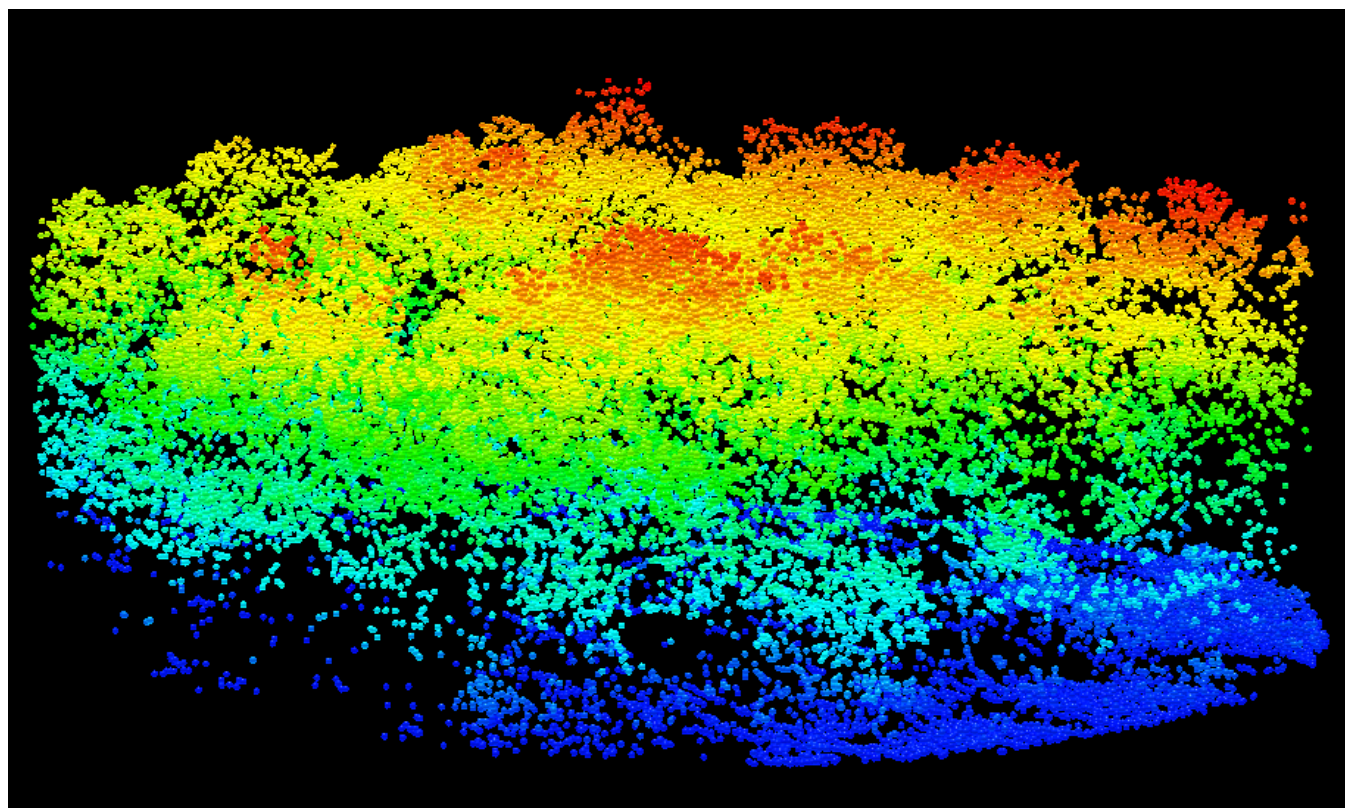




Vegetation Structure within the National Capital Region Network using LiDAR data and analysis

Prince William Forest Park, Catoctin Mountain Park, C & O Canal National Historical Park, and Harpers Ferry National Historical Park

Natural Resource Data Series NPS/NCRN/NRDS—2013/475



ON THE COVER

A three dimensional perspective view of Light Detection and Ranging (LiDAR) data from Prince William Forest Park, showing the crown of a ~30m tall forest (red) overlaying the forest floor (blue). Each point represents one LiDAR return (i.e., laser reflection) and the viewing angle is approximately 30 degrees above horizontal. Clearly a forest with this structure exhibits few LiDAR returns from understory vegetation (represented by scattered light blue points), which is either sparse or obscured by the dense upper canopy vegetation.

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National Park Service
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Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Data Series is intended for the timely release of basic data sets and data summaries. Care has been taken to assure accuracy of raw data values, but a thorough analysis and interpretation of the data has not been completed. Consequently, the initial analyses of data in this report are provisional and subject to change.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. Data in this report were collected and analyzed using established methods and the report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

Views, statements, findings, conclusions, recommendations, and data in this report do not necessarily reflect views and policies of the National Park Service, U.S. Department of the Interior. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the U.S. Government.

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Contents

	Page
Figures.....	v
Tables.....	v
Executive Summary.....	vii
Acknowledgments.....	xi
Introduction.....	1
Methods.....	3
Study Area	3
LiDAR data collection.....	4
Digital Elevation and Canopy Model processing and analysis	5
Canopy Gaps.....	6
Understory vegetation analysis.....	6
Results.....	9
Elevation and canopy height.....	9
Canopy gaps.....	13
Understory vegetation.....	13
Discussion	15
Literature Cited	19

Figures

	Page
Figure 1. Photographs from two forest monitoring plots with contrasting vegetation structure at Catoctin Mountain Park (CATO), showing (A) dense understory vegetation and (B) dense overstory vegetation with little to no understory.	9
Figure 2. The study area includes parts of four, primarily forested, parks embedded within a matrix of urban, forest, pasture, and cultivated land.....	11
Figure 3. LiDAR elevation compared well to USGS benchmark elevations.....	16
Figure 4. Elevation was inversely proportional to canopy height throughout the parks	16
Figure 5. Plots of canopy height distributions for PRWI.....	10
Figure 6. Plots of canopy height distributions for CATO.....	11
Figure 7. Plots of canopy height distributions for HAFE and CHOH	12
Figure 8. Forest gaps were preferentially found along streams and on relatively flat (slope < 5 deg) land at PRWI.....	20
Figure 9. At PRWI, the number of gaps decreases rapidly with gap area (size) with half of all canopy gaps smaller than 12 m ²	21
Figure 10. Understory canopy cover ranged from 0 to 100% at each of the park	22
Figure 11. Forest canopy gaps are found preferentially along roads and streams	23
Figure 12. Understory vegetation canopy cover is quite noisy due to the presence of many pixels with just one or two LiDAR returns below 3m	23

Tables

	Page
Table 1. Return density statistics by park for all point returns and ground returns. Return densities are expressed as returns per 2-m grid cell.....	5
Table 2. Digital Elevation Model residual statistics	6
Table 3. Statistics describing the ability to detect the density of understory vegetation at each of the parks	13

Executive Summary

This report describes data products and analysis of the three-dimensional structure of vegetation in portions of four, primarily forested national parks: Prince William Forest Park, Catocin Mountain Park, C & O Canal National Historical Park, and Harpers Ferry National Historical Park. All four parks are within the National Capital Region Inventory and Monitoring Network and contain forest monitoring plots that have been measured yearly since 2005. We acquired Light Detection and Ranging (LiDAR) surveys of these parks during leaf-on conditions in 2009 and 2010. From these data four primary products were generated: (1) digital elevation models (2-m resolution DEMs), (2) Canopy height models (at 1- and 2-m resolutions), (3) canopy gaps (defined as 2-m grid cells with canopies shorter than 3m), and (4) understory percent cover (2-m resolution). All data products are made available in standard GIS-compatible file formats and are intended to be used to understand spatial patterns in vegetation structure and as documentation of baseline conditions. Future assessments of vegetation structure using the same or similar methods would enable assessment of change in vegetation structure over time.

Acknowledgments

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Introduction

Vegetation structure is quantified through measurements of the horizontal and vertical arrangement of both stem and foliage biomass. Structure within forest and herbaceous canopies is influenced by many factors including resource availability, land-use history, and species composition. Internal and external factors, such as light availability at the forest floor, herbivory pressure, extreme weather events, gradual climate change, and altered nutrient dynamics due to atmospheric deposition, can alter vegetation structure at large spatial scales and feed back to alter ecosystem processes (e.g., Lauenroth et al. 1993, Chapin et al. 2002). Therefore, the measurement and monitoring of vegetation structure is an important component of any resource management plan, and is critical to understanding the stability of ecosystem services derived from intact forest ecosystems.

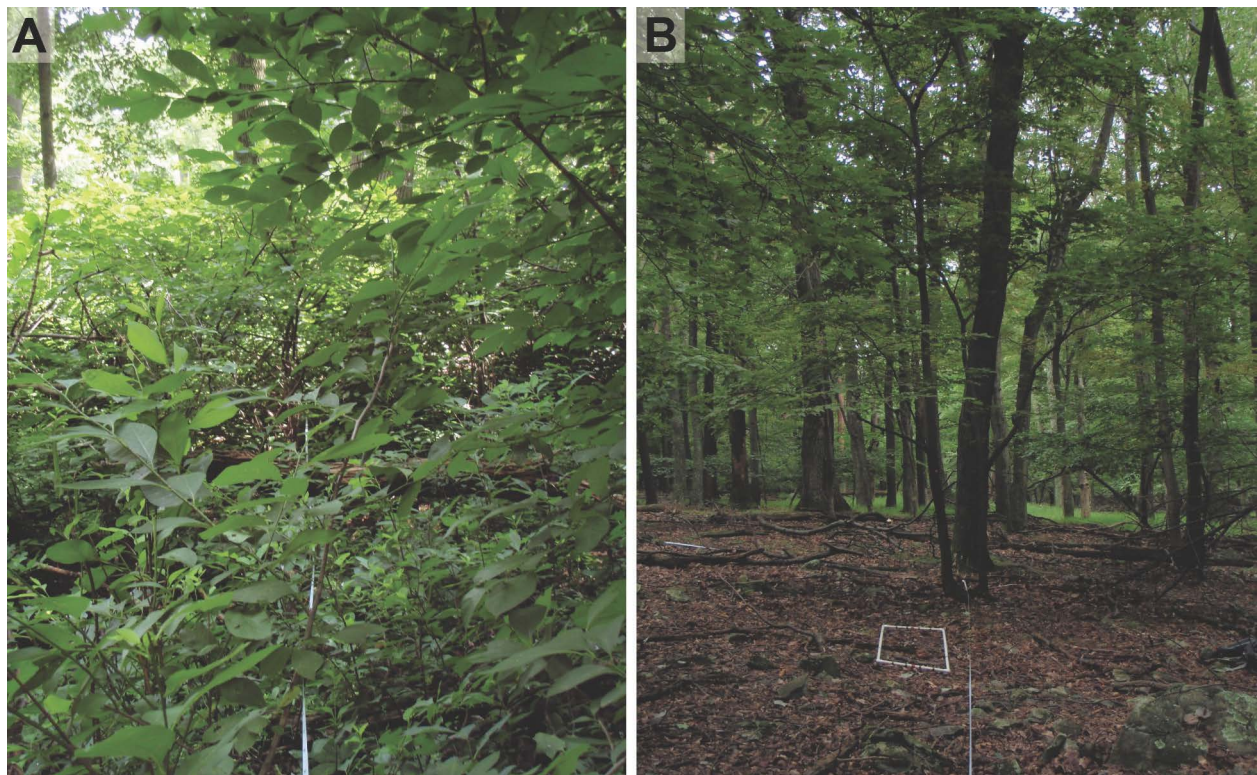


Figure 1. Photographs from two forest monitoring plots with contrasting vegetation structure at Catocin Mountain Park (CATO), showing (A) dense understory vegetation and (B) dense overstory vegetation with little to no understory.

The spatial variation in parameters such as canopy height, canopy gaps, and the presence or absence of an understory are critical measurements for understanding the natural resources and potential threats to natural resources of an area (Figure 1). However, routine measurement of vegetation structure is problematic without the aid of remote sensing technologies. Satellite and aerial images have been used to measure the spatial variation of different aspects of vegetation structure for over 3 decades (e.g. Leaf area index (Jordan 1969)) With the advent of Light Detection And Ranging (LiDAR) technologies (Blair et al. 1999) spatial measurements of

vegetation structure have become much more robust, in some cases offering sub-meter horizontal resolution observations with 5-cm vertical accuracy (Lefsky et al. 1999, Lefsky et al. 2002).

LiDAR is a relatively new active remote sensing technology that is operated from a small aircraft. Discrete pulses of near-infrared laser light are emitted from the aircraft at regular intervals. Each pulse interacts with the earth's surface and vegetation canopy layers and is reflected back to the aircraft. The timing and intensity of each return pulse (from the top of the canopy, top of sub-canopy, or bare earth) relative to when it was emitted from the aircraft is recorded. A 3-dimensional model of the vegetation structure can be constructed using spatial variation in the two-way travel times of each laser pulse. Final products can range from the difference between top-of-canopy returns and bare earth returns (canopy height), to detailed analyses of inter-canopy structure and foliage biomass (Lefsky et al. 2002, Morris et al. 2005). For example, canopies with more than one local maximum in the distribution of canopy density can be detected and related to the presence/absence of an understory canopy (Maltamo et al. 2005). Shrub and seedling canopy have been detected using height-distributions and topography metrics with some success (Martinuzzi et al. 2009), but detailed information on understory density and species distribution continue to be elusive (Korpela et al. 2012). Surveys from seedling stands show that measurements of small trees are particularly limited (Korpela et al. 2008).

This report describes the acquisition and analysis of LiDAR data for 4 parks in the National Capital Region (NCR) of the National Parks Service (NPS). In consultation with staff from the National Capital Region Network Inventory and Monitoring program (NCRN I&M), three primarily forested parks were selected (Prince William Forest Park, Catoclin Mountain Park, and Harpers Ferry National Historical Park as well as a small forested portion of the Chesapeake and Ohio Canal National Historical Park), which have many ongoing management activities that might be informed through the use of LiDAR data and analysis. We expect these data to be useful for cost effectively measuring forest height across the parks, monitoring forest growth over time, measuring the distribution of and tracking the development over time of forest gaps, and to better understanding the extent of understory vegetation throughout the parks.

Methods

Study Area

The National Capital Region (NCR) of the U.S. National Park Service, centered on the District of Columbia, includes parts of three U.S. states (Maryland, Virginia, and West Virginia). The region is a highly fragmented patchwork of forest, agriculture, and developed land. The parks were designed to protect both locations of historic and cultural interest as well as regionally and nationally significant aspects of natural resources, including wetland and forest resources. This array of managed parkland situated among urban and agricultural land-use poses unique challenges to the management of natural resources. For this study, we selected 4 parks (or portions of parks) of the NCR (Figure 2) that were significantly forested. Harpers Ferry National Historical Park (NHP) is a mix of forest and agricultural land and is bisected by the Potomac and Shenandoah Rivers; portions of the C & O Canal NHP in the vicinity of Harpers Ferry NHP are primarily forested; Prince William Forest Park and Catoclin Mountain Park are over 95 percent forested and Catoclin Mountain Park contains the greatest variation in elevation of any of the parks. All 4 parks are located in the Coastal Plain, Piedmont and/or Blue Ridge physiographic provinces of the eastern U.S.

The native land cover of the mid-Atlantic region (spanning the eastern states from New York to Virginia) is primarily deciduous forest, roughly 80% of which falls into two forest categories, Oak-Hickory and Maple-beech-birch (Jenkins et al. 2001). Forests in the NCR are composed of 90% deciduous hardwood species (e.g., Brown et al. 1999), such as hickory (*Carya* spp.), Tulip poplar (*Liriodendron tulipifera* L.), black cherry (*Prunus serotina*.), sweet birch (*Betula lenta*), oak (*Quercus* spp.), maple (*Acer* spp.), American beech (*Fagus grandifolia*), Sweet-gum (*Liquidambar styraciflua*), blackgum (*Nyssa sylvatica*), and ash (*Fraxinus* spp.) {Schmit, 2012 #12200}. Evergreen forests are primarily constrained to eastern hemlock (*Tsuga canadensis* (L.) Carrière) stands within riparian zones, and stands and scattered individuals of Virginia pine (*Pinus virginiana*). The most common understory shrub is the deciduous northern spicebush (*Lindera benzoin*) {Schmit, 2012 #12200}. However, understory vegetation can be evergreen consisting of mountain laurel (*Kalmia latifolia*), the distribution of which is patchy and a function of the overstory canopy and topographic position (Chastain and Townsend 2008); and, American holly (*Ilex opaca*), which can obtain mid-canopy height. A number of understory

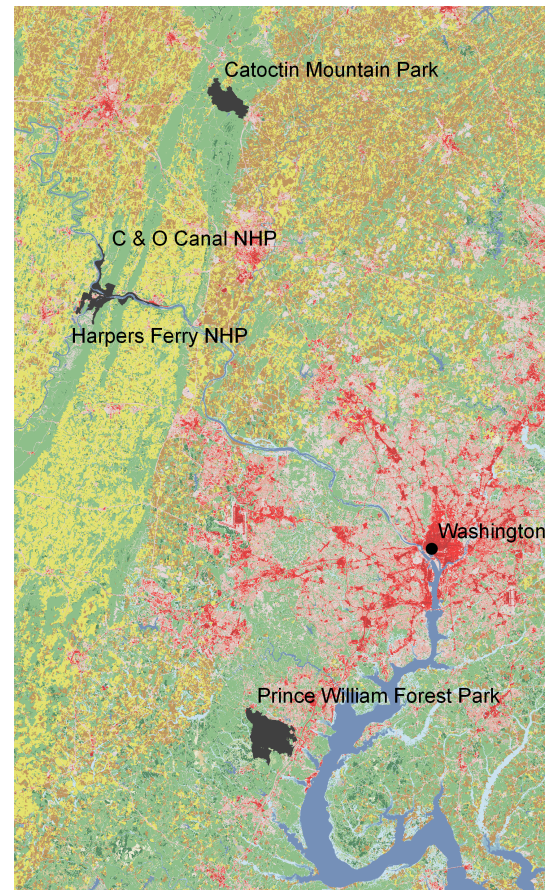


Figure 2. The study area includes parts of four, primarily forested, parks embedded within a matrix of urban, forest, pasture, and cultivated land.

invasive plants are present, particularly in forest edge habitat and small fragments of forest (Minor et al. 2009). Invasive shrubs include multiflora rose (*Rosa multiflora*), bush honeysuckles (*Lonicera* spp.), burning bush (*Euonymus alatus*), and Japanese barberry (*Berberis thunbergii*).

LiDAR data collection

Successful measurement of canopy structural attributes depends on many factors, including sensor and flight configuration and the canopy state at the time of the survey. The density of emitted and return pulses is of primary concern, with many returns (e.g., > 8) per square meter required to accurately estimate canopy height. Likewise, a high return density is required to guarantee sufficient ground returns (laser reflections originating from the ground surface as opposed to canopy surfaces), necessary to accurately describe the underlying topography and therefore the height of the canopy. In forested canopies transmission losses can obscure understory canopy elements and the ground surface (Korpela et al. 2012). An obvious solution is to survey during leaf off conditions, however, such an approach leads to a gross reduction in canopy returns, reducing the ability to discern vegetation structure. Given these considerations we decided to collect leaf-on imagery at pulse densities that exceeded industry standards, thus focusing the study on vegetation structure and reducing the emphasis on collecting high-resolution topographic information.

Data collection and post-processing was conducted by the West Virginia University Natural Resource and Analysis Center (WVU NRAC) over two dates, 7 August 2009 (PRWI) and July 27, 2010 (CATO, HAFE, and CHOH). WVU NRAC instrument is an Optech ALTM 3100 mounted in a Piper Navajo twin-engine aircraft. The collection flights were flown at an average speed of 135 knots at approximately 3000 feet above ground level (AGL), resulting in a laser beam width of 24cm at the ground surface with positional accuracy of each laser return estimated to be within 15 centimeters in the vertical axis. LiDAR data was collected with the following parameters: pulse rate frequency of 100 kHz; scan frequency of 50 Hz; scan angle of 15.3 degrees (PRWI) and 24 degrees (CATO, HAFE, and CHOH). The wider field of view used during the July 27, 2010 flight enabled greater flight path overlap and therefore greater pulse return densities. WVU NRAC post-processed the data and delivered to the project team the following: (1) all-point LiDAR data with an all-point density of 6-8 points per square meter, and (2) ground only LiDAR data with point density dependent on vegetation structure. Delivered data included x-y-z coordinates of each return, return number (1- 4), and return intensity, in both ASCII and LAS 1.2 format. For the PRWI survey only, high-resolution (25cm/pixel) digital infrared imagery was collected synchronously with the LiDAR survey, but were not used in the subsequent analyses. All raw data products are stored at the National Capital Region Network in industry standard formats and are freely available for future research and management applications.

Digital Elevation and Canopy Model processing and analysis

The resulting LiDAR ground point files were analyzed for spatial density (Table 1) and interpolated to digital elevation (surface) models (DEMs) and topographic slope at 2m/pixel resolution. Topographic slope was subsequently used to understand spatial patterns in the canopy gap product (next section), but was not used to adjust area estimates for any of the parks (i.e., all areas reported are vertically projected area, assuming flat topography.) The algorithm we employed computed the elevation of each grid cell using the average elevation of all points within the cell. LiDAR return elevations typically have errors due to ranging and Global Positioning System - Inertial Measurement Unit (GPS-IMU) error. Using the average of all ground return elevations in the cell acknowledges this error and results in a surface that lies within the cloud of bare-earth points. Cells that contain no points were filled by interpolation using neighboring cells unless they fell on the edge of the data coverage and had no neighbors with valid elevations in one or more directions. Such cells were given a value of NODATA. During DEM generation, statistics were generated documenting the mean residual elevation measured between LiDAR returns and the interpolated surface (Table 2). These statistics show that due to the variable degrees of overlap between flight lines, there was great variability in the density of LiDAR returns. Additional variation is generated by vegetation itself; a single LiDAR pulse could result in between 1 and 4 returns depending on the complexity of the forested canopy. Overall, it is apparent that the LiDAR point density and therefore DEM- ground return fit was lower at PRWI than at the other parks. This was due to the number of overlapping flight lines used to generate the survey. PRWI was flown first, and while it met pre-flight requirements, a higher point density was deemed desirable for the other parks, which were surveyed in the second year of the study.

Table 1. Return density statistics by park for all point returns and ground returns. Return densities are expressed as returns per 2-m grid cell.

	All Returns				Ground returns			
	Total Returns	Mean return density	Minimum return density*	Maximum return density	Total Returns	Mean return density	Maximum return density	Percent of 2-m grid cells with >1 ground return
PRWI	286,832,657	23.2	0	548	9,884,904	0.8	28	41.6%
CATO	140,970,229	29.2	0	1264	5,427,144	1.1	168	48.5%
HAFE	173,949,063	33.1	0	1536	29,943,680	5.7	280	49.6%
*Less than 100 2-m grid cells contained 0 returns and these were all located near the edge of the survey areas.								

Two canopy height models (i.e., digital models of the height of the upper canopy surface) were generated, one each with 1-m and 2-m grid cell size. In each grid cell (1m or 2m resolution), the LiDAR return with the highest elevation was identified. The ground elevation interpolated from the bare-earth surface model (2-m resolution) was subsequently subtracted from the elevation of the highest return to arrive at the canopy height. This procedure resulted in a raster representation of canopy height that is not smoothed or interpreted across canopy gaps. This ensures that if a

particular 1-m or 2-m grid cell contains shorter vegetation than the surrounding forest, it will appear as such in the canopy model. The canopy height distribution (i.e., a plot of park area vs. canopy height) was calculated for each park, with the tallest trees/stands being noted and recorded. The canopy model was also analyzed in conjunction with ancillary data such as elevation.

Canopy Gaps

The size distribution and spatial characteristics of canopy gaps was derived from the canopy model and ancillary spatial data on roads, trails, streams, and structures provided by NPS staff. By definition, gaps contain early successional vegetation embedded within forest. If vegetation has achieved a height greater than 3m, the area is no longer a forest gap, but instead approaching a mid-aged stand. Certainly, vegetation taller than 3m is unreachable by white-tail deer, an important attribute in these parks. Because there are many areas in the parks that are kept open (picnic areas, campgrounds, and mown hayfields (mostly at HAFE), steps were taken to provide attributes for each gap that could be used to characterize areas of low vegetation that aren't necessarily forest gaps. Therefore, gaps were preliminarily defined as all 2-m grid cells with a canopy height less than 3m. We then removed all isolated grid cells with no neighbor (4-neighbor rule), and filled these grid cells with forest polygons. In this way, gaps were defined as areas larger than 4 m² with vegetation shorter than 3m.

Ancillary information was then used to identify and attribute forest gaps along roads, field edges, and in the vicinity of buildings with their distance to such features. For some applications, locations where trails and streams create forest gaps, for example, could be managed differently than other forest gaps. Therefore, forest gaps were converted to polygons, and attributed with the following parameters for each gap: (1) area, (2) elevation, (3) within gap canopy height, (4) slope, (5) minimum distance to streams, (6) minimum distance to roads, (7) minimum distance to trails, (8) and whether or not the gap bordered a large cultivated field. These data were analyzed for each park to gain a general understanding of the distribution of forest gaps.

Table 2. Digital Elevation Model residual statistics. In each column, statistics are given for the distance (in meters) between LiDAR ground return elevations and the derived digital elevation surface.

	Ground returns				
	Mean difference	Std. Dev of differences	Minimum difference	Maximum difference	RMSE
PRWI	-0.1941	1.5306	-29.7772	4.3299	1.5306
CATO	0.0004	0.1132	-13.3382	16.391	0.1132
HAFE	-0.0005	0.1412	-8.8068	12.5244	0.1412

Understory vegetation analysis

The ability to detect understory vegetation is contingent on the density of the upper story vegetation canopy. During leaf-on conditions only a small fraction of the LiDAR returns originate from the understory (here, defined as within 3m of the ground surface). Of these, some will penetrate all the way to the ground surface, but some reflect off of understory vegetation. It is these understory returns that indicate the presence or absence of understory vegetation. However, if no returns originate from anywhere below 3m (i.e., the upper canopy is too dense),

we can acquire no information about understory vegetation. Understory vegetation analysis therefore consists of three steps: (1) generation of a raster layer depicting percent canopy, defined as the percent of returns above 3-m from the ground surface; (2) calculate the number of returns within 3-m of the ground surface; (3) calculate the fraction of the returns in (2) that are intercepted by vegetation (i.e., are not ground returns). This final step effectively produces a raster layer of percent understory canopy.

Results

Elevation and canopy height

The 2m-resolution digital elevation models satisfactorily compared to available elevation data, both as compared with USGS benchmarks within the parks and available digital elevation models produced previously (Figure 3). On average across the three survey areas, 45% of 2-m pixels contained at least one ground return (as opposed to a canopy return) leading to the decision to forgo an attempt to generate a 1x1m DEM (see Table 1 for park-specific statistics). At each park, the most common ground return density was 0, and the number of grid cells decreased logarithmically with increasing ground return density.

Canopy height distributions were similar at all parks, with the tallest trees in the range of 45 to 47m. Canopy height was negatively correlated with elevation, and at CATO this was most evident (Figure 4). However, tall trees in valleys containing streams

were often separated by short (less than 3m tall) vegetation, defined as canopy gaps. The canopy height distribution exhibited one large peak located at a canopy height of 25.3m (PRWI; Figure 5A), 27.2m (CATO; Figure 6A), and 23.4m (HAFE and CHOH; Figure 7A). The peak canopy height value represents the canopy height that covers the largest area in the park. The cumulative distribution of canopy heights allows analyses of threshold heights (Figure 5B). For example, at PRWI, 1000ha of forest have a canopy height below 20m. For canopies shorter than 3m, the canopy height distribution was weighted towards the shortest canopies. This represents the influence of canopy gaps (with no or short canopies) and open areas where land is maintained to have little or no tree cover.

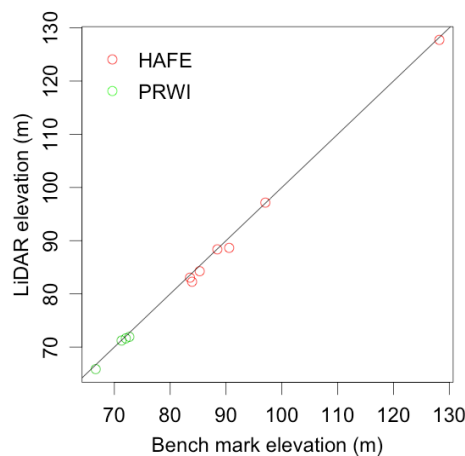


Figure 3. LiDAR elevation compared well to USGS benchmark elevations. CATO contained only one benchmark at 573m, which falls far outside of this plot, but similarly close to the 1:1 line.

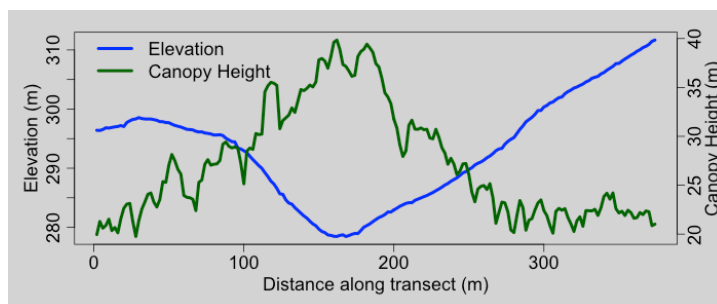


Figure 4. Elevation was inversely proportional to canopy height throughout the parks. Presented here is an example transect from CATO.

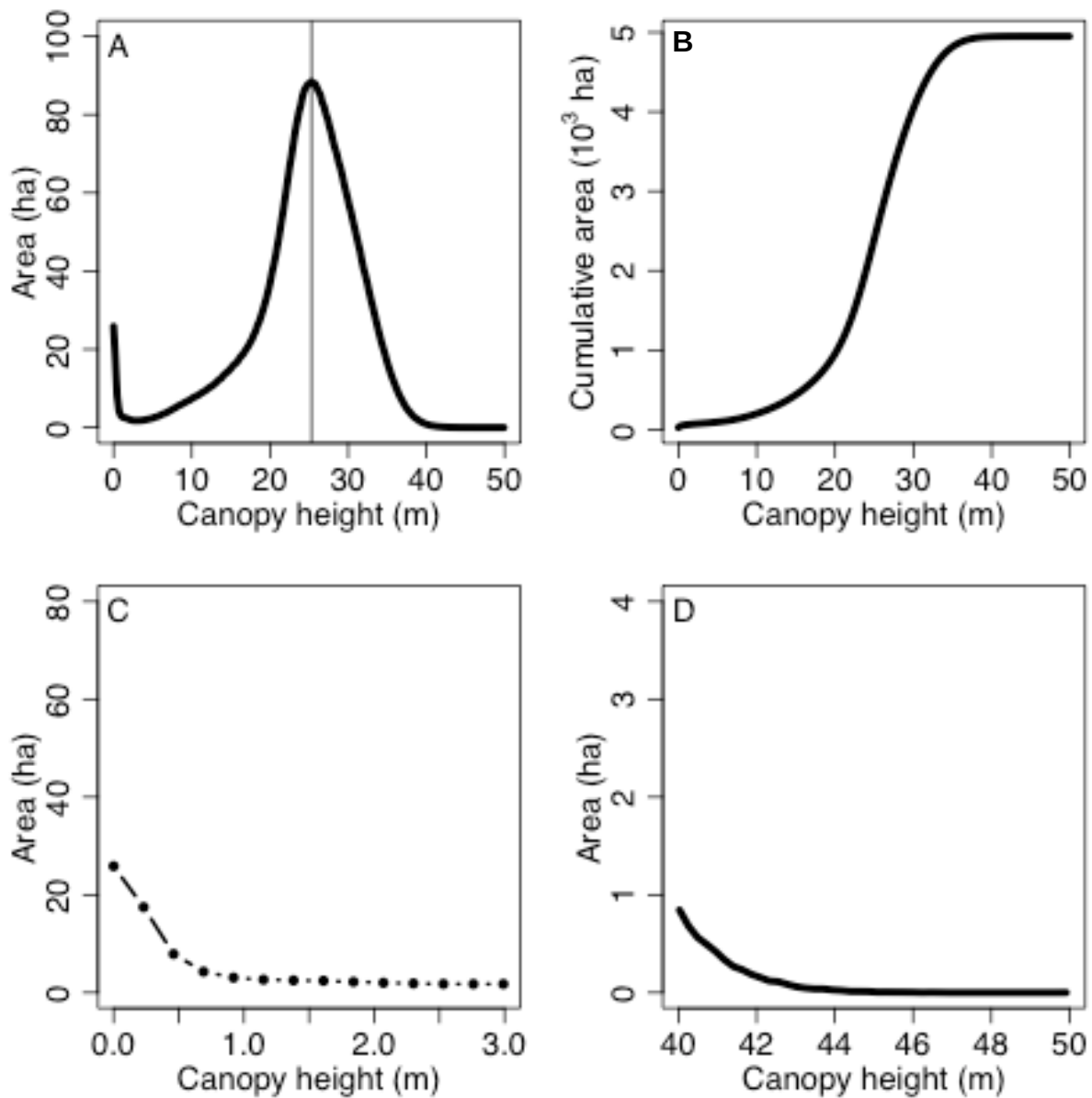


Figure 5. Plots of canopy height distributions for PRWI. (A) Full canopy height distribution for the park, showing that canopy heights between 20-30m are most common. (B) The cumulative canopy height distribution is useful for measuring the area of the park with trees above (or below) a threshold height. (C) Canopies shorter than 3m are canopy gaps, roads, water bodies, and developed areas. (D) The tallest canopy in the park was 46.7m tall and located at 38° 34' 43.62"N, 77° 22' 28.45"W.

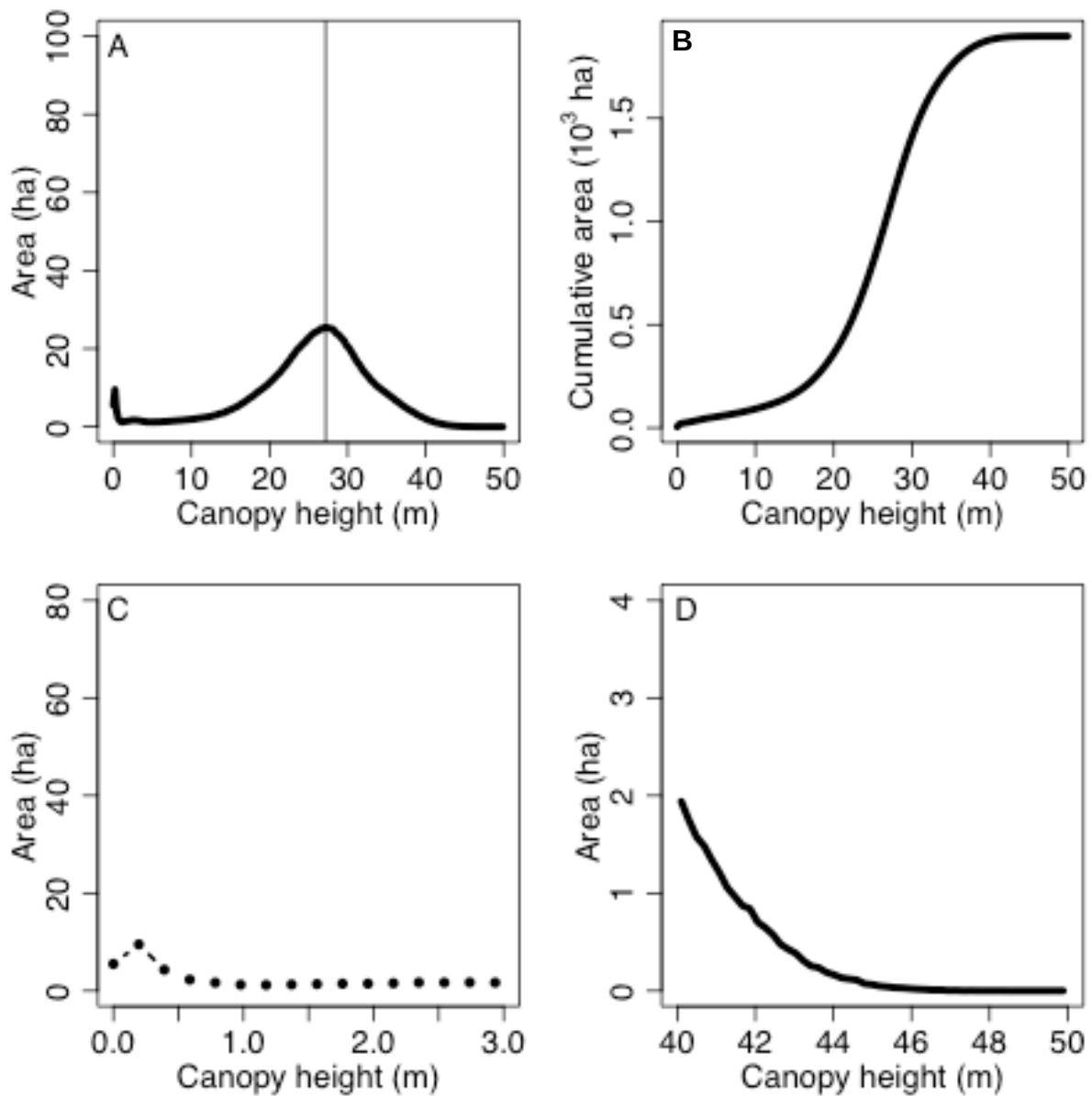


Figure 6. Plots of canopy height distributions for CATO. (A) Full canopy height distribution for the park, showing that canopy heights between 25-30m are most common. (B) The cumulative canopy height distribution is useful for measuring the area of the park with trees above (or below) a threshold height. (C) Canopies shorter than 3m are canopy gaps, roads, water bodies, and developed areas. (D) Canopy height distribution for trees taller than 40m.

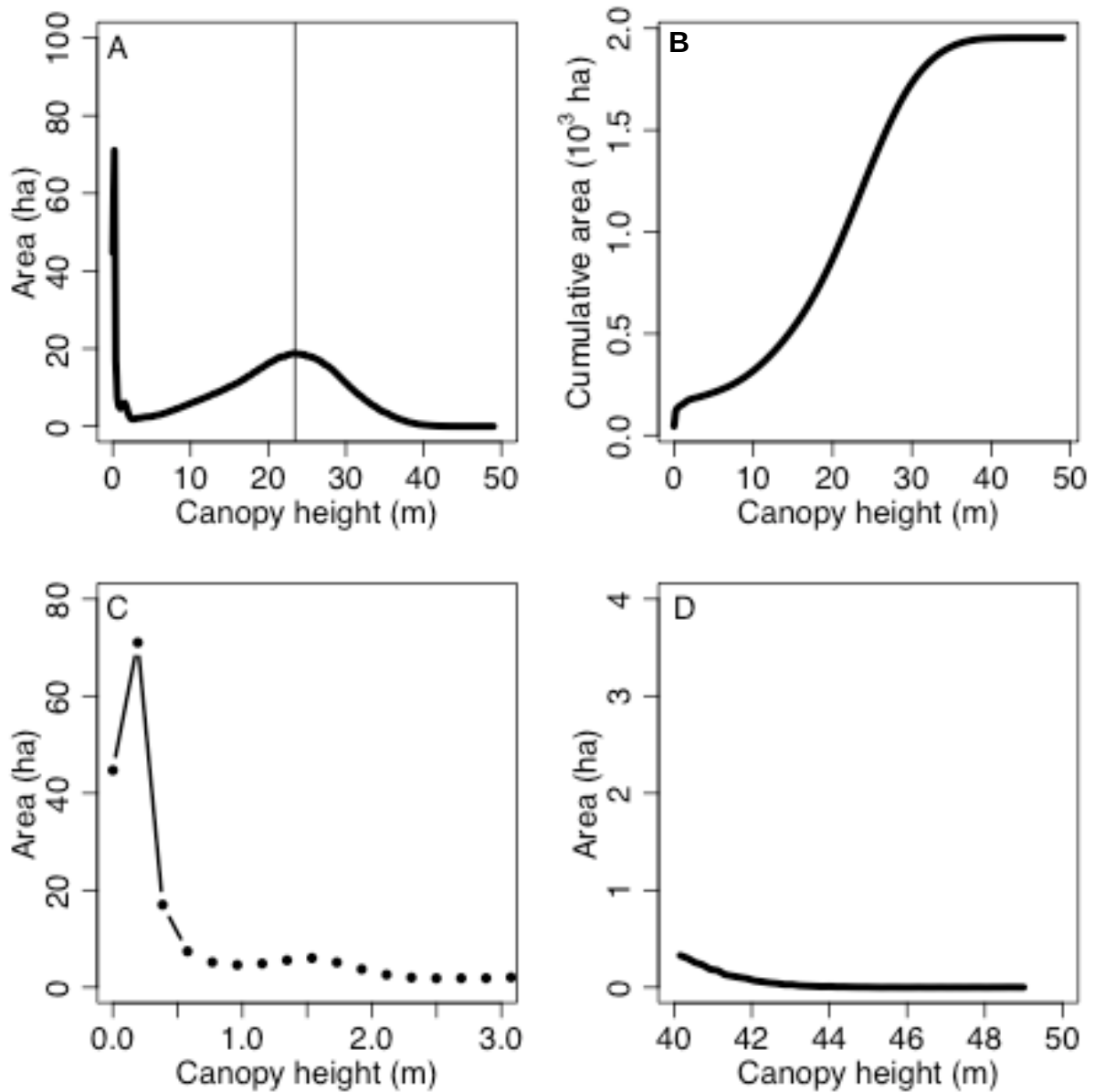


Figure 7. Plots of canopy height distributions for HAFE and CHOH. (A) Full canopy height distribution for the park, showing that canopy heights between 20-30m are most common. (B) The cumulative canopy height distribution is useful for measuring the area of the park with trees above (or below) a threshold height. (C) Canopies shorter than 3m are canopy gaps, roads, water bodies, and developed areas. (D) Canopy height distribution for trees taller than 40m.

Canopy gaps

Gaps were found more often on flat land than on sloped and at lower elevations in each of the parks, even after accounting for canopy gaps created by streams (Figure 8). Nearly 50% of gaps were found along streams and rivers and these were not always confined to the immediate path of the stream. Many floodplains contained gaps that could be up to 50m from streams. At PRWI roughly half of the gaps found in the park were located in a large area in the western side of the park. Conversations with NPS resource scientists suggest that these gaps were the result of a large fire that occurred in this area. The canopy gap size distribution at all parks was heavily weighted towards small gaps, even after excluding gaps smaller than 4m² in area (example for PRWI given in Figure 9).

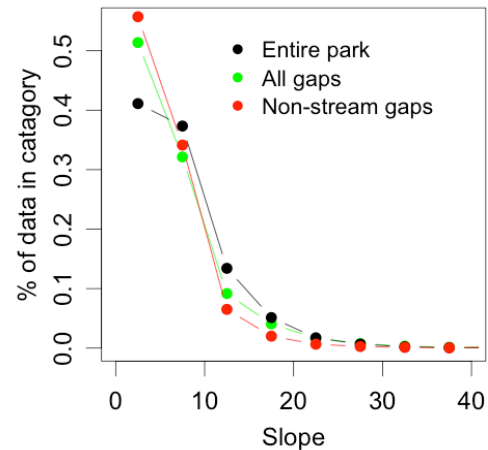


Figure 8. Forest gaps were preferentially found along streams and on relatively flat (slope < 5 deg) land at PRWI.

Understory vegetation

Understory vegetation canopy density ranged from 0 to 100% at each of the parks (Figure 10). However, understory vegetation was only detectable where upper canopy cover was less than 100%, which ranged from 52 to 68% of the park area (Table 3; the similarity between CATO and HAFE in this statistic was apparently a coincidence). On average, over the detectable area (estimated as grid cells with more than 5 LiDAR returns below 3m), the parks exhibited a mean understory canopy cover above 50% (Table 3). At CATO, the two most common understory canopy densities were 0% and 100%. At PRWI, a more continuous canopy density was found, suggesting a greater variety in the number of LiDAR returns originating from below 3m. At HAFE and CHOH, understory percent cover was greater than at the other parks and detectable areas with low understory cover were rare.

Table 3. Statistics describing the ability to detect the density of understory vegetation at each of the parks. The detectable area is the area of the park with 5 or more returns below 3m. The third column reports the percent of these returns (i.e., below 3m) that are not ground returns, indicating they are returns from vegetation.

Park	Percent of park with upper canopy cover < 100%	Percent of park with 5 or more returns below 3m (detectable area)	Average %understory cover in detectable area
PRWI	52.3%	16.5%	67.7%
CATO	68.5%	32.0%	73.9%
HAFE&CHOH	68.7%	30.7%	84.0%

Discussion

We used LiDAR surveys to create digital representations of elevation, canopy height, and the presence/absence of forest gaps and understory vegetation. In combination, these datasets represent a wealth of information on the three dimensional physical structure of the forested landscape. The datasets produced will be available for further studies focused on understanding the influence of past and present land management on vegetation structure. Secondly, studies examining the influence of vegetation structure on ecosystem processes are also enabled by these data.

At a resolution of 2m the produced DEM is sufficiently detailed to observe many fine-scaled features typically absent from 10-m resolution DEMs available from the USGS. For example, medium to large stream channels are clearly delineated and the evolution of these over time could be studied using future LiDAR acquisitions. Presumably there are locations in each of the parks where steep topography is “smoothed” by the 2m data. This would be particularly true in areas of dense canopy vegetation. However, our analysis using USGS benchmarks did not reveal any such areas. The DEMs produced were sufficiently detailed to produce canopy height maps and to analyze spatial variation in canopy height relative to elevation (Figure 4). The observation that tree height is inversely proportional to elevation and is consistent with the idea that ridges (even the small ones exhibited at PRWI) are exposed to disturbances leading to shorter trees. A second, complementary, explanation invokes the availability of soil resources (water, nutrients), which are likely to be reduced on ridges compared with valleys.

Canopy height (1m) shows tremendous detail in the topography of the outer canopy surface. Future work should examine the spatial variability in canopy height in the context of land use history. Limited data on land use history is available for each of the parks. At PRWI, we compared an air photograph from 1936 with the canopy height and found that areas without forest in 1936 have the shortest trees today. Clearly the forest structure holds many legacies of past land use that have yet to be explored. Current land use also impacts canopy height at each of the parks. For example, the tallest trees at PRWI are located in the campground at the north side of the park. Many stands of tall trees also exist in close proximity to streams, trails, and buildings, all within an easy hike from parking areas. The canopy height maps might guide future exploration of these unique natural resources.

The canopy gap products emphasize the small number and size of canopy gaps throughout the parks. For example, at PRWI there are 4.5 times more gaps 4 m² in size than 8 m² in size. 41% of all gaps were smaller than 100 m² and 14% are smaller than 10 m². These very small gaps are likely due to the death of a single tree and provide only limited regeneration. Many of the gaps are spatially correlated with streams and rivers. River floodplains provide many disturbances (e.g., beaver, flooding) that lead to the opening of forest gaps. Without the action of streams,

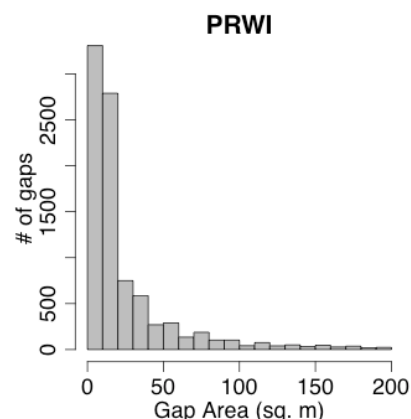


Figure 9. At PRWI, the number of gaps decreases rapidly with gap area (size) with half of all canopy gaps smaller than 12 m².

many of the forests throughout these parks would lack any significant gaps. However, the presence of gaps was not always correlated with the presence of streams. A large region in PRWI with many gaps was the result of a forest fire (Figure 11). We also found that forest gaps were more likely to be found on flat land than sloped land. This was only partially due to the effect of floodplains on gap formation, because the effect was still apparent after removing gaps within 50m of streams (Figure 8). Future work should evaluate the utility of defining gaps using different criteria. For example, there are many areas of the park with a canopy height in the range of 3 to 15m. This is far lower than the maximum canopy height of mature forests, suggesting that these areas are still in some form of regeneration. The canopy gap height distribution could be analyzed in the context of land use history to evaluate variation in the rates at which forests are regenerating.

Understory vegetation is difficult to detect with accuracy given the high density of the upper story canopy. We found that at each of the parks roughly half of the forested area exhibited upper canopy densities too dense to allow LiDAR penetration below 5m. In many cases only one (or two) LiDAR returns made it below the 3-m threshold. In these cases, if the return(s) did not hit the ground surface we reported 100% (50% if only one of the two penetrating returns hit the ground) understory canopy cover. Further, it should be recognized that a non-ground return from below 3m is potentially not from understory vegetation. For example, such returns could be reflections from the trunk of a large standing tree, a fallen tree, or a large rock. The cumulative effect is a rather noisy representation of understory percent cover, particularly when a limited number of returns penetrate the canopy (Figure 12). This noise is often represented by stripes in the understory data products due to striping in the LiDAR point density. Striping in LiDAR data is quite common due to the “sweep broom” configuration of the sensor leading to overlap from adjacent flight lines. If only pixels with greater than 5 returns originating below 3m are used to detect understory the resulting products are less noisy, but useful over a more restricted area (e.g., just 16% at PRWI; Table 3). It might be appropriate to assume that pixels with no or few LiDAR returns below 3m have no or little understory vegetation. However, the great number of pixels with just one return below 3m but with no ground returns suggests that it is often the case that a single return penetrating the upper canopy can reflect off of vegetation near the ground surface.

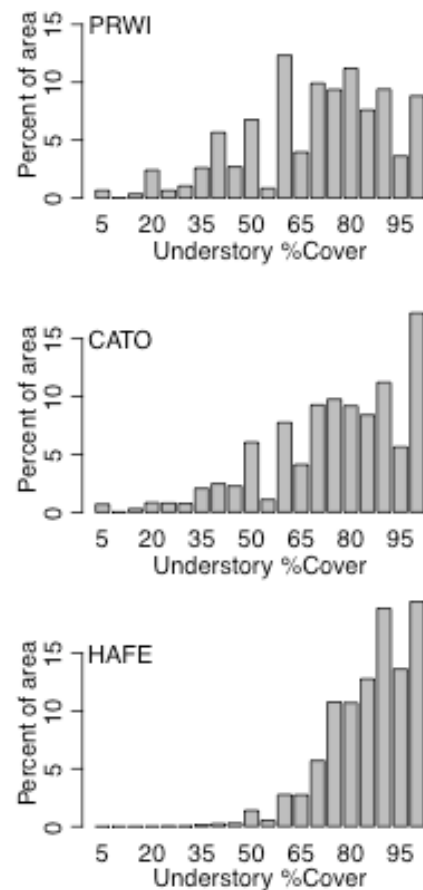


Figure 10. Understory canopy cover ranged from 0 to 100% at each of the parks. At CATO, the large number of pixels with either 0%, 50%, or 100% understory canopy cover is due to the relatively few LiDAR returns to penetrate below 3m.

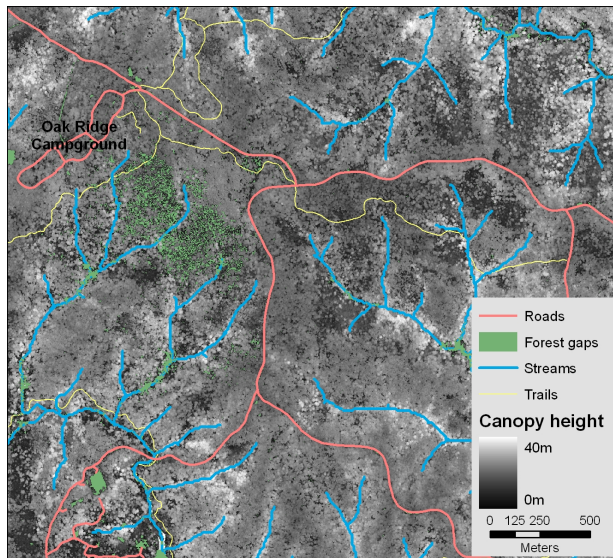


Figure 11. Forest canopy gaps are found preferentially along roads and streams. However, a large area to the southeast of the Oak Ridge Campground at PRWI experienced a fire, which resulted in a large area of gaps.

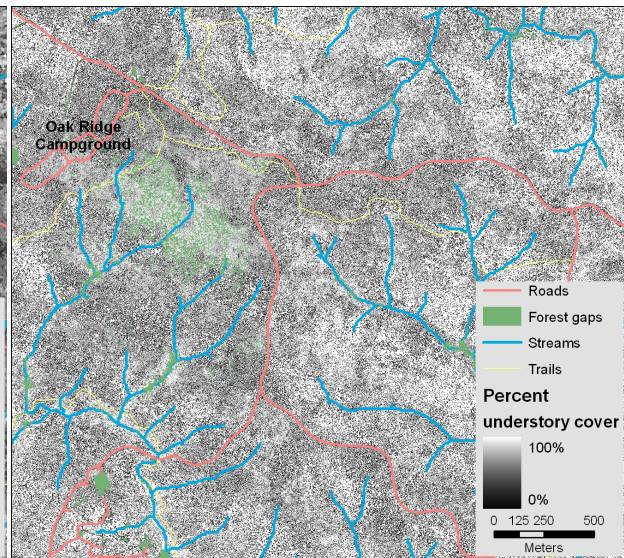


Figure 12. Understory vegetation canopy cover is quite noisy due to the presence of many pixels with just one or two LiDAR returns below 3m. However, it can still be seen that understory vegetation is denser around streams and in the vicinity of forest gaps.

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