km	30 min	migrant	Klamath
								unknown			
4: poultry	191534	Cinnamon teal	F	CA	11 Mar–2 Apr 2020 and 19 Sep–27 Nov 2020	0/0	3536	10 km	30 min	migrant	Klamath
								62 km			
	TEAL24.2	Cinnamon teal	F	CA	12-20 and 23 May 2019 and 9–11 Jul 2019	0/1	137	328 km	2hr	migrant	Suisun
5: poultry	191534	Cinnamon teal	F	CA	9–18 Sep 2020	0/0	662	668 km	30 min	migrant	Klamath
	TEAL38.2	Cinnamon teal	F	CA	21 Jun-9 Oct 2018	0/1	1502	124 km	1hr	migrant	Suisun
6: dairy	191534	Cinnamon teal	F	CA	11-25 Apr 2021	702/56	139	*unknown*	30 min	migrant	Klamath
7: cattle	VATE12	northern pintail	M	WA	6 Jan-17 Feb 2017	54/30	203	83 km	1–12hr	migrant	Suisun
	VATE18	Mallard	F	WA	12 Jan-19 Feb 2017	57/51	153	21 km (4d)	6-12hr	migrant	Suisun
	TEAL07	Cinnamon teal	M	WA	14-Sep-17	0/0	9	97 km	1hr	migrant	Suisun
	TEAL08	Cinnamon teal	M	WA	2-3 Oct 2017	0/0	23	85 km	1hr	migrant	Suisun
8: dairy	VATE22	northern pintail	F	WA	15-20 Nov 2016	13/13	29	1251 km	NA	migrant	Suisun

*Suisun = Suisun Marsh, California; Klamath = Klamath Basin, Oregon.

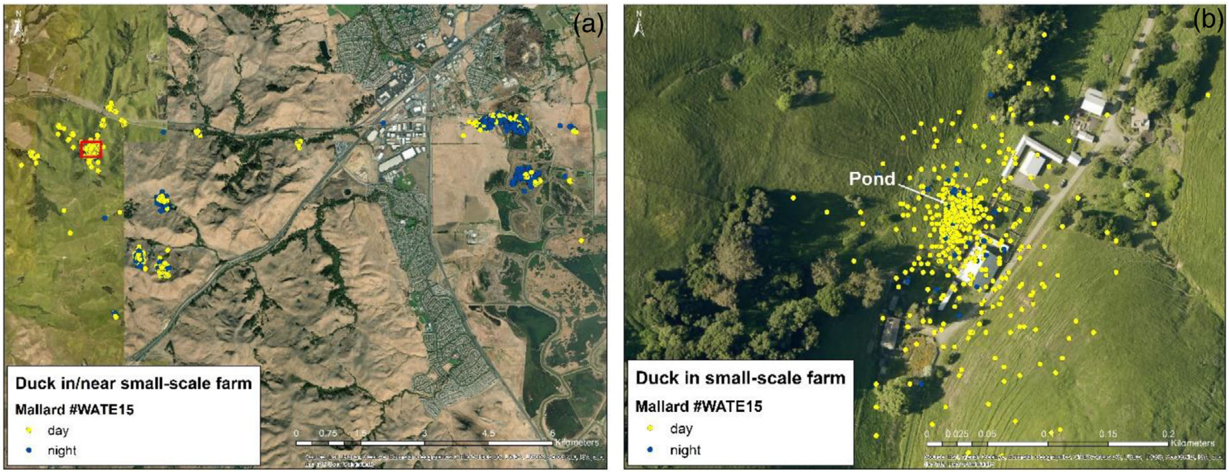

FIGURE 1 (a) Facility 1: GPS locations of mallard (female) frequently revisiting a small-scale farming operation (likely cattle) shown by the red polygon in panel a) and surrounding wetlands, ranch and farm ponds in California in March-May 2016 and March 2017 during day (yellow) and night (blue). (b) shows the cluster of locations within 200 m of the farm buildings corresponding with the pond

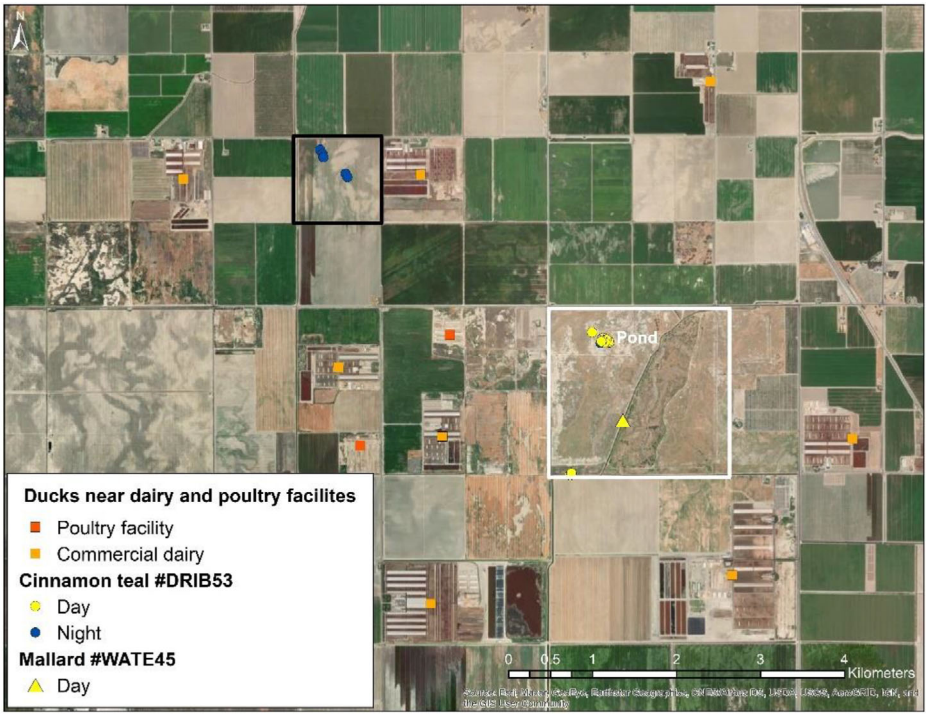

FIGURE 2 Facility 2: GPS locations from a female cinnamon teal (day = yellow circles; night = blue circles) on 15 and 16 June 2018 and a day location of a female mallard (yellow triangle) on 23 December 2015. Both birds were tracked to unfarmed land (white polygon) and cropland (black polygon), with surface water, channels, and ponds, adjacent to numerous poultry facilities (dark orange squares) and dairy farms (light orange squares) in California, USA

lands just over ~1 km from Facility 5, in which nocturnal locations (n = 284) exceeded diurnal locations (n = 191; Figure 5b). Subsequently, the teal returned to the NWR (40 km south-east), remaining until 27 November 2020 (n = 1462; Figure 3) after which it left the region until returning in spring 2021 (Figure 4). After a single location in February 2021 in the conservation easement wetland (which was the only location acquired across a large data gap spanning 28 November 2020 to 11 April 2021), the bird was next observed (11–15 April 2021) moving between days spent in effluent ponds and a feed lot within the boundary of a dairy farm (Facility 6; day n = 702; night n = 56; Figure 4) and nights in nearby (<4 km) wetlands (night n = 139) which were also only 2.7 km from poultry facilities. Most locations were acquired at 15-min intervals with some longer data gaps).

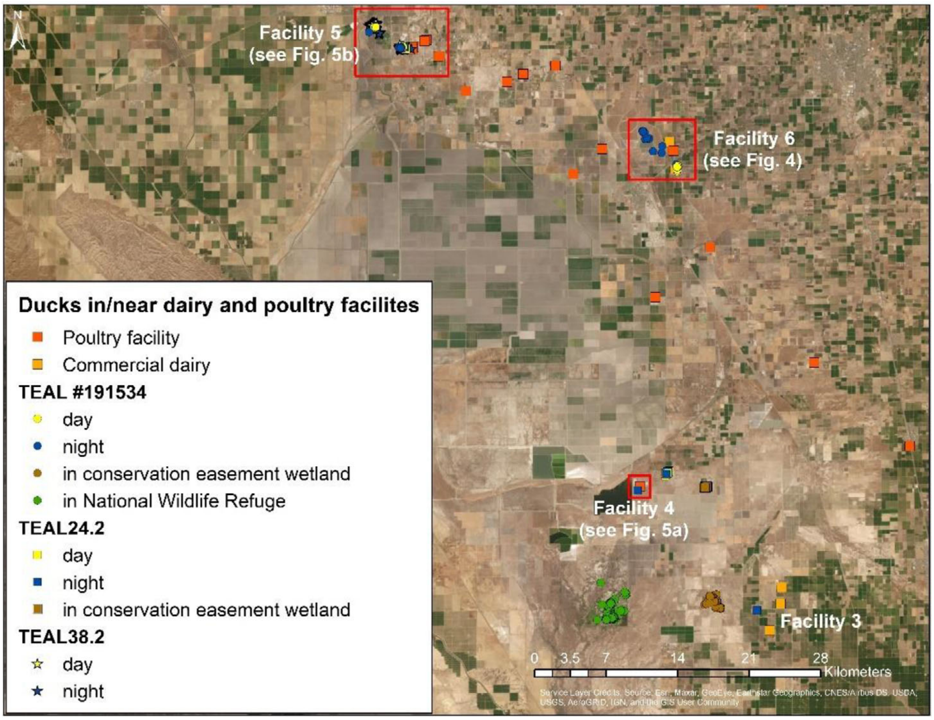

FIGURE 3 Facilities 3, 4, 5 and 6: GPS locations from three female cinnamon teal that migrated to a region of California with numerous poultry (dark orange squares) and dairy (light orange squares) facilities. Two individuals were observed using poultry facilities (TEAL24.2 in Facility 4 and TEAL38.2 in Facility 5; see also Figure 5a,b) with single night locations (blue square and star respectively), and the third used a dairy (see also Figure 4). The birds moved between private conservation easements (brown circles and squares) wetlands and NWR (green circles) within 10 km of facilities. The red polygon outlines the facility boundaries

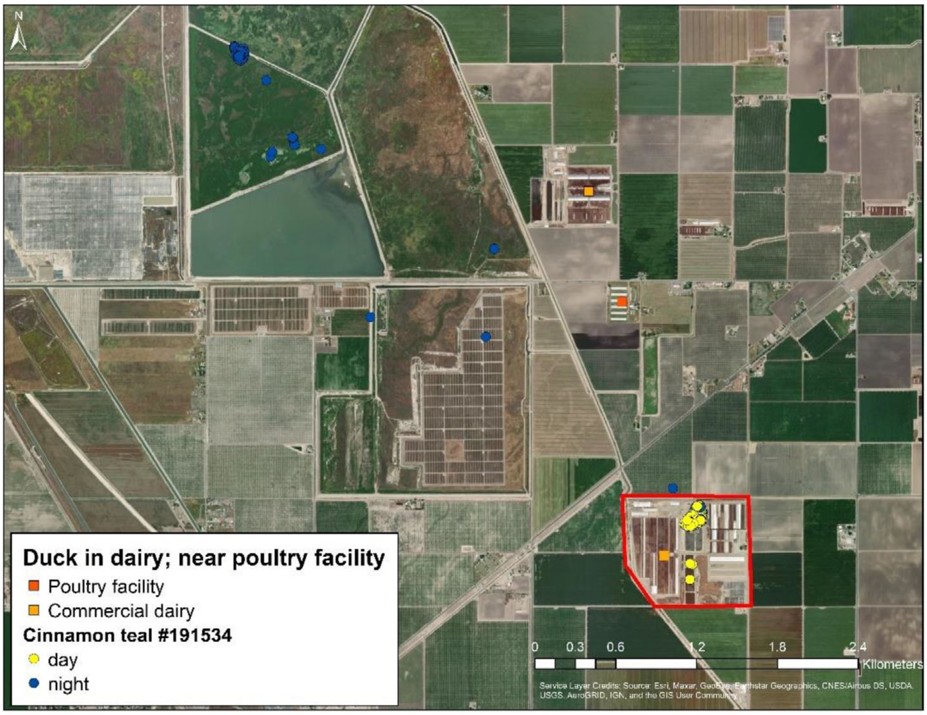

FIGURE 4 Facility 6: GPS locations of a female cinnamon teal occupying a dairy farm (red polygon) in California in April 2021 mostly during the day (yellow circles) and a nearby wetland at night (blue circles). The red polygon outlines the facility boundary

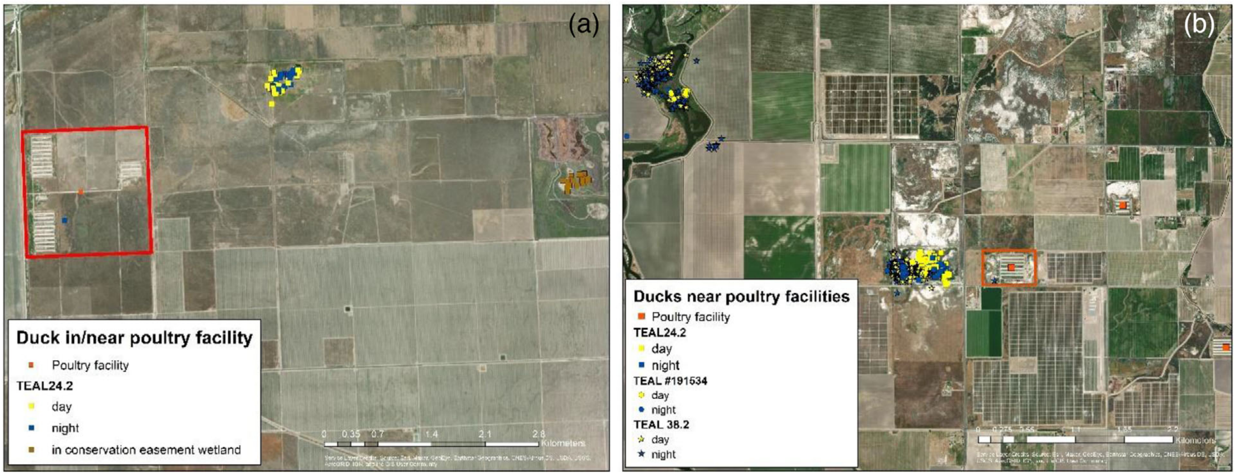

FIGURE 5 (a) Facility 4: GPS locations of a female cinnamon teal (TEAL24.2) with a single night location (blue square) inside a California poultry facility with day (yellow squares) and night locations in nearby private unfarmed land/wetland and a conservation easement (brown squares) in May 2019; (b) Facility 5: single nocturnal GPS locations of a female cinnamon teal (TEAL38.2; blue star) inside a California poultry facility and a nearby private wetland (~1 km; stars) that was also visited by TEAL24.2 (squares) and TEAL #191534 (circles). Further locations of TEAL38.2 and TEAL#191534 in a nearby (< 5 km) river in 2018 and 2020, respectively. The red polygon outlines the facility boundaries

Two other female cinnamon teal (TEAL 24.2 and 38.2) also migrated to this region and were each observed by a single, non-flighted, nocturnal GPS location, inside two of the same poultry facilities during summer. TEAL24.2 visited Facility 4 on 14 May 2019 (n = 1; Table 1; Figure 5a) having migrated 328 km in the previous week—the same poultry facility noted above as being north of the NWR that teal #191534 used (Figure 3). The teal spent 8 days between 12 and 20 May 2019 in private wetlands 2.7 km from facility 4 (day n = 56, night n = 35; Figure 5a) and, on three occasions, inside a private conservation easement wetland (19 and 23 May 2019; n = 3, and 9–11 July 2019; n = 42) 6.2 km from the poultry facility (Figure 5a). It then spent a week (11–18 July 2019) in the private wetland that had been used by #191534 and was also used by TEAL38.2 in 2018 (Figures. 3 and 5b), after which it migrated >50 km south.TEAL38.2 used this larger private wetland area for almost 2 months from 25 June to 19 August 2018 (day n = 445; night n = 276; Table 1; Figure 5b). The teal visited the nearby poultry facility 780 m away (Facility 5; one GPS location - 25 June; Figure 5b) a few hours after its nighttime arrival from 124 km to the north. Most data for both birds were hourly with some 6 hr gaps at night.

3.4 | Facilities 7 and 8: Waterfowl in/near Washington State cattle production facility

Two cattle production (beef) facilities in Washington State (Facility 7 and Facility 8) were visited by five ducks of three species (n locations = 397), during winter 2016–2017 and late summer-fall 2017 (Table 1; Figure 6). Two male cinnamon teal (TEAL 07 and 08) used habitat (river and NWR) adjacent to facility 7 (~3.38–5.97 km away) but were not tracked inside the facility grounds. One teal (TEAL07) stopped in the NWR near this facility for 12 hr while conducting its fall migration in 2017 (between Washington and California; 14 September; n locations = 7), having arrived from 97 km away, but was never closer than 3.38 km from the facility. The second teal (TEAL08) was tracked from 85 km in the week prior to both the NWR and agricultural fields around facility 7 just 2 weeks later, getting as near as 0.71 km from the facility (n locations = 18; Figure 6).

A male northern pintail (VATE12; n locations = 190; Figure 6), migrated 82 km to the area during winter 2017 (7 January–20 February), with both day (n = 53) and night (n = 29) locations inside the boundaries of Facility 7 (Figures. 6 and 7a). It used feed lots almost exclusively during the day (n = 26; n = 1), while a retention pond at the north boundary of the facility was used more at night (day n = 8; night n = 18). Farm pond areas to the east were used slightly more in the day (n = 19) than at night (n = 10). When not within the facility, this bird used the nearby NWR and river, mostly at night (day n = 18, night n = 70; Figure 6) and surrounding agricultural fields mainly in the day (day n = 15; night n = 3), always within ~4.5 km of the facility. Location acquisition varied between 2 and 6 hr with some multi-day data gaps.

A female mallard (VATE18; n locations = 153; Figure 7a) was observed in the same area at the same time of year (7 December 2016–19 February 2017) as the male Northern pintail, both birds repeatedly visiting Facility 7 over more than two months (Figure 7a,b). While the Northern pintail primarily occupied the northern half of Facility 7, the mallard's locations were in the southern half (n = 108) during both day (n = 57) and night (n = 51; Figure 7a). Like the Northern pintail, the mallard spent about half its time in feed lots (n = 58) primarily in the day (n = 44), although 14 night locations all occurred immediately prior to sunrise, reflecting the birds early arrival to these feed lots. Of the remaining locations within the facility grounds, a handful were in nearby farm ponds (all during the day, n = 8) while most night locations were in retention ponds (day n = 1, night n = 41) at the western periphery of feed lots (Figure 7a). Like the male northern pintail, this bird spent time in the nearby NWR and river a maximum of 4.2 km away

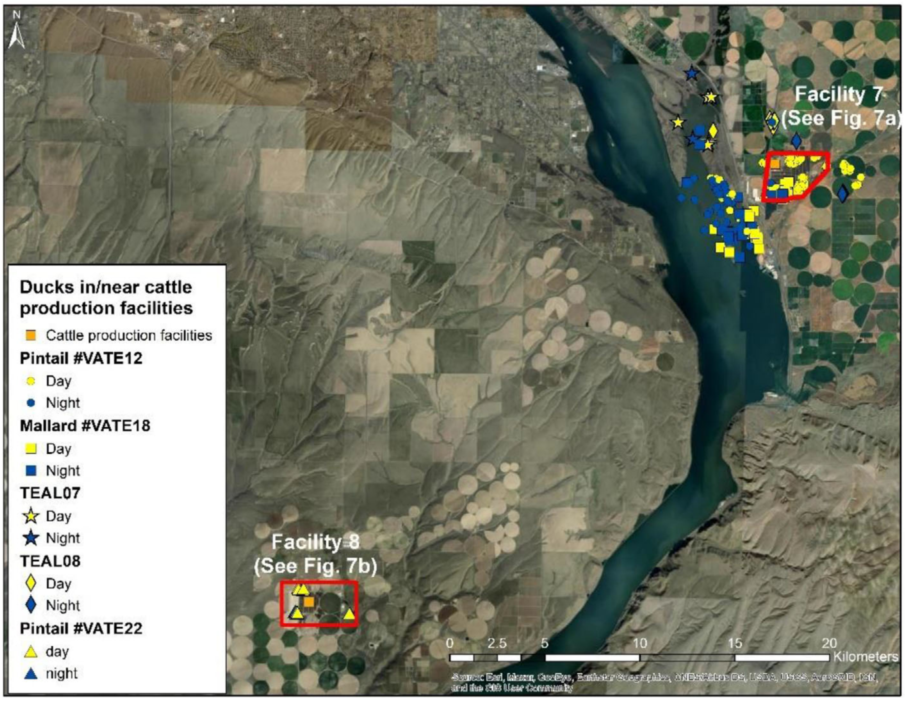

FIGURE 6 Facilities 7 and 8: GPS locations from five individuals of three species of ducks (cinnamon teal, mallard and northern pintail; see Table 1) present in feed lots and ponds of two cattle production facilities (red polygons; see Figures 3 and 4 for detail) and nearby agricultural farmland and NWR during day (yellow shapes) and night (blue shapes) in Washington, USA

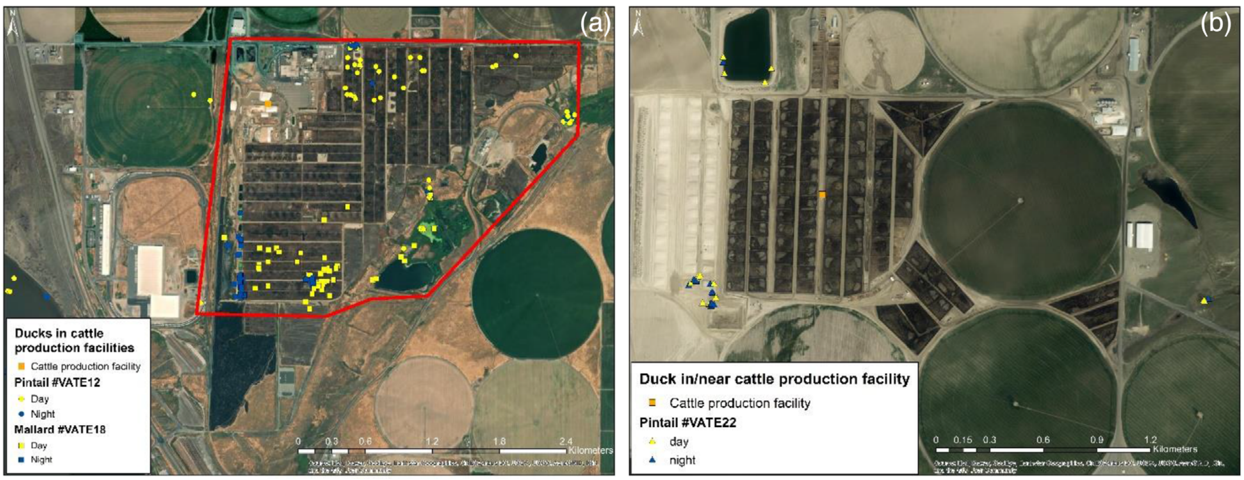

FIGURE 7 (a) Facility 7: GPS locations from a northern pintail (male) and a mallard (female) that used cattle feed lots (mostly day = yellow shapes), ponds (rectangular dark areas along edge, mostly night = blue shapes) and wetland/water retention areas (green, mostly day) of a cattle facility (red polygon) in Washington state, USA. The red polygon outlines the extent of area within the facility boundary where the ducks were located; (b): Facility 8: GPS locations from a northern pintail (female) in retention ponds of a cattle production facility and adjacent agricultural fields during day (yellow triangles) and night (blue triangles) in Washington state, USA

over multiple days, primarily at night (day n = 17; night n = 28; Figure 6). We could only ascertain the distance it travelled to the facility (21 km) for the 4 days prior to arrival due to data gaps. Location acquisition was 6-hourly with an extended data gap from 7 December 2016 to 12 January 2017.

A female northern pintail (VATE22; n locations = 29) visited the same region in Washington in late 2016 (16–20 November; Table 1) but used a different cattle production facility (Facility 8; day n = 13; night n = 13; Figure 7b) ~38 km away from Facility 7 (Figure 6). Locations were in retention ponds adjacent to feed lots and another 3 locations

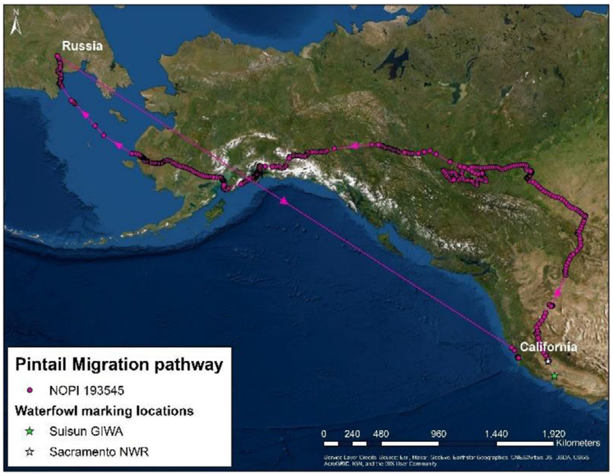

FIGURE 8 GPS track of migratory northern pintail from Sacramento NWR on 21 February 2020, to Russia (June) via stops at sites in Oregon (March), Canada (April, May) and Alaska (June). After its mid-June arrival in Russia, tracking continued until mid-July after which no tracking data were acquired until the bird's return to California on 22 October. Pink arrows show direction of movement and the white star shows the CA GPS marking site

(day n = 2; night n = 1) were in an agricultural pond 1.7 km east of the main facility and < 0.5 km from the nearest feed lot. This bird migrated the greatest distance (1251 km) of all birds in the week prior to arrival. Location interval varied from 2 to 12 hr.

3.5 | Northern pintail intercontinental migration

One northern pintail (#193545) marked in California at Sacramento NWR on 21 February 2020 performed its northbound spring migration, stopping in Oregon, USA (March) the Canadian prairies (April/May) and Alaska (June) before continuing across the Bering Strait to Russia where it arrived in June 2020 (Figure 8). The bird arrived in Russia on 17 June and departed sometime after 14 July 2020. A gap in data meant we collected no locations between 14 July and 21 October, when the bird was next tracked on its return to California (at Crescent City and Arcata Bay) on 22 October 2020. These recent data contribute to previous literature linking the migration of ducks between the Asian continent and the Pacific Flyway as a possible mechanism in the spread of AIV intercontinentally to North America (Hill et al., 2012; Lee et al., 2015; Takekawa et al., 2010).

4 | DISCUSSION

Our study reveals the use of various commercial livestock facilities by wild waterfowl of three species in two states of the western USA. To our knowledge, this is the first study to use GPS to electronically track these species that carry and shed AIVs (Evseev & Magor, 2019; Kim et al., 2009) into commercial livestock facilities, and demonstrate patterns of use and connectivity with the surrounding landscape. Our results provide empirical support for the proximity of wild waterfowl and commercial livestock, and the opportunity of an AIV transmission pathway from waterfowl to livestock. Northern pintail, mallard and cinnamon teal had access to commercial livestock when they used cattle production facilities and visited poultry facilities and dairy farms in the Pacific Flyway. While AIV transmission dynamics have been modelled using satellite data and spatio-temporal infection risk models to quantify a potential intersection of wild and domestic birds (Hill et al., 2021), the interface of wild and domestic bird taxa in feed lots and facility buildings and linkages with surrounding wetlands and NWRs, have not previously been demonstrated. Ducks generally feed at night and roost during the day, but opportunistic day feeding is not uncommon (Cox Jr & Afton, 1996, 1999). Therefore, the birds' presence in retention ponds and feed lots during day and night, as well as concentrations of GPS locations in small areas indicating short distances moved, imply that the ducks were using the facilities for both roosting and foraging, which increases the likelihood of interaction between livestock and wild ducks.

The high detectability available with GPS tracking also allowed us to understand movement and habitat connectivity with the surrounding wetlands across the landscape. Most commercial facilities used by ducks in this study were relatively close to natural, often protected, waterfowl habitats that included public or private wetlands, conservation easements and National Wildlife Refuges where these individuals were also found, but nearby artificial habitats such as private agricultural land also attracted ducks. Extensive decadal natural wetland losses (Dahl, 1990), partly driven by the agricultural expansion that reduced historical waterfowl breeding and wintering areas over the past century, means natural habitat has decreased and ducks fulfill their habitat needs elsewhere (e.g., artificial (man-made) habitats; Baldassarre et al., 1983; Bellrose & Trudeau, 1988; Mackell et al., in press). In our study, unfarmed land may have provided vegetation as refugia where the ducks could roost without being disturbed by farming activities or predators. Agricultural areas are commonly exploited by waterfowl (Fox et al., 2017; Ringelman, 1990) and as a result, many species of ducks have adapted to foraging on a variety of grain (e.g., corn, rice, and wheat) in agricultural fields (Baldassarre et al., 1983; Bellrose & Trudeau, 1988). The presence of ducks inside cattle feed lots during the day suggests that they may have opportunistically exploited spent or fallen grain that feeds livestock. In most instances ducks using commercial livestock facilities moved back and forth between nearby natural wetlands and the farms, suggesting that natural habitats were not fulfilling their resource requirements or livestock facilities provided more accessible food. Small pockets of food (grain/seeds) and habitat (water) found on livestock facilities may support some resource requirements, increasing the likelihood of coincident waterfowl-livestock space use. The proximity between natural waterfowl habitat and livestock facilities enhances the chance of direct contact (Takekawa et al., 2010; Velkers et al., 2021), introduces a risk of AIV dispersal from waterfowl overflying facilities (Gilbert et al., 2010), and may reduce the efficacy of waterfowl deterrents (Atzeni et al., 2016).

As a consequence of wild waterfowl asymptomatically hosting and shedding AIV (Evseev & Magor, 2019; Kim et al., 2009), wetlands and refuges, which attract large flocks of these species, are also considered to be virus reservoirs (Ramey et al., 2020). Therefore, connectivity between wetlands and commercial livestock facilities, through duck movement and habitat use patterns, presents a route of transmission from the AIV reservoir to domestic animals in commercial facilities. Also concerning are the much longer wetland-facility movements (up to 1251 km) ducks frequently made in the week prior to arrival at a facility; indicating that ducks can and will travel long distances to use, even for short durations, facilities, or the wetlands nearby. Since the AIV incubation period is at least 3–5 days (Food & Agriculture Organization of the United Nations, 2021), these movements would facilitate a duck transmitting the virus into a facility from a distant wetland, broadening the geographic scope of disease spread. Connectivity between distant wetlands and livestock facilities through bird movement could in turn increase the risk of livestock exposure to novel or highly pathogenic disease variants. Moreover, our track of a northern pintail migrating from California to Russia and back underscores previously identified intercontinental waterfowl and AIV connectivity between northern Asia and the southern Pacific Flyway (Miller et al., 2001; Ramey et al., 2016), a concern since northern pintail are likely long-distance, intercontinental vectors of AIV from Asia (Koehler et al., 2008; Ramey et al., 2016; Ramey et al., 2018). As such, migration timing could portend different risks. For example, birds using livestock facilities during the southbound fall migration (e.g. northern pintail in facility 7, November 2016), when they may be returning from Asia carrying AIV, might be more likely to introduce cross-continental strains than individuals using facilities during their northbound migration (e.g. northern pintail in facility 8, January–February 2017). Such variation could have implications for when, where and how to impose biosecurity measures.

Another potential virus dispersal pathway is via water. AIV can be highly concentrated in duck faecal particles which remain infective for extended periods when deposited in water supplies, allowing the transmission to domestic livestock (Kim et al., 2009; Ramey et al., 2020; Webster et al., 1992). Livestock retention, or farm ponds, as demonstrated by duck use in our study, provide viable duck habitat, and in California, approximately 25% of poultry farms have ponds (1500–2000 estimated) from which water is pumped into barns (P. Pandey *pers comm.*). Water is generally treated when provided to livestock, but the presence of these water bodies on the landscape is attractive to waterfowl, potentially increasing the likelihood of coincident use and transmissibility of AIV to domestic poultry. Although our detection of wild waterfowl within poultry facilities was low, the presence of two ducks within poultry farms demonstrates the risk, and wild waterfowl have been traced to poultry-rearing areas in Asia where HPAI outbreaks have occurred (Cappelle et al., 2014; Prosser et al., 2011; Prosser et al., 2013).

Direct interaction between wild waterfowl and commercial livestock is of particular concern because domestic avian species, such as ducks, chickens and turkeys, are susceptible to AIV (Bertran et al., 2014; Yu et al., 2018), but it is not necessary for virus transmission. Bridge hosts, which are species that share habitat or come into contact with both waterfowl and domestic livestock, can transmit pathogens from hosts to receptive populations (e.g. vulnerable poultry; Caron et al., 2014). Additionally, while there is currently no evidence of AIV transmission between birds and cattle, cross-species transmission is well-documented (El-Sayed et al., 2013; Kalthoff et al., 2008; Reperant et al., 2009) and cattle can be infected with and shed various AIV variants (Kalthoff et al., 2008; Lin et al., 2010). Of further concern is that commercial livestock facilities also present an animal-human interface (Miller et al., 2013; Van Kerkhove et al., 2011) through which viruses could spread, for example, viral particles transferred by farm workers moving between facilities (El-Sayed et al., 2013; but see Kaplan et al., 2016).

When AIV outbreaks occur within a region with commercial livestock facilities, biosecurity protocols are increased, and several actions are taken to reduce the risk of spread (HPAI Response Plan: The Red Book; https://www.hsdl.org/?view&did=721913). Of most concern are HPAI, or an LPAI outbreak with H5 or H7 subtypes that tend to amplify into HPAI (Monne et al., 2014). In cases of H5 or H7 (either LPAI or HPAI) infected stocks may be depopulated, and zones around the infected premises are subsequently set to closely monitor the outbreak. The HPAI Response Plan lists the zones around the infected premises to include the infected zone, a buffer zone, and a surveillance zone (HPAI Response Plan: The Red Book; https://www.hsdl.org/?view&did=721913). Buffer and surveillance zones aim to help eliminate virus dispersal to neighbouring facilities and zone size varies among outbreaks. In California, buffer zones generally range from 3 to 10 km, each encompassed by a surveillance zone ranging from 10 to 20 km (Carnaccini et al., 2015). These zonal distances for poultry facilities in our study would easily encompass wetland habitats attractive to ducks as well. In such cases, best practices recommended to minimize or prevent virus transmission and outbreaks may be rendered inadequate.

Casazza et al. (2021) demonstrated that ducks are attracted to beneficial pond-like features in sub-optimal wetland habitats, such as tidal and sub-tidal wetlands, and our study suggests that even relatively small or isolated natural and artificial habitats in or near commercial livestock facilities can attract waterfowl. Furthermore, even in our small sample size, we tracked multiple individuals to the same areas and facilities and several displayed the high site fidelity typical of waterfowl (Baldassarre, 2014; Nicolai et al., 2005), visiting the same sites repeatedly over months or across years. For example, we tracked two birds—a male northern pintail and a female mallard—from Suisun Marsh (marked in the same trap on the same day) through their spring and fall migrations, which included using the same cattle production facility (Facility 7) and nearby wetlands on multiple occasions/years. Similarly, three cinnamon teal used the same wetland within ~1 km of a poultry farm (Facility 4), in different years. Site fidelity across seasons or years may be due to reliably consistent local conditions provided by livestock facilities (e.g. food resources or perceived safety from predation or disturbance) and a lack of alternatives in a sparse wetland landscape (Dahl, 1990). The longer birds remain in any given location the greater the risk of an environmental AIV outbreak or an epidemic in a commercial facility (Humphreys et al., 2020; Ito et al., 1995), even though the risk of HPAI entering commercial facilities may be relatively lower than LPAI (Hénaux & Samuel, 2011). The individuals in our study represented only a fraction of the total sample of GPS-marked ducks in the larger study of these species (< 0.02%; n = 11 of 688). However, this sample is a very small proportion of the entire population (~9 million) of Pacific Flyway ducks (Baldassarre, 2014) suggesting that many more birds (even flocks) may similarly use livestock facilities and local habitats. Therefore, the use of livestock facilities or adjacent habitats by our sample of GPS-marked ducks, especially when in proximity to poultry facilities, presents a serious potential risk of AIV transmission and outbreak. Future research with higher frequency data is required to assess whether the relative proximity of facilities to natural, beneficial waterfowl habitat and migratory routes influences the extent ducks use facilities, revisit frequency and foraging patterns. Resource or step selection functions could analyze the use and selection of stock ponds and livestock facilities relative to the use of natural wetlands (Boyce, 2006; Thurfjell et al., 2014) to better understand these behaviours, identify spatio-temporal overlap and presence of wild waterfowl in areas that present significant contact risk to domestic livestock. Additionally, tracking with accelerometry or very high-frequency GPS would help determine if livestock facilities offer better foraging opportunities and physiological or energetic advantages.

5 | CONCLUSION AND RECOMMENDATIONS

Our evidence of wild waterfowl presence at livestock facilities, repeat visits during both day and night, and links with surrounding habitats, natural wetlands near and far, and migration routes (intercontinental and regional) are data that cannot be obtained via human or video observation or risk modelling. The large distances these species moved between natural wetlands and livestock facilities demonstrates that facilities face risk from both local and migratory birds. GPS movement data improve our understanding of the potential for a wild bird–livestock interface and AIV transmission pathways, even in areas that are thought to be bio secure. With precise GPS data we can identify specific locations and farm types where wild waterfowl may come into contact with domestic animals, and connections with near and distant natural habitats, allowing accurate and efficacious AIV outbreak risk analyses. Furthermore, GPS–GSM data can be virtually instantaneous, presenting the ability to assess and manage risk in near real time. This could be a substantial advantage in abating outbreaks for bodies such as the CDCs One Health Office, which recognizes the close connection between human and animal health, our shared environment and the threat of interspecies AIV dispersal and infection (U.S. Department of Health & Human Services, 2021). Our data suggest that identifying and preventing or reducing the use of surrogate habitat that may attract wild waterfowl (e.g. farm ponds), eliminating food and other resources near livestock (particularly when visible to overflying ducks), and minimizing feed grain spillage on facilities, especially those near natural waterfowl habitat, may limit virus transmission by reducing the likelihood of attracting waterfowl. Additionally, natural wetlands could be restored and enhanced to provide more and higher quality habitat, and sufficient food for waterfowl, further reducing the risk of AI transmission between wild waterfowl and domestic livestock.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ETHICS STATEMENT

The ethical policies of the journal, as noted on the journal's author guidelines page, have been adhered to and the appropriate ethical review committee approval has been received. This study was approved by the U.S. Geological Survey Western Ecological Research Center Animal Care and Use Committee conducted under Federal Banding Permit #21142 and state SC permit #SC-8090.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in US Geological Survey Science Base at https://www.sciencebase.gov/catalog/.

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