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Exploring golden eagle habitat preference using lidar-based canopy bulk density

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ABSTRACT

A lidar-derived canopy height profile (CHP), generated from canopy bulk density (CBD) estimates for a sequence of 1-m increments through the canopy, provides a physical measure of forest structure. Measurement of physical properties are intuitively understandable and thus facilitate the use of lidar for investigating hypotheses regarding avian resource use. We illustrate the use of lidar-derived physical measures to explore the hypothesis that golden eagles (*Aquila chrysaetos*) prefer an open understory, which potentially aids visual identification of prey. Two golden eagles fitted with GPS tracking devices overwintered in the New Jersey Pinelands National Preserve. We generated CHPs from discrete-return lidar data for an area occupied by the birds. We compared the CHPs of sites the birds occupied to the surrounding available habitat and found that the occupied sites were significantly lower in CBD from the ground up to 5 m for perched/stationary birds, and from the ground up to 8 m for birds in flight. These results could be used by forest resource managers for promoting golden eagle habitat through prescribed fire. In addition, these results demonstrate the power of lidar to generate physically and intuitively meaningful measures of forest structure.

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1. Introduction

Light detection and ranging (lidar) data can be used to generate detailed forest structure information that has proved to be useful for characterizing avian habitat (Vierling, Swift, Hudak, Vogeler, and Vierling 2014). In habitat modelling, keeping the number of explanatory variables small is generally regarded as desirable, in part because the fewer the variables, the easier it is to understand the model. For this reason, many lidar-based forest structure studies focus on summary, integrative measures that describe overall properties of the canopy, such as mean, skewness, percentiles or other statistical measures of the distribution of the lidar returns (Acebes, Lillo, and Jaime-González 2021). However,

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physically based metrics that describe the distribution of biomass in the canopy can be particularly useful for exploring and understanding habitat characteristics. Nevertheless, physically based estimates of forest structure using lidar that go beyond measures of height and canopy cover (e.g., Hagar, Yost, and Haggerty 2020) are only rarely used for avian studies. In this paper, we illustrate the potential of canopy height profile data for answering questions regarding golden eagle (*Aquila chrysaetos*) habitat preference. Specifically, we explore the hypothesis that golden eagles preferentially occupy habitat with an open understory, which would facilitate the finding of prey, whether in flight or perched.

The golden eagle is one of the largest raptors in the world, and has a broad distribution across North America, Eurasia and parts of North Africa (Katzner, Kochert, Steenhof, McIntyre, Craig, and Miller 2020). Superb hunters, golden eagles mostly prey on leporids (e.g., hares and rabbits), sciurids (e.g., squirrels), and waterfowl; carrion can also be an important part of their diet, especially in the winter months (Bedrosian, Watson, Steenhof, Kochert, Preston, Woodbridge, and Crandall 2017; Katzner, Kochert, Steenhof, McIntyre, Craig, and Miller 2020). Golden eagles hunt from flight or when perched, typically on prominent sites, but also within the canopy (Katzner, Kochert, Steenhof, McIntyre, Craig, and Miller 2020, Miller personal observation). Research on the ecology of the golden eagle, including its habitat, is of interest in support of conservation of the species (Katzner, Smith, Miller, Brandes, Cooper, Lanzone, and Bildstein 2012). Habitat can have both direct and indirect influences on the availability and ease of hunting of prey. For example, reduced breeding success was observed once a closed-canopy forest formed following afforestation in Scotland (Watson 1992). However, characterizing the golden eagle's habitat can be challenging due to low population densities, especially in the Eastern U.S. (Morneau, Tremblay, Todd, Chubbs, Maisonneuve, Lemaître, and Katzner 2015; Katzner, Kochert, Steenhof, McIntyre, Craig, and Miller 2020). Tracking devices can overcome some of these challenges by generating highly detailed information regarding animal movement and habitat use. Lidar-derived habitat information provides a valuable complement to avian telemetry data, because it potentially can be used to characterize the habitat at each of the locations occupied, something that would generally not be feasible using field work.

2. Study area, data and pre-processing

2.1. Study area

The study area is within the New Jersey Pinelands National Reserve (PNR) in Burlington County, New Jersey (Figure 1). The PNR covers 445,000 ha in seven counties and is an International Biosphere Region (Pinelands Commission 2021). The region is relatively flat, and underlain by sandy, acidic soils. The upland forests grade from pure pine (dominantly *Pinus rigida* Mill.) to pure oak (including *Quercus alba* L.*Q. velutina* Lam., *Q. coccinea* Muenchh. and *Q. prinus* Willd.) (Little 1998). The PNR ecosystem is fire-adapted, with fire generally promoting pioneer pine species. Fire was likely more frequent in the pre-European era; for the last ~80 years, fire in the PNR has included prescribed burns and occasional wildfires (La Puma, Lathrop, and Keuler 2013).

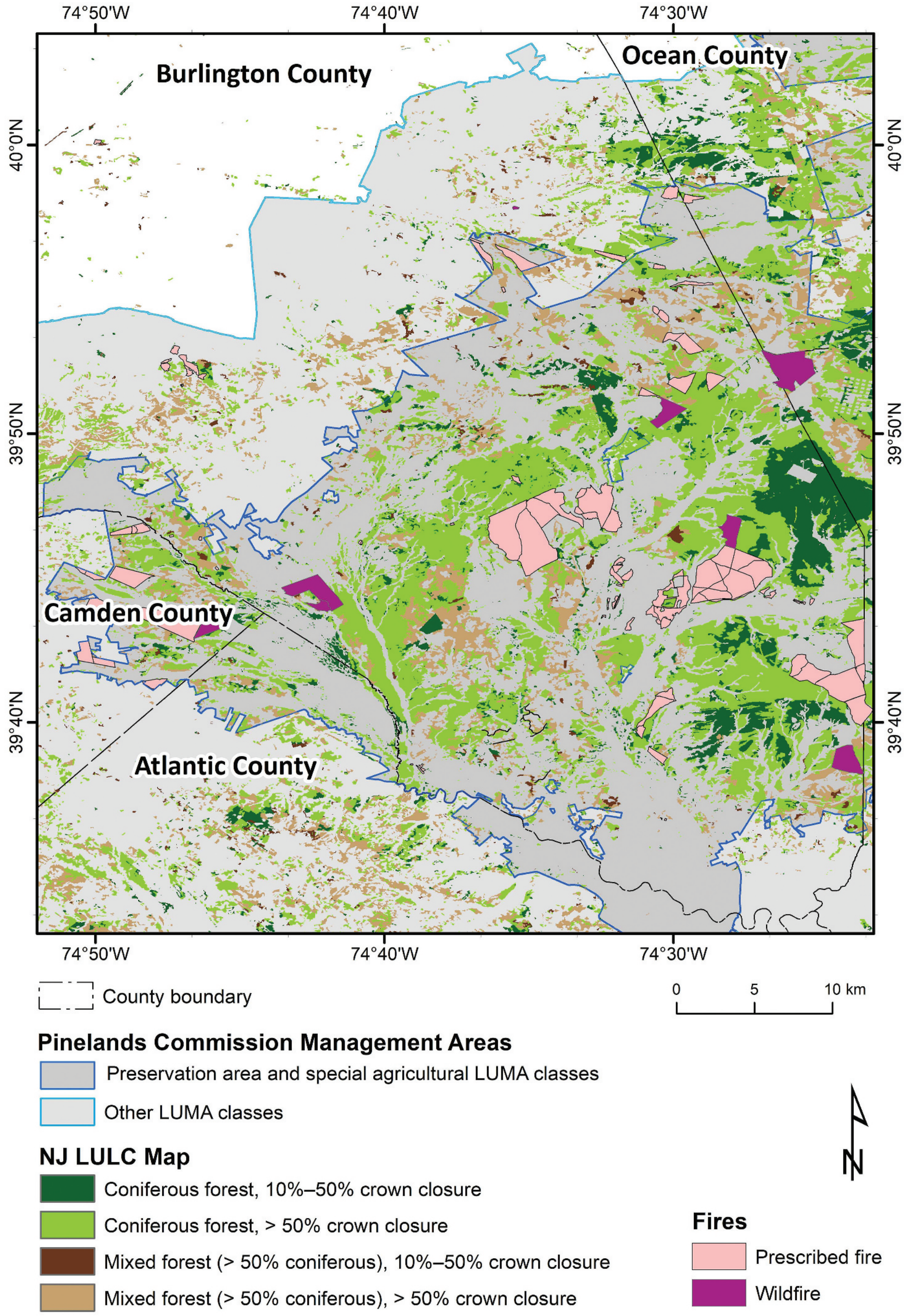

Figure 1. The study area. Selected land use/land cover (LULC) classes (New Jersey Department of Environmental Protection 2015) and Pinelands Land Use Management Area (LUMA) Classes (Pinelands Commission 2021). Boundaries of fires during the period between the lidar acquisition and golden eagle telemetry data are also shown.

The Pinelands Commission, a legislatively mandated oversight organization for the PNR, has classified the region into nine land use management areas (LUMA classes) (Pinelands Commission 2021). The largest LUMA is the Preservation Area District, which is characterized by large, contiguous areas of wilderness-like forest. Special Agricultural Production Areas, which are primarily used for berry agriculture and cultivation of native plants, include large blocks of forest, and therefore are combined with the Preservation Area District in Figure 1 Other management areas include zones associated with other agriculture, low density residential development and small villages, all of which are grouped under 'Other LUMA classes' in Figure 1.

2.2. Golden eagle GPS location data

Two golden eagles (labelled 252 and 253) were captured in 2016 and fitted with solar global positioning systems (GPS) tracking devices (Cellular Tracking Technologies (CTT), LLC, Rio Grande, NJ). Bird 253, a hatch-year male, was recorded in the study area between 17 October 2016 and 24 October 2016, and bird 252, an adult female, was recorded in the study area between 25 December 2016 and 13 March 2017 (Figure 2).

GPS data were collected from 1 h before sunrise to 1 h after sunset and stored onboard the telemetry unit. The unit attempted to send the data via the cellular phone network once per day to CTT servers. An onboard accelerometer, used to detect movement, estimated when the eagle was in flight, and if so, increased GPS data collection to 6 s intervals. After detecting more than 1 min of stationary behaviour, the data collection cycle decreased to 15 min intervals to conserve battery power. Information collected by the GPS included position, altitude above mean sea level (m), velocity (km $hour^{-1}$), course over ground (°), and measures of vertical and horizontal error. Using velocity recorded by the GPS, we categorized data as one of four classes: *flight* (>2 km $hour^{-1}$), *flight or perched/stationary* (>1 and <2 km $hour^{-1}$), *likely perched/stationary* (>0 and <1 km $hour^{-1}$), or *perched/stationary* (0 km $hour^{-1}$).

2.3. Lidar data and pre-processing

Discrete return lidar data of the study area were collected in April 2015, a little less than two years prior to the bird data collection. The Leica Geosystems (Heerbrugg, Switzerland) lidar sensor was able to collect up to four returns per outgoing pulse. The maximum scan angle was set to 36°, the flying height was 1580 m, and an average of 8 points/m^2 was collected. The resulting bare earth digital elevation model was estimated to have a vertical uncertainty of 4.1 cm (Quantum Spatial Inc 2015).

The lidar data were processed to generate canopy height profile (CHP) data. CHP is a lidar-based metric originally developed for large-footprint, full waveform lidar data, in order to describe the vertical distribution of foliage (Lefsky et al. 1999). Skowronski, Clark, Duveneck, and Hom (2011) used discrete lidar data to generate a CHP based on canopy bulk density (CBD), a measure of biomass per unit volume. Relative CHP is calculated as the proportion of incoming lidar pulses for an arbitrary area (i.e., a pixel) that are returned from within a specified height interval (i.e., voxel), typically 1 m. The CBD values within each pixel's CHP are calculated from the top of the canopy down, to facilitate correction

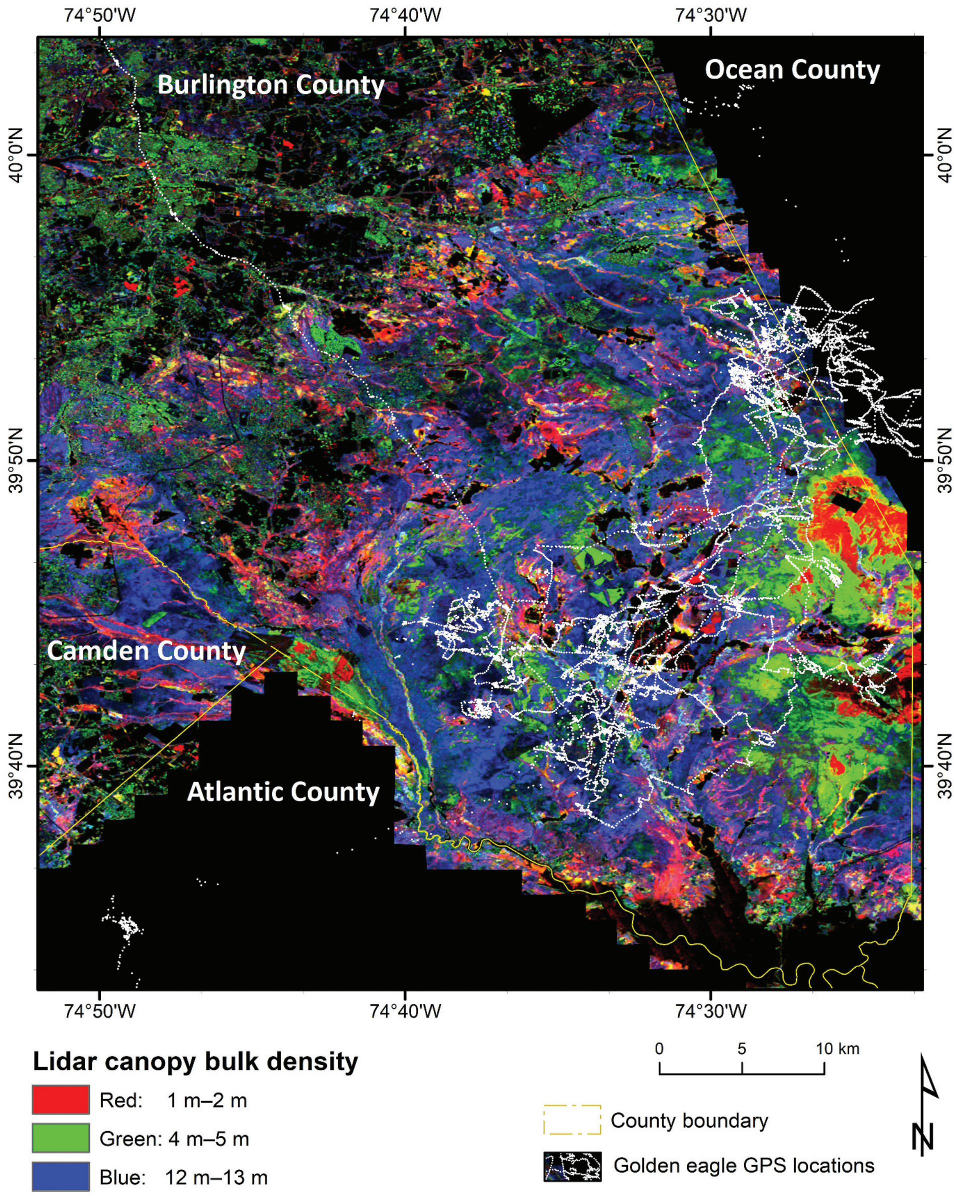

Figure 2. Lidar-derived canopy bulk density for selected layers (1–2 m, 4–5 m and 12–13 m). The lidar data were acquired in April 2015. Also shown are the golden eagle GPS locations from October 2016 to March 2017.

for the reduction in the number of incoming pulses due to occlusion by canopy in the voxels above (Skowronski, Clark, Duveneck, and Hom 2011; Skowronski, Gallagher, and Warner 2020; Warner, Skowronski, and La Puma 2020).

We generated CHPs with 23 vertical layers, using 30 m × 30 m (horizontal) × 1 m (vertical) voxels using the Toolbox for Lidar Data Filtering and Forest Studies (Tiffs; Chen 2007). The voxel dimensions were chosen to allow the representation of even tall trees (up to 23 m), and also to ensure a sufficient number of lidar returns within each layer to characterize the biomass. The relative CBD was converted to physical units using the field measurement-derived empirical conversion of Skowronski, Clark, Duveneck, and Hom (2011) for this region:

$$CBD_{bin} = 0.182\rho_{bin} + 0.005 \quad (1)$$

where CBD_{bin} is the CBD for the voxel, with units of kg m^{-3}, ρ is the relative CBD as described above, and the subscript bin is the voxel height label. Based on our previous experience (Warner, Skowronski, and La Puma 2020), in which we found that a slight smoothing of the CBD data improved the correlation with field measurements, we applied a Gaussian low-pass filter of size 3×3 pixels, and .85 standard deviation.

Figure 2 is a false composite formed by three sets of heights (voxels) from the CHP data. Areas in red are dominated by biomass close to the ground (the 1–2 m layer), green at intermediate heights (4–5 m), and blue at higher values (12–13 m). Developed areas have little vegetation and have characteristically dark tones and speckled appearance in the image. Open water and areas where no data were collected (Ocean and Atlantic counties), are depicted in black.

2.4. Other data sets

The digital land use/land cover (LULC) of New Jersey 2012 map (New Jersey Department of Environmental Protection 2015), generated through visual interpretation of aerial and satellite imagery, was used to constrain the analysis to upland coniferous-dominated forests, in order to minimize confounding effects from different forest and land use types in the analysis. Specifically, we selected the coniferous forest classes of 4210 and 4220 (10–50% and >50% crown closure, respectively) and coniferous-dominated mixed forest classes of 4311 and 4312 (10–50% and >50% crown closure, respectively) (Figure 3).

As noted above, there was slightly less than 2 years between the lidar data acquisition and the collection of the golden eagle telemetry. However, Vierling, Swift, Hudak, Vogeler, and Vierling (2014) found that a six-year gap between lidar acquisition and avian field data, a considerably longer period than in this study, had only minimal effect on their results. For our study, the only major change during this time that could be observed in the lidar data in the PNR area of interest was due to fire. We therefore obtained a vector database of PNR fire boundaries, established by La Puma, Lathrop, and Keuler (2013) and maintained by New Jersey Forest Fire Service, to mask areas that experienced fire after the lidar collection date.

3. Methods

We evaluated the golden eagle habitat preferences by comparing the distribution of CBD values in the sites occupied to the CBD distribution in the available habitat (upland coniferous and coniferous-dominated mixed forest occurring within the Pinelands Commission Preservation Area District and Special Agricultural areas of Burlington County; Figure 1). The GPS telemetry data within the area defined as available habitat comprised 3,873 *flight*, 519 *flight or perched/stationary*, 2,315 *likely perched/stationary* and 1,532 *perched/stationary* points, totaling 8,239 points. As a final step, the GPS points were

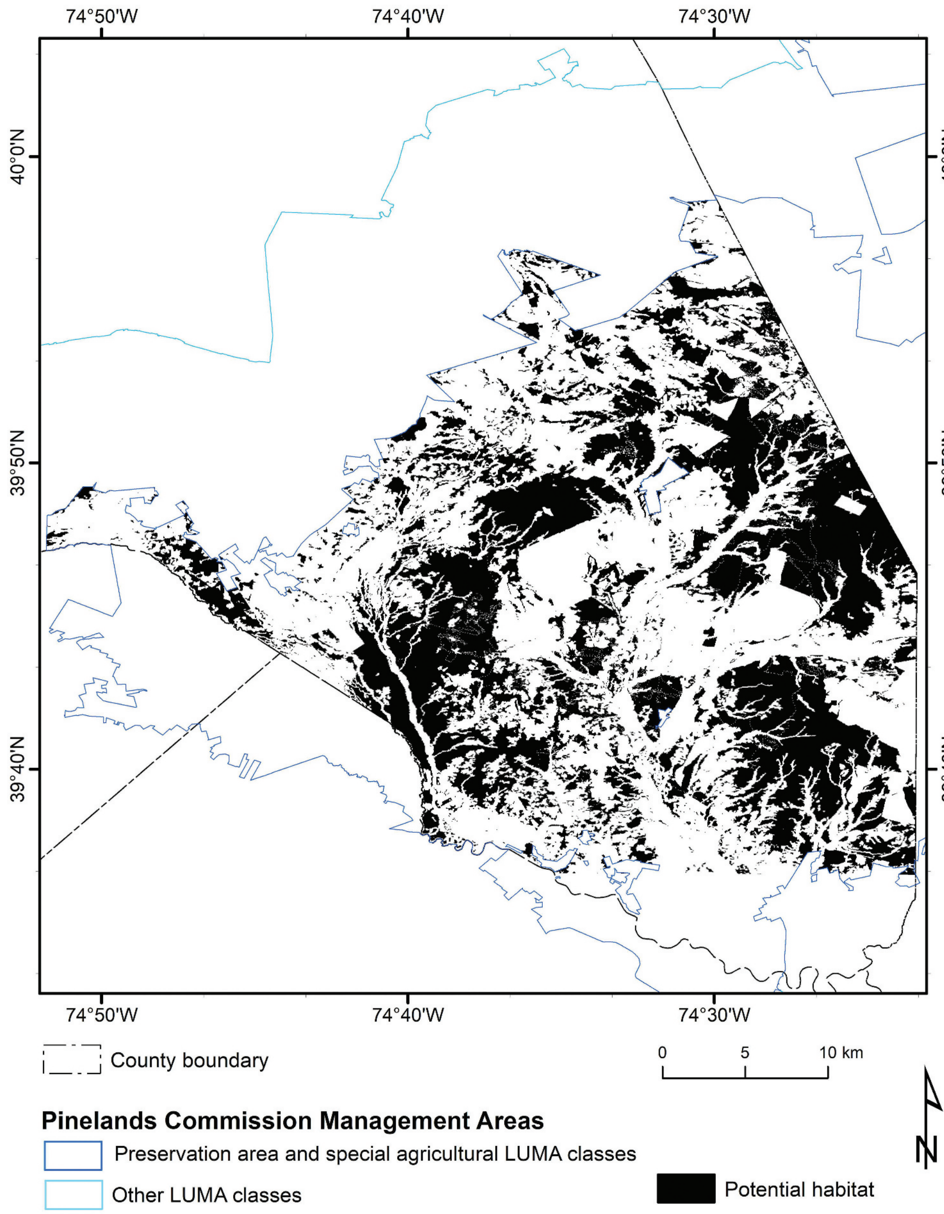

Figure 3. Pixels defined as potential habitat for the statistical analysis.

also masked in the available habitat raster, so that there would be no overlap between the occupied points and the available (but not recorded as having been occupied) habitat. This resulted in 368,882 pixels defined as available habitat (Figure 3).

We used the R function wilcox.test in the 'stats' package v4.0.0 (R Core Team 2020) to run a non-parametric Wilcoxon rank sum test (equivalent to a Mann-Whitney U test) (Hogg, Tanis, and Zimmerman 2020). The null hypothesis was that, for each 1 m stratum within the forest, there was no difference between the distributions of forest CBD values for the available habitat and the habitat occupied by the golden eagles. The alternative hypothesis was that the distribution of CBD values in the occupied sites was lower than that of the potential habitat (i.e., the test is one-tailed). The statistical analysis was initially carried out on all the eagle GPS data. The analysis was then repeated, with two separate analyses using only GPS data classified as *flight* and *perched* (the classes of *flight or perched/stationary*, and *likely perched/stationary* were excluded in these subsequent analyses, since these locations had uncertainty in their designation). Because the analysis involved multiple comparisons, we used the Benjamini–Hochberg procedure to control the false discovery rate (incorrect rejections of the null hypothesis) at a critical value of .05 (Benjamini and Hochberg 1995).

4. Results

In Figure 4, the distribution of CBD values for each stratum is shown graphically using violin plots. Distributions for which occupied sites were found to be significantly lower than that of the overall habitat are shown by the asterisks (*). Combining all GPS points, the lower six strata (1–6 m) and also the uppermost layer (23 m) had significantly lower CBD distributions than the available habitat distributions (Figure 4(a)). When the *flight* and *perched/stationary* classes were analyzed separately, a similar pattern was found, with the lower 1–5 m strata and uppermost 23 m layer having a significantly lower distribution in CBD values (Figure 4(b)). For locations classified as *flight*, significantly lower CBD distributions were found for layers 1–8 m, and the uppermost three layers (21–23 m) (Figure 4(c)).

5. Discussion

The statistical analysis indicates that golden eagles in flight preferentially utilized forest that was significantly more open (had a lower CBD) from the ground up to 8 m, and when perched, the birds favored a more open understory up to 5 m. Similar results were found for the analysis for all points. These results confirmed our hypothesis that golden eagles preferred forest habitat with a relatively open understory. The fact that the flight locations, like the perched locations, favoured an open understory, and in fact one that extends higher into the canopy (8 m vs 5 m), suggest that the golden eagle may hunt when in flight, and not just when perched. The preference for a lower CBD in the upper canopy (20 m and above) was not expected. However, at these levels, many CBD values were 0 kg m^{-3}, because the forests are mostly less than 20 m high. Thus, the results at the upper end of the canopy should be treated with caution.

These results could be useful for golden eagle conservation. Our previous research generally indicated that CBD in each of the canopy layers (1–23 m) shows an association with the number of previous fires and the types of fires that an area experienced (Warner, Skowronski, and La Puma 2020). The number of prescribed fires was associated with reduced CBD from 1 to 14 m, whereas the number of wildfires was associated with increased CBD from 1 to 7 m. Therefore, prescribed fire could potentially be used to increase the development of a more open understory the golden eagle seems to favour.

The strengths of this study include the fine spatial and temporal resolution of the telemetry data, which provided more than two and a half months of continuous monitoring. In addition, the lidar data gave us a detailed 3D view of the structure of the forest at every

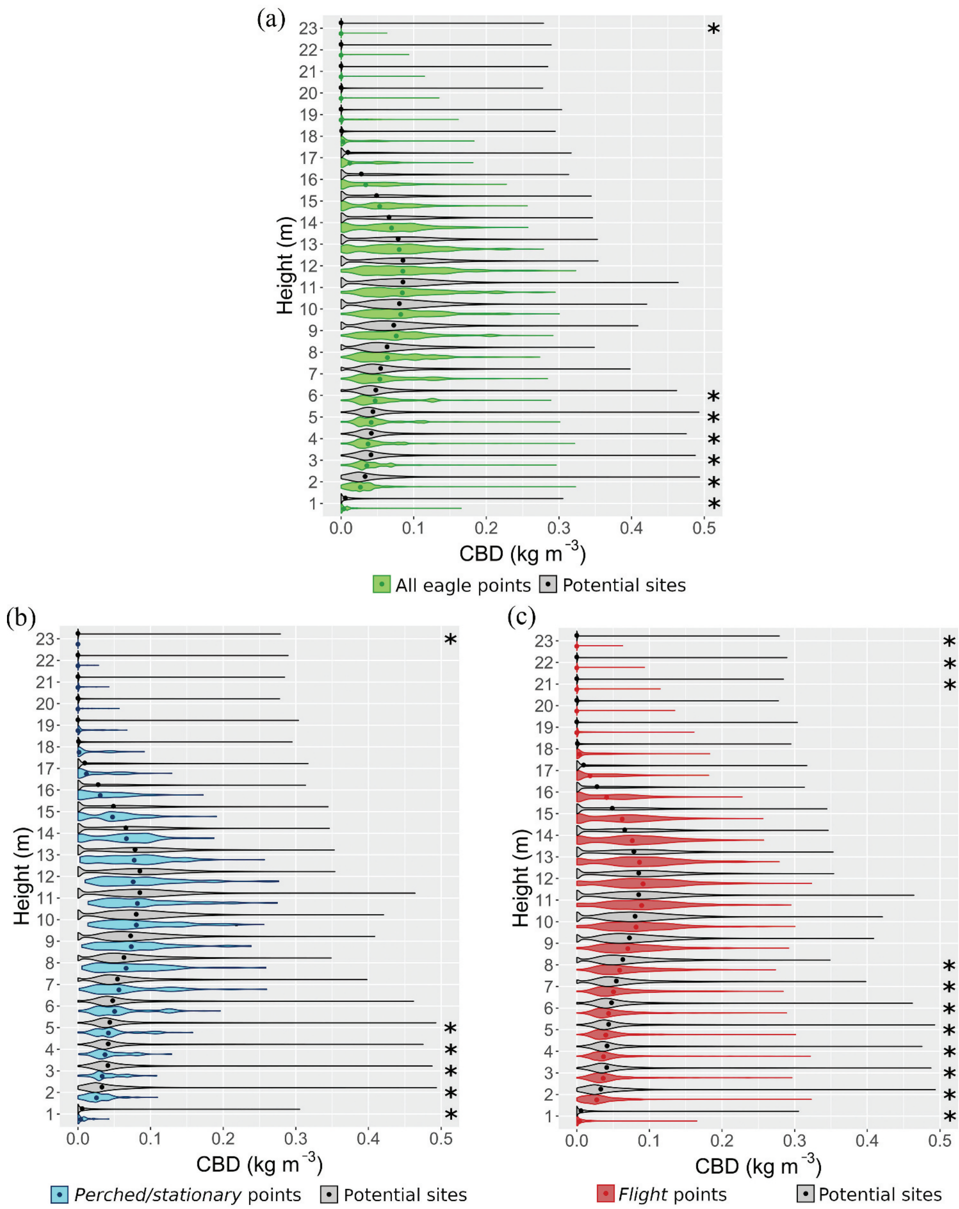

Figure 4. Violin plots of the distribution of canopy bulk density values for sites utilized by the golden eagles. (a) All eagle GPS points. (b) *Perched/stationary* points only. (c) *Flight* points only. In all plots, grey represents the available habitat, as defined by figure 3. The centre dot in each distribution is the median value. Note that the *y*-axis labels represent the top of each 1 m layer. Golden eagle occupied CBD distributions labelled with an asterisk (*) in the final column are statistically lower than the potential habitat, based on the Wilcoxon rank sum test and the Benjamini and Hochberg (1995) procedure, controlling the false-positive rate at a value of 0.05.

GPS location within the study area. The conversion of the lidar point cloud data to voxels representing the vertical profile of canopy bulk density, calibrated in physical units, was key to this work. The CHP allowed a quantitative evaluation of hypotheses regarding forest structure and golden eagle preferences that would not be possible with simple lidar measures, such as canopy height. The study was, however, limited by a dataset that included only two birds, and the two-year gap between the acquisition of the telemetry and lidar data. Nonetheless, our study demonstrates the utility of lidar data to describe details of habitat that are typically available only from ground surveys. Future studies with larger samples of birds might shed additional light on fine-scale habitat selection of golden eagles in other areas, such as southern pine forests that are also managed by prescribed fire.

6. Conclusions

This study demonstrated the value of lidar data for exploring habitat preferences of the golden eagle during the winter months in the eastern US. The lidar data were converted to the physical measure of CBD for each of 23 height layers through the canopy. By overlaying these data with telemetry data, we found that the golden eagles in this study favoured a more open understory, both when perched/stationary and in flight. The preference for an open understory was significant for 1–6 m height through the canopy for all telemetry data, 1–5 m for *perched/stationary* locations and 1–8 m for *flight* locations. These results support our hypothesis that an open understory would be preferred because it facilitates visual observation of prey. Resource managers can potentially use prescribed fire to open the understory and thus promote habitat that golden eagles were found to occupy.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The telemetry data are available upon request from TAM. The remaining data that support the findings of this study are available from the corresponding author, TAW, upon reasonable request.

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