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An abundance estimate of free-roaming horses on the Navajo Nation

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ABSTRACT

Free-roaming horses *(Equus ferus caballus)* occur throughout arid and semiarid regions of the western United States, where they can decrease plant biomass and diversity, impair water quality, and reduce forage available to native wildlife and domestic livestock. Management of free-roaming horses on Bureau of Land Management (BLM) and US Forest Service lands is determined by protections and population targets established by law, but these do not apply to other federal or Tribal Lands, where relatively little is known about the abundance and distribution of free-roaming horses. To address this information gap, we conducted the first comprehensive survey of free-roaming horses within the Navajo Nation, which is the largest Tribal Land holding in the contiguous United States and covers portions of the states of Arizona, New Mexico, and Utah. We used stratified random sampling and double-observer distance methods to produce estimates of horse abundance corrected for detection bias. During the summer of 2016, we used fixed-wing aircraft to survey 4 975 km of transects across our 67 089-km^2 study area. We observed 4 290 horses distributed among 527 groups and estimated 38 223 horses lived within the study area during the survey period (standard of error [SE]: 6 052, 90% confidence interval: 29 365–47 080), with 29 394 horses in open areas (SE: 5 511, 90% confidence interval [CI]: 21 328–37 460) and 8 829 horses in forested areas (SE: 2 331, 90% CI: 5 417–12 240). Overall density of 0.570 horses/km^2 (SE: 0.090, 90% CI: 0.438–0.702) was 23% higher than density of horses and burros *(Equus asinus)* in all BLM herd management areas (HMAs) in 2016 and exceeded by 17% the density in Nevada, the only state with an HMA of comparable size to the Navajo Nation. Our results will inform management of a free-roaming horse population that this study has revealed to be the among the largest in the United States.

Introduction

Horse *(Equus ferus caballus)* species native to North America became extinct about 10 000 yr ago (Faith and Surovell 2009). Horses of Old World common ancestry were introduced to the continent by Spanish colonists in the 15th century, and all extant free-roaming horses in North America are considered untamed animals descended from domestic stock (BLM 2017). In 2016, an estimated 55 311 feral horses and 11 716 feral burros *(Equus asinus)* occupied 217 774 km^2 of rangeland managed by the Bureau of Land Management (BLM) across 10 western states of the United States. This translates to an average density of 0.465 horses and burros/km^2 in BLM herd management areas (HMAs; areas actively managed for horse and burro populations) and 0.308 horses and burros/km^2 in herd areas (HAs; historically occupied areas that encompass HMAs and include additional areas that are currently managed for a target of no horses and burros) (BLM 2016). By 2019, the estimated population in that area was 71 892 feral horses and 16 198 feral burros, representing increases of 30% and 38%, respectively (BLM 2019). Note that we refer to estimates on BLM lands as “feral” since they were estimating abundance of horses not owned or supported by humans, but our study was focused on all free-roaming horses and burros.

The physiology and behavior of horses make them less selective grazers than other ungulates and domestic livestock and, thus, more likely to denude areas of vegetation (Beever 2003). As a result, grazing by free-roaming horses can reduce forage available to native wildlife and domestic livestock, decrease plant biomass,

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reduce diversity of native plants (but see Ostermann-Kelm et al. 2009), compact soil, and impair water quality (Beever and Brussard 2000; Beever and Aldridge 2011). Concerns about unregulated commercial use of free-roaming horses led to implementation of the Wild and Free-Roaming Horses and Burros Act (Pub.L. 92–195), which established protections and population targets for free-roaming horses and burros on BLM and US Forest Service (USFS) lands where they were extant in 1971. However, these regulations and associated mandates for population monitoring do not apply to lands owned and managed by indigenous American tribe, where concerns exist about environmental impacts of free-roaming horses, yet little is known about their current abundance and distribution.

The Navajo people are a indigenous American tribe residing in the Four-Corners region of the southwestern United States. Before Spanish colonists arrived in this region in 1598, the Navajo had established an agrarian society in what is now northwestern New Mexico (Weisiger 2009). Increasing use of domesticated livestock during the next 2 centuries enabled a gradual shift from farming to nomadic pastoralism and expansion of the Navajo's use area more than 150 km to the south and west into present-day northeastern Arizona. Overgrazing and erosion were concerns of many who observed livestock grazing practices of the Navajo people during the late 1800s (Iverson 2002). Anecdotal accounts suggest high densities of livestock during this period, with some individual tribal members owning 400–3 000 horses (Iverson 2002). By 1930, about 40 000 Navajos owned 67 500 horses, 575 000 sheep, 187 000 goats, and 37 500 cattle on their ~70 000-km^2 reservation (Young 1955). A major drought in the western United States during the 1930s led to forced reductions of livestock numbers through the 1950s that included horses (Iverson 2002; Weisiger 2009). In 1943, District and Central Grazing Committees were implemented by the Navajo Nation Counsel to establish a limit for each land management unit on the Navajo Nation (CFR 25:167.6). Mandated reductions had a measurable effect on livestock numbers: For the period 1951–1955, average annual reported livestock numbers were 27 000 horses, 250 000 sheep, 49 000 goats, and 10 000 cattle (Young 1955). Currently, the Navajo Nation Department of Agriculture compiles an annual census of livestock based on reports by grazing permittees; however, these counts do not address free-roaming livestock, including horses, burros, and goats.

Multiple methods are available to estimate density of free-roaming horses, and differences in sampling design, survey methodology, and analytical approach can strongly affect the accuracy of results. For example, Lubow and Ransom (2009) found that failure to account for factors affecting detection of horses could produce density estimates that were 22.7% less than actual numbers. Numerous factors affect the ability of observers in aircraft to detect free-roaming horses, including horse group size, distance of horse groups from aircraft, vegetative cover, direction of sun during surveys, observer experience, observer fatigue, and position of observers in front or back seats of aircraft (Ransom 2012). Some of these issues can be avoided in survey design (i.e., observer experience, fatigue, and sun direction), while others should be addressed using analytical methods (i.e., horse group size, distance from aircraft, observer seating position, and vegetative cover). Although additional random factors may influence the accuracy of density estimates, current methods for survey design and analysis have greatly improved accuracy of population estimates for free-roaming horses (Ransom 2012) and other species, including golden eagles (*Aquila chrysaetos;* Good et al. 2007; Nielson et al. 2014), moose (*Alces;* Anderson and Lindzey 1996; Cumberland 2012; Fieberg et al. 2013; Wald and Nielson 2014), and polar bears (*Ursus maritimus;* Nielson et al. 2013).

In response to ongoing environmental impacts of free-roaming horse populations and recent concerns about a potential increase in their abundance, the Bureau of Indian Affairs and Navajo Nation Department of Fish and Wildlife (NNDFW) contracted Eagle Environmental, Inc. (EEI) to conduct the first systematic survey of free-roaming horses on the Navajo Nation. Our objective was to apply the most current methods in survey design and analysis to generate a scientifically robust estimate of the population size, density, and general distribution of free-roaming horses on the Navajo Nation.

Methods

Study area

Our study area was defined by the external boundary of the contiguous Navajo Nation, excluding the Reservation of the Hopi Tribe and Grand Canyon National Park Special Flight Rules Area (Fig. 1). This 67 089-km^2 area contained diverse vegetation and topography, including extensive desert shrublands and grasslands, forested mountains and foothills, pinyon-juniper woodlands, mesas, buttes, and canyons. Common plants of grassland and shrubland habitats included Indian ricegrass *(Achnatherum hymenoides),* western wheatgrass *(Pascopyrum smithii),* galleta *(Hillaria jamesii),* blue grama *(Bouteloua gracilis),* black grama *(Bouteloua eriopoda),* blackbrush *(Coleogyne ramosissima),* shadscale *(Atriplex confertifolia),* fourwing saltbush *(Atriplex canescens),* Mormon tea (*Ephedra* spp.), and big sagebrush *(Artemisia tridentata).* Montane conifer forests were dominated by ponderosa pine *(Pinus ponderosa),* and woodlands by Utah juniper *(Juniperus osteosperma)* and Colorado pinyon pine *(Pinus edulis)* (Griffith et al. 2014). Elevation ranged from 830 m at the confluence of the Little Colorado and Colorado Rivers on the western boundary of the Navajo Nation with Grand Canyon National Park to > 3 000 m on Navajo Mountain in Arizona and the Chuska Mountains on the Arizona–New Mexico border. Annual precipitation in this region averages 25.4 cm and varies with terrain and elevation (Western Regional Climate Center 2016).

Sampling design

We stratified the study area by forest cover to account for potential differences in density and detectability of horses in forested and open areas. We predicted horses in forested areas would be at lower densities and be more difficult for observers to see from low-flying aircraft than horses in open areas. To define the sampling strata, we identified contiguous areas of forested habitat, which consisted primarily of pinyon-juniper woodland and ponderosa pine forest, and defined all other areas as "open," which included primarily grassland, shrubland, and barren habitats. Our goal was to capture 95% of forested cells in the study area within a series of polygons that were large enough to be effectively sampled from the aircraft. To accomplish this, we processed a remotely sensed data layer of vegetation cover (LANDFIRE 2013) in a geographic information system (GIS; QGIS Geographic Information System Version 2.14, http://www.qgis.org/; accessed 1 March 2016) using the following steps: 1) selected all 30-m^2 cells classified as forest vegetation; 2) buffered forested cells by 1 km to fill gaps between clusters of cells; 3) dropped groups of adjacent cells with area < 5 km^2 to remove isolated stands; 4) dissolved borders of overlapping areas into larger connected polygons; 5) filled holes in polygons; and 6) removed polygons with < 100 km^2 area. The resulting forested stratum consisted of 11 discrete polygons that captured 95.7% of forested cells from the vegetation data layer and covered 19 629 km^2 (29%) of the study area. All other areas were included in the open stratum, which covered the remaining 47 460 km^2 of the study area (see Fig. 1).

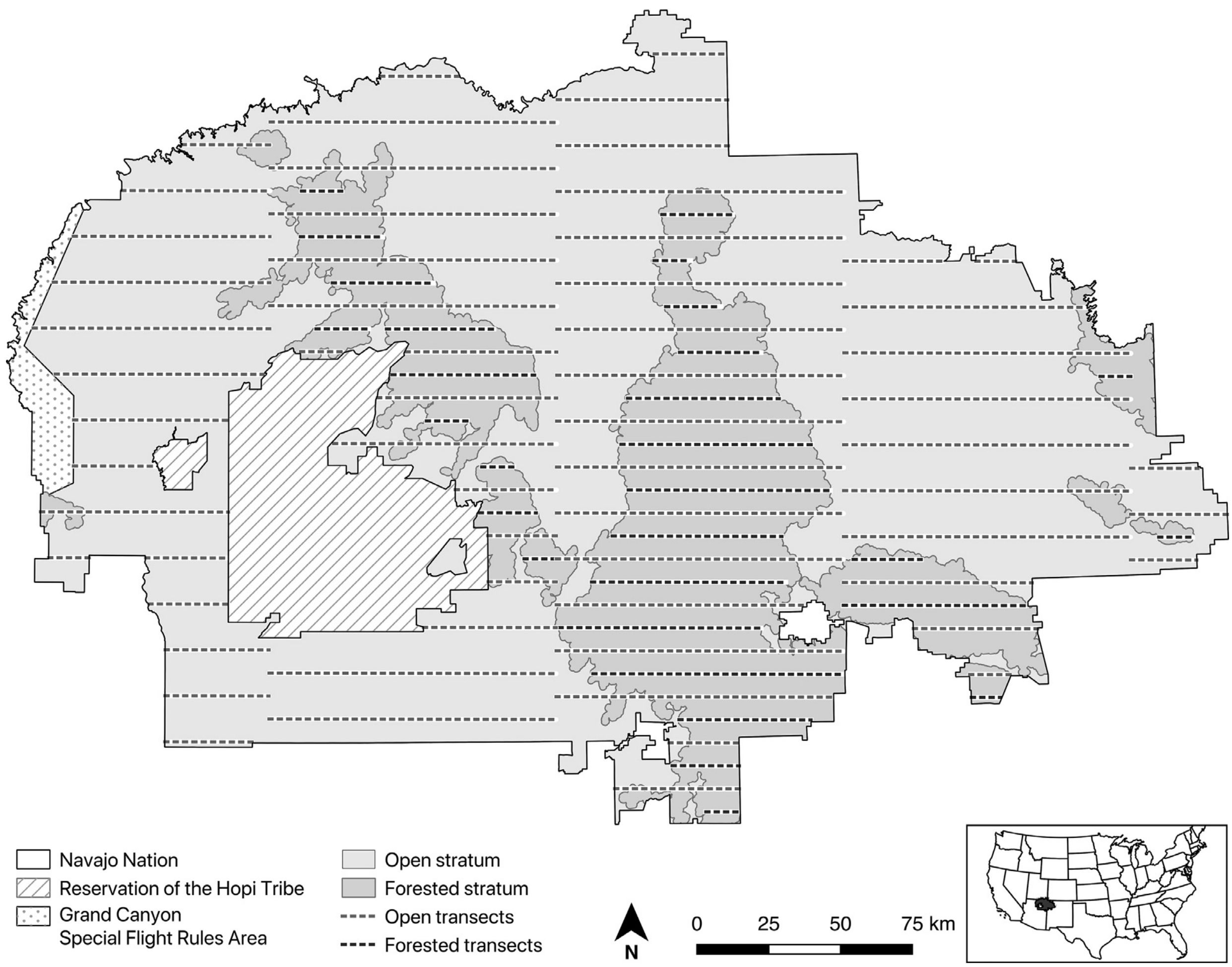

Fig. 1. Study area for survey of free-roaming horses on the Navajo Nation, including forest cover strata and line transects. Inset shows the United States with the Navajo Nation depicted in dark gray.

We established a systematic sample of east-west transects across the study area, based on a grid with a random start point. To ensure adequate sample sizes and approximately equal effort for both strata, north-south spacing of transects was 16 km in the open stratum and 8 km in the forested stratum. This resulted in a potential sample of 91 transects with a total length of 4 998 km, including 2 834 km in the open stratum and 2 164 km in the forested stratum. Transects averaged 55 km in length (range: 10–100 km), depending on the shape of the Navajo Nation boundary and forested areas (see Fig. 1). We surveyed five 50-km transects during early June to test our survey method and generate coarse estimates of time per transect, horse density, and detection probability. We based our sampling intensity on information from practice survey transects, scientific literature, and available funding.

Survey protocol

Transects were surveyed in a Cessna 206 airplane traveling at ~100 knots (185 kph). Surveys generally began by 0730 hours with a westbound transect to avoid flying toward the rising sun and ended by 1330 hours to minimize observer fatigue. We flew transects at 122 m (400 ft) above ground level (AGL) to minimize disturbance to horses, livestock, and wildlife. Relatively smooth terrain and favorable weather conditions enabled us to safely maintain consistent flight speed and altitude on linear transects over both open and forested areas. We used a simultaneous double-observer distance sampling (DS) protocol (Borchers 2006) that enabled us to produce estimates of horse density that accounted for the distance of detected horse groups from the transect line and different detection rates from the front and back seats of the aircraft. Three observers (seated front-right, back-right, and back-left) searched independently for horse groups. Seating positions were determined daily using a random number table, and all observers had ≥ 800 hr aerial wildlife survey experience. To ensure independence between observers, a cardboard partition separated the front-right and back-right seats, and observers on the right side allowed ≥ 5 sec to pass before announcing detections. This allowed both observers the opportunity to independently detect each horse group. We used an on-board Global Positioning System (GPS) to follow survey routes and record flight tracks. For each horse group detected, we recorded which observer(s) made the detection, a GPS waypoint at the location of the horse group when it was first detected, the number of horses in the group, estimated distance of the group from the transect line and from the nearest occupied dwelling, and habitat type. We defined horse groups as distinct aggregations of horses that were detected simultaneously by the observer, assumed group size was counted without error, and recorded waypoints at the approximate centroid of clusters. The pattern of detections and misses from this survey method were then used in a mark-recapture–style analysis to correct for differences in detection efficiency between the front and back seats of the aircraft. This survey methodology followed that outlined by Nielson et al. (2014). We timed surveys to occur in midsummer after foaling ended, and we recorded the number of foals in each horse group on the basis of their smaller size. At the request of NNDFW, all horses that were within corrals or fenced pastures were not counted during the survey. Upon completion of the survey, we used GIS to measure the perpendicular distance of each horse group from the transect line based on their GPS waypoint locations and survey flight tracks. We also recorded detections of feral burros using the same methods, although we did not anticipate sample sizes would be sufficient for analysis.

Statistical analysis

Our approach to estimating horse abundance based on aerial surveys was similar to that used to estimate abundance of golden eagles (*Aquila chrysaetos;* Nielson et al. 2014). This method generally followed the mark-recapture DS procedure described by Borchers et al. (2006) and consisted of 4 steps: 1) estimating the shape of the detection function, 2) using the mark-recapture data to properly scale the detection function, 3) integrating the scaled detection function to estimate the average probability of detection within the search area, and 4) applying standard DS methods to adjust the number of horses observed by the average probability of detection to estimate horse density (Buckland et al. 2001).

Lower detection probabilities at the nearest available sighting distance compared with greater distances farther from the transect line have been documented for surveys from fast-moving fixed wing aircraft (Becker and Quang 2009; Nielson et al. 2014). Given the speed at which the aircraft moves, objects closer to the transect line can be in an observer's field of view for less time and, thus, more difficult to detect. For this reason, we used a nonmonotonic, nonparametric, Gaussian kernel estimator (Wand and Jones 1995) to model the shapes of detection functions as a function of distance from the transect line (step 1; Chen 1999, 2000). The kernel density estimator used was of the form

$$\hat{f}(x) = (nh)^{-1} \sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right), \tag{1}$$

where x was a random perpendicular distance within the range of observed distances, x_i was one of the n observed distances, h was a smoothing parameter (bandwidth), and K was a kernel function satisfying the condition $\int K(x)dx = 1$. Estimation of the smoothing parameter (h) followed the "plug-in" procedure described by Sheather and Jones (1991). Based on theoretical considerations and recommendations in Park and Marron (1992), we used two iterations of functional estimation for our analysis.

Instead of assuming that probability of detection was known at some distance from the transect line (Buckland et al. 2001), we used the mark-recapture trials to estimate probability of detection at the distance from the transect line where probability of detection was highest, assuming point independence at that distance (Borchers et al. 2006). We assumed that the kernel distance function should equal the mark-recapture detection probability at the distance where detection rates were highest and scaled the kernel function appropriately (step 2; Borchers et al. 2006).

Analysis of the mark-recapture data involved estimating the conditional probability of detection by the front-seat observer (observer 1), given detection by the back-seat observer (observer 2) at distance x_i (labeled $p_{1|2}(x_i)$), and the probability of detection by observer 2, given detection by observer 1 (labeled $p_{2|1}(x_i)$). We used logistic regression (McCullagh and Nelder 1989) to model the conditional probability of detection for observer j ($j = 1,2$) using the equation

$$p_{j|3-j}(x_i) = \frac{\exp\left(\beta_{j|3-j} X_i\right)}{1 + \exp\left(\beta_{j|3-j} X_i\right)}, \tag{2}$$

where $\beta_{j|3-j}$ was the vector of coefficients to be estimated for observer j given detection by observer 3 – j, and X_i was a matrix of distance covariates. We considered three logistic regression models where probability of mark-recapture success was 1) constant at all distances (i.e., intercept term only) or related to a 2) linear or 3) quadratic function of distance from the transect line. For each observer position, we chose the model with the lowest value of the second-order variant of Akaike's Information Criterion (AIC$_c$; Burnham and Anderson 2002). Because mark-recapture trials were only conducted on the right side of the aircraft, we assumed probability of detection by the back-left observer (observer 3) was the same as $p_{2|1}$ because both back-seat positions had the same visibility, and we accounted for differences in individual skill by rotating observers randomly among seating positions in the aircraft.

Although observers surveyed independently within the aircraft, observers on the right side shared the same sighting platform; thus, groups of horses that were more likely to be detected by observer 1 were also more likely to be detected by observer 2. To properly scale the detection function (equation [1]), we needed to assume that the unconditional probability of detection $p_j(x_i)$ equaled the conditional probability of detection $p_{j|3-j}(x_i)$ at some distance from the transect line. The conditional probability is related to the unconditional probability as $p_{j|3-j}(x_i) = p_j(x_i)\delta(x_i)$, where $\delta(x_i)$ can be thought of as a bias factor (Borchers et al. 2006). Because $\delta(x_i)$ cannot be estimated from mark-recapture data (Borchers et al. 2006), we chose the distance from the transect line at which most observations occurred as the most likely candidate for offering a scenario where $\delta(x_i) = 1$, which allowed us to use the conditional estimates of probability of detection (equation [2]) to scale the detection functions. We identified where the largest number of observations by the front- and back-seat observers occurred on the basis of the location of the maximum value of estimated kernel detection functions (Borchers et al. 2006). Observations at this distance were least likely to depend on unmeasured factors that might have affected the detection process and most likely to provide point independence. We then scaled the detection function (equation [1]) so that the maximum height of the function was equal to mark-recapture probability (equation [2]) at the distance where the maximum occurred. For example, if the maximum of the kernel detection function for the back-left observer was at a distance of $x_{max[\hat{f}(x)]} = 200$ m and the mark-recapture probability of detection at 200 m for the back-seat observer was estimated as $\hat{p}_{2|1}(200) = 0.8$, then the kernel function (equation [1]) would be scaled such that $\hat{f}(200) = 0.8$. We calculated the conditional probability of detection on the right side of the aircraft at distance x_i by at least one observer when both observers were present was calculated as (Borchers et al. 2006)

$$\hat{p}^c_{\cdot}(x_i) = \hat{p}_{1|2}(x_i) + \hat{p}_{2|1}(x_i) - \hat{p}_{1|2}(x_i)\hat{p}_{2|1}(x_i), \tag{3}$$

and the detection function for observations on the right side of the aircraft when both right-side observers were present was scaled such that $\hat{f}(x_{\max[\hat{f}(x)]}) = \hat{p}^c_{\cdot}(x_{\max[\hat{f}(x)]})$.

We estimated detection functions and average group sizes for groups of horses observed while our aircraft was flying at 122 m AGL. The minimum available sighting distance for aerial horse surveys (W_1) was set to 55 m. Observers recorded all horse observations regardless of distance from the transect line, though the average probability of detection was estimated out to 1 500 m (W_2).

We calculated density estimates for all horses, including foals, within each stratum using a standard distance formula (Buckland et al. 2001):

$$\hat{D} = \frac{\sum_{i=1}^{n} s_i}{2(W_2 - W_1)L\hat{P}}, \tag{4}$$

where n was the number of observed horse groups; s_i was the size of the i^{th} group; W_1 and W_2 were the minimum and maximum sighting distances, respectively; L was the total length of transects flown (thus, $2[W_2 - W_1]L$ was the total area searched); and $\overline{P}$ was the estimated average probability of detection within the area searched ($\widehat{P_a}$ in Buckland et al. 2001, p. 53). We first calculated the total area searched for horses across all transects based on the AGL flown and estimated the density of horses ($\widehat{D}$) for each stratum. We calculated the estimated density for the entire study area as an area-weighted average of strata densities (Buckland et al. 2001).

Relatively large groups of individuals may be detected from a transect line more readily than smaller groups or individuals (Buckland et al. 2001). If so, average group size could be overestimated (Buckland et al. 2001) and introduce bias in equation [4]. We used Pearson's correlation analysis to investigate the relationship between group size and distance from the transect line. If the 90% CI for the estimated correlation coefficient did not include 0.0, indicating a statistically significant relationship at an alpha level of 0.10, we used the regression method (Buckland et al. 2001) to estimate average group size. In this method, horse group size is regressed against distance from transect and the horse group size at the maximum value of the kernel detection function is determined from this relationship and considered the average group size.

We bootstrapped (Manly 2006) individual transects to estimate standard errors (SEs) for estimates of horse abundance within the entire study area. This process involved taking 10 000 random samples with replacement and rerunning the analysis steps 1–4 to produce new estimates of horse abundance. We calculated SE of the estimated density using the standard deviation of the bootstrap replicates and the finite population correction factor (FPC; Cochran 1977):

$$\hat{D} \pm 1.65 \times \widehat{SE}\sqrt{\frac{A-a}{A}}, \tag{5}$$

where 1.65 is the 95th quantile of the normal distribution, A was the study area size, a was the area surveyed ($2[W_2 - W_1]L$), and $\sqrt{\frac{A-a}{A}}$ is the FPC. The FPC reduces the estimated variance by accounting for surveying a large portion of the study area, but it is often ignored when the sampling fraction is below 5% (Cochran 1977; Buckland et al. 2007). Unlike the closed form variance presented in Borchers et al. (2006) or Becker and Christ (2015), the bootstrap method accounts for the variance of the encounter rate along the transect (Fewster et al. 2009).

We used the R language and environment for statistical computing (R Version 3.1.1, www.r-project.org, accessed 1 September, 2016) to estimate densities and population totals of all horses and foals within strata and the entire study area.

Results

From 24 July to 3 August, 2016, we surveyed 89 transects across the Navajo Nation with a total length of 4 957 km. Only 23 km (< 0.5%) of transect segments were excluded for logistical reasons. On the basis of our search width ($w_2 - w_1 = 1$ 445 m), we visually surveyed 14 326 km^2, or 21% of the study area. Survey flights traversed a total of 2 820 km in the open area and 2 137 km in the forested area. We observed a total of 4 290 horses in 527 groups, with average group size of 8.14 horses (range: 1–75). We included in the analysis 502 observations that were within 1 500 m on either side of the aircraft, comprising 344 horse groups in the open stratum and 158 in forested stratum (Fig. 2). We observed 55 burros in 17 groups, with an average group size of 3.24 burros. Sample size of burros was not sufficient to make a density estimate for the study area. We estimated 22% of horse groups, and 14% of total horses observed were ≤ 250 m from a dwelling, with larger horse groups occurring farther from dwellings. Only 16 of 527 groups (3%) were running when detected or ran ahead of the circling aircraft. Additionally, we recorded 222 horses in 27 groups seen opportunistically off transects.

Table 1
Average probabilities of detection ($\bar{P}$) for free-roaming horse groups observed in open and forested strata of the Navajo Nation study area in summer 2016. Shown are the number of horse groups observed from each seating position in the aircraft (N) and estimated $\bar{P}$ with upper and lower limits of 90% confidence interval (CI).

Stratum	Position	N	$\bar{P}$	CI
Open	Back	159	0.433	0.485 0.344
	Front	137	0.526	0.569 0.430
	Both	NA	0.608	0.646 0.508
Forested	Back	60	0.329	0.392 0.244
	Front	64	0.308	0.361 0.235
	Both	NA	0.426	0.491 0.326

Table 2
Estimated numbers of free-roaming horses of all ages and of foals in open and forested strata of the Navajo Nation study area in summer 2016, with upper and lower limits of 90% confidence interval (CI).

Stratum	All age classes		Foals	
	Abundance	CI	Abundance	CI
Open	29 394	37 460 21 328	4 483	5 727 3 239
Forested	8 829	12 240 5 417	1 151	1 665 636
Overall	38 223	47 080 29 365	5 604	6 944 4 263

Detection probabilities were lower in forested areas ($\bar{P}$: 0.426, SE: 0.050, 90% CI: 0.326–0.491) than open areas ($\bar{P}$: 0.608, SE: 0.042, 90% CI: 0.508–0.646) and varied among observer seating positions (Table 1 and Fig. 3). Apex distances for detection were 431 m in open areas and 499 m in forested areas. The top logistic regression model for probability of mark-recapture success was constant (i.e., intercept term only) for all combinations of observer position and forest cover strata, except for front-seat observer in the open strata, which included a covariate for distance from survey transect. To account for a significant correlation between distance observed and horse group size in the open stratum (R: 0.175, SE: 0.053, 90% CI: 0.070–0.275), we used the average group size at the detection apex as the group size for all calculations.

We estimated a total of 38 223 horses of all ages were within the study area during the survey period (SE: 6 052, 90% CI: 29 365–47 080), including 29 394 horses in open areas (SE: 5 511, 90% CI: 21 328–37,460) and 8 829 horses in forested areas (SE: 2 331, 90% CI: 5 417–12 240; Table 2). On the basis of the ratio of horses classified as foals to the total number of horses observed ≤ 1 500 m from the transect line (1:5.82), we projected a total of 5 604 horses would have been classified as foals (SE: 916, 90% CI: 4,263–6,944), composed of 4 483 foals in open areas (SE: 850, 90% CI: 3 239–5 727) and 1 151 foals in forested areas (SE: 352, 90% CI: 636–1 665). Overall horse density was 0.570 horses/km^2 (SE: 0.090, 90% CI: 0.438–0.702), with 0.619 horses/km^2 in open areas (SE: 0.116, 90% CI: 0.449–0.789) and 0.450 horses/km^2 in forested areas (SE: 0.119, 90% CI: 0.276–0.624; Table 3).

Discussion

We conducted the first large-scale, systematic survey of free-roaming horses on Tribal Lands and provided robust estimates of abundance, density, and detectability. While comparisons of our estimates with historical and anecdotal reports from the Navajo

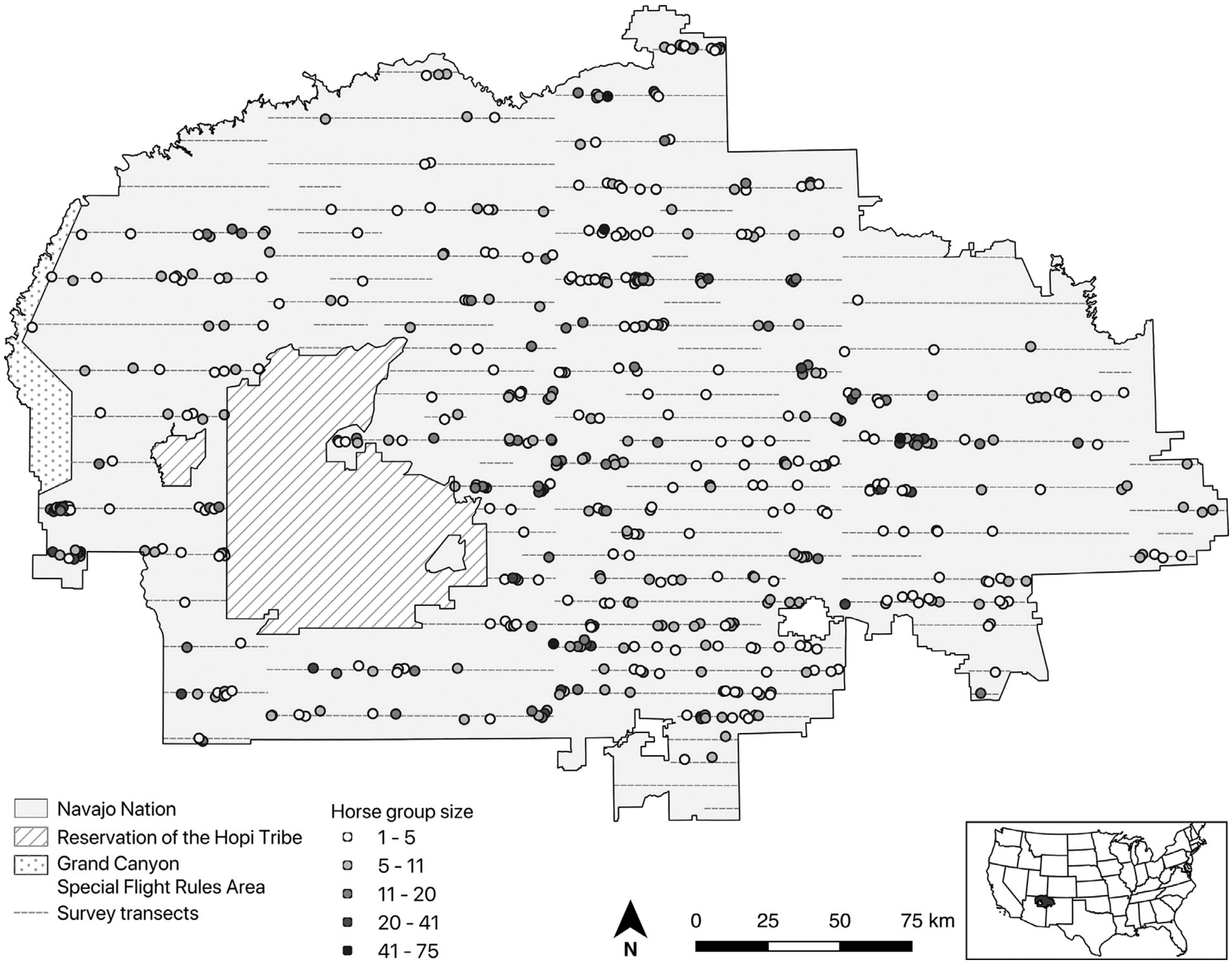

Fig. 2. Locations and sizes of horse groups detected during fixed-wing aerial surveys of the Navajo Nation study area in summer 2016. Inset shows the United States with the Navajo Nation depicted in dark gray.

Table 3
Estimated mean densities of free-roaming horses (horses/km^2) in open and forested strata of the Navajo Nation study area in summer 2016, with upper and lower limits of 90% confidence interval (CI).

Stratum	Density	CI
Open	0.619	0.789 0.449
Forested	0.450	0.624 0.276
Overall	0.570	0.702 0.438

Nation are confounded by differences in survey methods, comparisons with concurrent estimates from other areas suggest density of horses on the Navajo Nation was high: the average density of 0.570 horses/km^2 that we estimated within our 67 089-km^2 Navajo Nation study area was ~23% greater than the density of 0.465 horses and burros/km^2 reported for the 127 881 km^2 of BLM HMA in 2016 (BLM 2016). Moreover, the number of horses on BLM HMA in 2016 was more than twice the agency's target Appropriate Management Level (AML), defined as "the number of wild horses … that can thrive in balance with other public land resources and uses" (BLM 2016). Although the BLM's AMLs do not apply to Tribal Lands, similar concerns of prolonged, excessive grazing pressure exist on the Navajo Nation. Comparisons of our results with state-level estimates of horse abundance generated annually by BLM (2016) using a simultaneous double-observer method (Ransom 2012) also suggested a higher density of horses occurred within the Navajo Nation. Unfortunately, variances of BLM estimates are not publicly available. Nonetheless, estimated density of free-roaming horses on the Navajo Nation exceeded state-level densities of horses and burros in 6 of 10 western states, including Nevada, the only state with HMA of comparable size to the Navajo Nation (Fig. 4). States with higher densities had substantially smaller areas of HMA, compared with the size of the Navajo Nation (see Fig. 4). Within the desert southwest region, estimated abundance of horses on the Navajo Nation was greater than the total estimated number of horses on BLM HAs and HMAs in all states adjacent to the Navajo Nation: Arizona (318 horses), Colorado (1 530 horses), New Mexico (171 horses), and Utah (5 540 horses; BLM 2016). Although direct comparisons of survey and analysis methods are not possible, we expect our approach and the method used by BLM (Ransom 2012) both underestimated abundance due to availability bias. Compared with our study, BLM surveys are generally conducted in smaller areas (BLM 2016) with higher sampling intensity and the goal of maintaining a coefficient of variation (CV) < 10% (Bruce Lubow, IIF Data Solutions, unpublished report to Bureau of Land Management). While the CV of the overall abundance estimate in our study was slightly larger (15.8%), we assume the methods of both surveys are broadly comparable and suggest neither is likely to suffer from the large amount of bias that would be necessary to negate the differences in estimated abundance. Abundance of free-roaming horses on

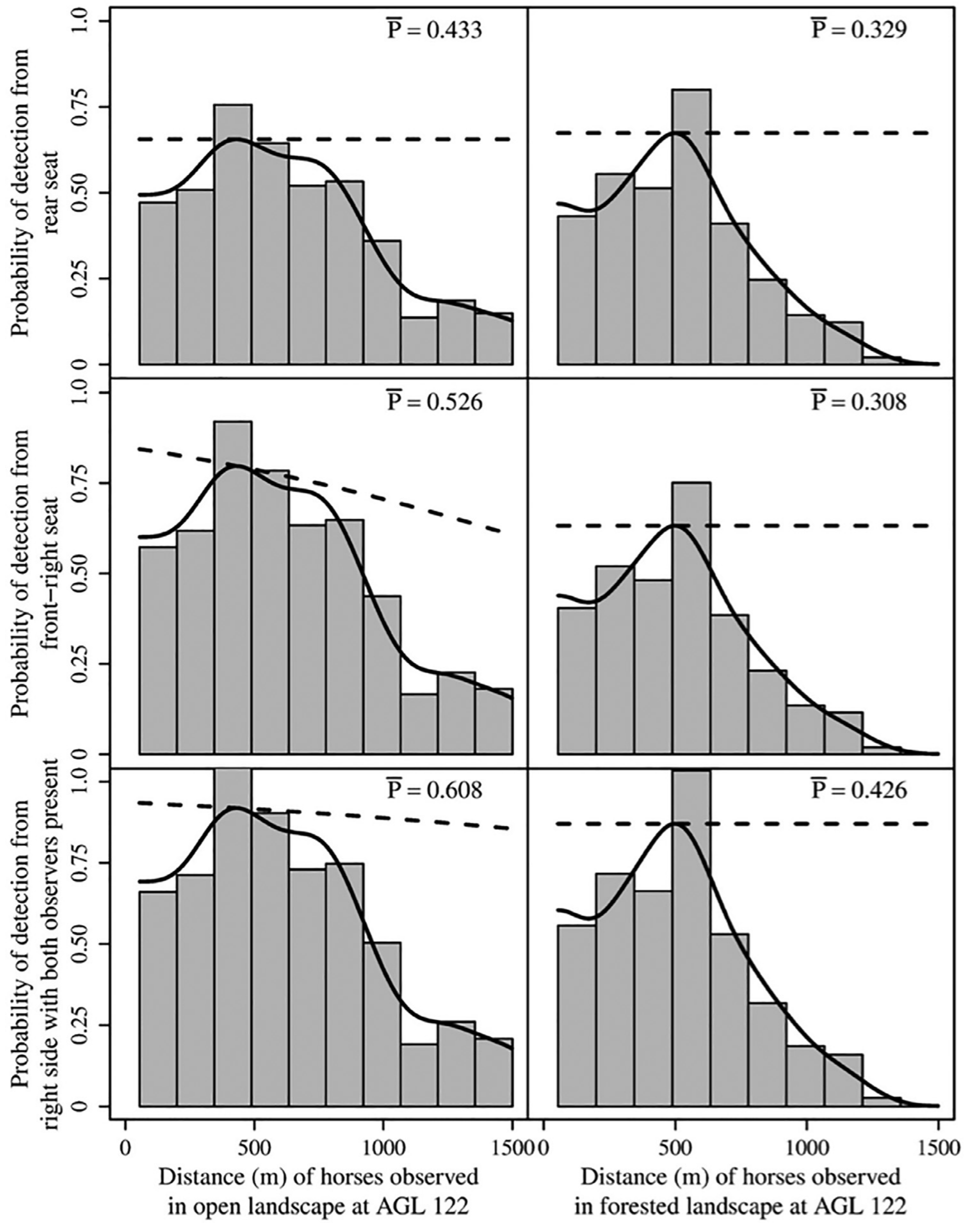

Fig. 3. Probability of detection of free-roaming horses from 122 m above ground level (AGL) in open areas (left) and forested areas (right) of the Navajo Nation study area in summer 2016. Dashed lines represent probabilities of detection estimated from mark-recapture sampling. Solid lines represent scaled detection functions that were integrated and divided by the search width to estimate the average probability of detection ($\bar{P}$) within 1 500 m of the transect line. Histograms show the relative numbers of observations in each distance interval.

the Navajo Nation also exceeded estimates for other Tribal Lands compiled by Beever et al. (2018). While some tribes with smaller land areas apparently had higher densities (e.g., 12 000 horses on 4 856 km^2 of the Yakama Nation), more information on survey methods and land areas is necessary for a quantitative comparison of our results with other Tribal Lands.

Overall detection probabilities from our study were within the range of other aerial surveys of horses (Lubow and Ransom 2016; Nielson et al. 2016). As we predicted, horse density and detectability were higher in open areas than forested areas, and we accounted for these differences by stratifying the study area by forest cover. Lower horse density in forests likely reflected less availability of suitable forage in pinyon-juniper woodlands and montane forests than open rangelands. Detection probabilities in forested areas were more similar among front- and back-seat observers, suggesting the higher detection rate from the front seat that we experienced in open areas was offset by overall lower visibility from both seats in forested areas. Detection rates also peaked at a greater distance from the transect line in forested areas, compared with open areas. This counterintuitive result can be explained by the fact that close objects move through the observers' view faster than objects farther away, and it may be easier to detect groups under cover from an angle, rather than more directly overhead.

Estimates of abundance from distance sampling rely on the assumption that individuals at the detection apex are available to be detected (Laake et al. 2008). Thus, individual horses that could not have been seen by either observer due to their location in the landscape are not represented in equation 4 (see "Statistical Analysis" earlier). An additional form of dependence is for horse groups obscured by vegetation or terrain beyond the detection apex, to the point they are unavailable to be seen by both observers. We acknowledge that any horses that were not available for detection

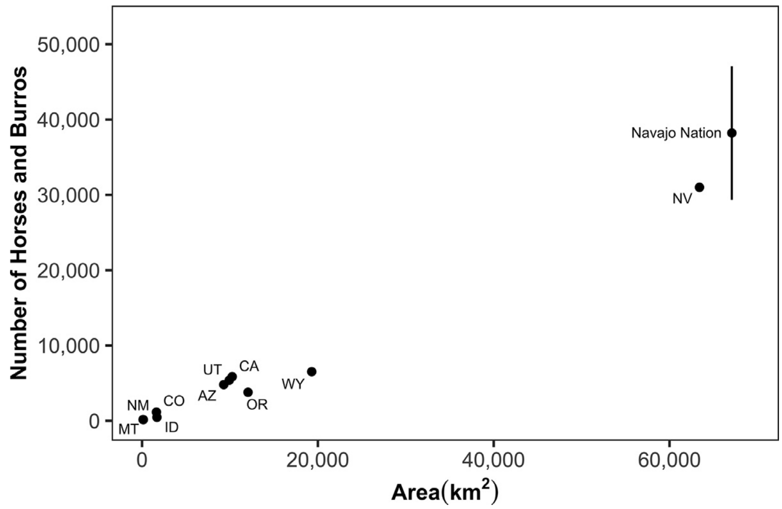

Fig. 4. State-level estimates of mean feral horse and burro abundance in Bureau of Land Management (BLM) herd management areas (BLM 2016), compared with estimated abundance of free-roaming horses on the Navajo Nation from this study. Estimated mean abundance for the Navajo Nation is shown with 90% confidence interval. Variances of BLM estimates are not publicly available.

during our survey could cause our estimates of total abundance to be lower than those from surveys using different methods or conducted at other times of the year. Given the timing of the survey in midsummer, we were initially concerned that horses in open habitats would seek shade under trees or in canyons, where they would not be available for detection; however, during the survey we were encouraged by observing many horse groups on the open range during midday. This may have been influenced by a monsoon season green-up that occurred just before our survey, compared with the substantially drier range conditions we observed in prior months while conducting other wildlife surveys in the study area. Repeating this survey in other seasons or comparing results with ground-based counts could address potential availability bias (e.g., Lubow and Ransom 2016) and enable comparison of distribution patterns with vegetation variables.

We stratified our study area and estimated separate detection functions for open and forested areas because we predicted forest cover was the primary factor that would influence detection probability. Our modeling approach also enabled us to account for the distance and size of horse groups, as well as observer position in the aircraft. We did not observe a strong relationship between group size and distance from the transect line, so we used the average group size of observations at the minimum available sighting distance, or the optimum detection distance, in the analysis. This assumed that group sizes at those distances represented all groups and that the probability of detecting groups of different sizes was independent of observer position in the aircraft. We addressed other potential influences on detection probability in the design of our survey methodology, including airspeed, observer, flight direction, and time of day. Alternative analytical approaches, such as the two-part normal detection function model of Becker and Christ (2015), could be useful to incorporate covariates into the DS model in future studies, especially in situations where important factors cannot be addressed in the sampling design or survey methodology.

Estimates from distance sampling also depend on accuracy of recorded locations and flight tracks used to measure perpendicular distances of observations from transects. While GPS technology allows locations to be recorded precisely, location accuracy ultimately depends on the ability of observers and pilots to identify and navigate to the point at which each group was first detected. We assumed group size was counted without error but acknowledge undercounting could cause a negative bias in density estimates (Cogan and Diefenbach 1998). We expect bias from these sources was minimal in our study because horse groups were relatively easy to relocate and count. Furthermore, most groups remained stationary while we circled to record a GPS location; only 3% of groups were running when detected or ran ahead of the circling aircraft. We suggest future surveys should also document flushing and running behavior of horses, apply appropriate analytical methods to account for bias from movement in response to aircraft if necessary (Conn and Alisauskas 2018), and use fixed-wing aircraft because they may be less likely to disturb horses than helicopters (Lubow and Ransom 2016). Classification of horses as foals or adults was based on visual judgment of relative size and thus subject to unknown error. Future surveys should consider photographing horse groups to verify age classifications and counts.

Unlike public rangelands, where all horses unaccompanied by a person can be defined as feral, horses on the Navajo Nation represent a continuum from domestic to feral. This spectrum extends from domesticated horses that are corralled and fed, to groups of free-roaming horses that live close to dwellings and may receive supplementary feeding, to large herds distant from dwellings that receive little or no supplementary feeding or contact with humans. On most western US rangelands, a few large ranches control livestock grazing on extensive tracts of deeded and leased acreage. By contrast, the Navajo Nation is characterized by widely scattered, small homesteads of Tribal permittees located within grazing allotments, each of which supports an assortment of livestock that typically includes horses. Given the complexity of this situation and to be consistent with Navajo Nation grazing regulations, NNDFW recommended we count all horses that were not confined to corrals. As such, our results should be interpreted as a point-in-time estimate of the number of uncorralled horses in the study area. Accordingly, we have used the term “free-roaming” for the horse population we sampled and acknowledge that our estimates may have included an unknown number of horses that were not technically feral, insofar as they were owned or supported by humans. To explore this issue, we made visual estimates of the distance of each horse group to the nearest occupied dwelling that was detected. We estimated 22% of horse groups and 14% of total horses were $\leq$ 250 m from a dwelling when observed, with larger horse groups tending to occur farther from dwellings. While these results indicate that some free-roaming horses are associated with towns and dwellings, they confirm that most horses documented during this survey were not close to dwellings.

The high abundance of the free-roaming horses documented in this study, combined with rapid growth rates (Garrott et al. 1991) and density-dependent dispersal (Berger 1987) of feral horse populations, could make the Navajo Nation a source for feral horses in the region. Although little is known about movement patterns of feral horses, regional wildlife managers have reported free-roaming horses crossing the northern, eastern, and western borders of the Navajo Nation onto public lands managed by the US Forest Service and Bureau of Land Management (J. Cole, Unpublished results). Feral horses use large areas: home ranges of herds in Wyoming were 73–303 km^2 (Miller 1983), while the only satellite telemetry study of space use by feral horses reported that they moved 8–28 km/d and ranged up to 55 km from water sources (Hampson et al. 2010). Despite maintaining large home ranges, the only study of dispersal in feral horses suggested male horses dispersed relatively short distances of $<$ 13 km (Berger 1987). Given the broad ranges of resident herds and apparently short dispersal distances, impacts from feral horses may be limited to lands immediately surrounding the Navajo Nation. Future research is necessary to understand dispersal and expansion of feral horse populations and evaluate the potential for source-sink dynamics between the Navajo Nation and surrounding areas.

Implications

Options available for management of free-roaming horse populations vary in cost, effectiveness, and social acceptability; they include roundup and offsite storage (Ward et al. 2016), temporary (Rutberg et al. 2017) or permanent (Collins and Kasbohm 2017) fertility control, and lethal control (Lawler and Geyer 2015). On the basis of our findings, management measures chosen by NNDFW to control the population of free-roaming horses would be best applied in open habitats, where the largest herds of free-roaming horses occurred far from dwellings. This could minimize conflict with proprietors of semidomesticated horses while focusing efforts on the largest herds.

The systematic random sample of transects established here could be resurveyed in future years to estimate trends in free-roaming horse populations. Surveys could also be repeated after management actions to assess their effectiveness or conducted in concert with ground-based surveys to compare estimates. Additional analyses possible using the data collected include developing habitat-use models to predict distribution of horses across the study area and identify environmental factors driving habitat selection. Resulting maps of horse occurrence could be coupled with spatial data on stocking rates and range condition to identify areas where efforts to manage horses would be most beneficial.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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