Supplement D

Example of the Use of LiDAR for Monitoring Vegetation Characteristics: An example from the Cienega Creek Nature Preserve

Supplement to the Pima County Ecological Monitoring Program:
Phase II Monitoring Plan Summary

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Tyson Swetnam, University of Arizona

Brian Powell, Pima County Office of Conservation Science and Environmental Policy

1 Abstract

Airborne Light Detection and Ranging (LiDAR) has a demonstrated potential to evaluate vegetation across multiple scales. Here we illustrate potential uses of LiDAR technology at the Cienega Creek Nature Preserve in Pima County, Arizona, and evaluate the use of LiDAR for long-term vegetation monitoring and wildlife habitat characterization in eastern Pima County. LiDAR data collections were contracted by Pima Association of Governments (PAG) and collected by Sanborn Inc. in 2008 across an area of approximately 1,800 square miles over the cities of Tucson, Marana, Oro Valley, Green Valley, Benson, as well as unincorporated Pima County and Federal and State managed lands (US Forest Service, National Park Service, Bureau of Land Management, and State Lands). The purpose of the 2008 LiDAR flight was to develop a bare earth model. LiDAR is also a vegetation characterization tool, capable of precise vegetation height and vegetation volume estimates. LiDAR is however not dense enough to parameterize canopy bulk densities, and may have data gaps due to less a than 50% side-overlap in the flight lines. Even with less-than-optimal data collection in 2008, the current LiDAR dataset for eastern Pima County shows great promise for assisting conservation efforts in the Sonoran Desert Conservation Plan in Pima County, characterizing wildlife habitat and establishing baseline vegetation characteristics. Informed parameterization requirements for the planned 2011 LiDAR flight by PAG will strengthen future vegetation and threatened species' habitat measurements.

2 Introduction

2.1 Purpose and Background Information

This supplement evaluates the applicability of Light Detection and Range (LiDAR) data collected in 2008 by the Pima Association of Government (PAG) for long-term monitoring of resources by the Pima County (see main body of the report). Cienega Creek Natural Preserve was chosen as a test area for this effort, because of the Preserve's important wildlife habitat and the presence of a wide range of vegetation types. The 2008 LiDAR flight covers the entire extent of the Cienega Creek Natural Preserve, as well as most of the adjacent watersheds that feed into Cienega Creek (Figure 1). The LiDAR system was fielded to meet American Society for Photogrammetery and Remote Sensing (ASPRS) Class 1 requirements (ASPRS 2004a, 2004b) by PAG; the flight occurred over a two week period in late February and early March 2008. United States Geological Survey (USGS) LiDAR specifications (USGS 2010) are similar to ASPRS Class 1, and the PAG 2008 data fit the USGS

2010 specification, however the units collected for the PAG flight are in international feet (instead of meters) which are acceptable to USGS standards.

PAG is planning another LiDAR flight in 2011. In addition to its application for characterizing vegetation for long-term monitoring, Pima County is interested in using these follow-up data to study changes over time across the flight area, including: channel erosion, basin sinking due to ground water extraction, vegetation growth or decline, and new human development to name a few potential uses.

2.2 The Pima County Ecological Monitoring Program

Applying broad-scale methods for monitoring species habitat is gaining recognition and importance as more planners take a broad spatial view of biodiversity conservation, as was done for the Sonoran Desert Conservation Plan (SDCP). Pima County is now in the process of developing the Pima County Ecological Monitoring Program (PCEMP) to detect meaningful changes to select parameters related to wildlife and plant species, their habitats, ecosystem structure, and threats (see main body of the report for more information). As part of the PCEMP planning process, vegetation structure and composition were identified as critical features of the program because of their link to sensitive species habitat. An important next step in the development of the EMP is to investigate the methods that inform changes in vegetation parameters over time. On-the-ground, plot-based measures are traditional in ecological monitoring, but can be expensive, time consuming, and can be subjective. By contrast, remote sensing technologies such as LiDAR can collect enormous quantities of objective data. LiDAR presents challenges (e.g., high initial up-front cost; technical computing proficiency), but has promise for program that have broad spatial scales such as the PCEMP. In addition, LiDAR may be very efficient at monitoring changes in stream channel morphology, which was not being considered for the PCEMP because of its high cost, but which may be included if LiDAR is used.

2.3 The Cienega Creek Natural Preserve

The Cienega Creek Natural Preserve is the “crown jewel” of the County’s land holdings: It contains rare mesic riparian vegetation such as cottonwood (*Populus fremontii*) and willow (*Chilopsis linearis*) that provide habitat for rare bird species such as southwestern willow flycatcher (*Empidonax traillii extimus*) and western yellow-billed cuckoo (*Coccyzus americanus occidentalis*). The creek contains perennial water and hosts a number of fish species including Gila chub (*Gila intermedia*) and Gila topminnow (*Poeciliopsis occidentalis*) and the lowland leopard frog (*Rana yavapaiensis*). This species-rich area also contains Sonoran upland vegetation communities. Because of the diversity of vegetation and the

significance of a number of species, Cienega Creek Natural Preserve was chosen as an ideal test area for this project.

2.4 Introduction to LiDAR

LiDAR is an optical remote sensing technology that uses an 'active' sensor - a rapid pulse laser beam, to measure the distances between the sensor and an object. The data we are presenting was collected by a private vendor, Sanborn Inc., in a small aircraft traveling approximately 1000m above the surface. LiDAR data are spatially extensive and intensive, mapping nearly every plant that has direct overhead exposure to the sensor. At fine scales (landscape to tree-stand) LiDAR has shown forest managers its exceptional accuracy and precision ($<1^3$m resolution) in regards to estimating total above-ground biomass, canopy height (tree tops), canopy base height (lowest living foliage) and percent canopy cover (Reutebuch et al. 2005, Zhao et al. 2005, Andersen et al. 2006, Zhao and Popescu 2009, Erdody and Moskal 2010).

Among the tools that are useful for managers: a detailed vegetation inventory quantifying every individual plant to estimate their vertical and horizontal measurements (Erdody and Moskal 2010, Anderson et al. 2006), thereby allowing characterization across any spatial scale (Temesgen et al. 2003). This is potentially the most powerful application to the habitat monitoring goals of the PCEMP. LiDAR data collected from the San Pedro River in 2004 (Farid et al. 2006) with similar point densities to the 2008 PAG flight reported an 80% to 90% accuracy at determining canopy heights, canopy diameters, and diameter at breast height for multi-age structured cottonwood trees, as well as identifying individual trees (Farid et al. 2006). Seavy et al. (2009) showed the usefulness of LiDAR derived canopy metrics at determining habitat associations of riparian passerine birds. Canopy metrics can include canopy base heights (lowest living foliage), canopy cover percentage, canopy bulk density (woody branches and leaves present in the canopy), and surface-to-volume ratios (continuous cover or opening between individual trees).

Table 1 compares LiDAR data collected locally by different agencies in the last 6 years for various projects, including vegetation and habitat monitoring. As mentioned above, a flight took place over the San Pedro in 2004 for a riparian study (Farid et al 2006). In 2007 PAG contracted for the Upper Sabino watershed, as a response to the flooding that occurred in July 2006. In 2008 the USFS contracted Watershed Sciences to fly LiDAR over the Pinaleño Mountains as part of the Pinaleño Ecosystem Restoration Program (PERP). The Pinaleño LiDAR (Laes et al. 2009) meets USFS LiDAR vegetation specifications (Gatziolis and Anderson 2008, Laes et al. 2008). The 2008 PAG LiDAR do not meet USFS vegetation specifications, such as ≥4 p/m^2 point density, a scan angle of <±15 degrees, and 50% side-overlap of scan

lines. However, the PAG LiDAR can still be useful for deriving canopy heights, canopy cover, and canopy base heights at a greater than individual tree scale (i.e. 5-10m pixel or cell size). Recommendations for future PAG flights of low elevations in Pima County is highlighted later in this report.

Table 1: Recent Southern Arizona LiDAR flights and associated parameters.

Scan Characteristic	Pinaleño (2008 USFS)	Sabino (2007 PAG)	Pima County (2008 PAG)	San Pedro (2004 SAHRA)
LiDAR Vendor/Provider	Watershed Sciences	Sanborn Inc.	Sanborn Inc.	University of Florida (NCALM?)
Acquisition Date	September 22-27, 2008; leaf-on	March 25-27 2007; leaf off	February 21 - March 13, 2008	June 22, 2004; leaf off
LiDAR Scanner	Leica ALS50 Phase 2	Optech 2050 ALTM	Leica ALS-50 and Optech ALTM 2050	Optech ALTM 1233
Pulse Rate	70-90kHz	50kHz	73.5 kHz (L), 50 kHz (O)	33kHz
Scan Rate	52.2Hz	31Hz	42 Hz (L), 34 Hz (O)	28Hz
Maximum returns per pulse	1-4, Intensity	1,2, Intensity	1,2, Intensity	1,2, (Intensity?)
Scan Angle	15 degrees	16 degrees	20 degrees	20 degrees
Stated Accuracy (Vertical/Horizontal)	3.2cm/1.0m	37.0cm/1.0m	37.0cm/1.0m	N/A, RMSE = 0.74-1m
Flight above ground level	800-1,300m	~1,700m	1,000 (O), 1500m (L)	600m
Flight line overlap	50% sidelap	<50% sidelap	<50% sidelap	50% sidelap
Average LiDAR pulse-return spacing	7.36 points/m2	3.44 points/m2	2.66 points/m2	2-4 points/m2
Average Ground point-density	0.98 points/m2	~1 point/m2	~1 point/m2	?
Acquisition Area	85,518 acres (34,608 Ha)	78,560 acres (31,792 Ha)	1,150,080 acres (465,420 Ha)	N/A
Total Number of Returns	2,892,925,979	1,153,550,429	12,922,422,098	~5,000,000
Units	Meters	International Feet	International Feet	Meters
Projection, Datum	WGS84, NAD83	Central Arizona State Plane, NAD89-92, NAVD88	Central Arizona State Plane, NAD89-92, NAVD88	?

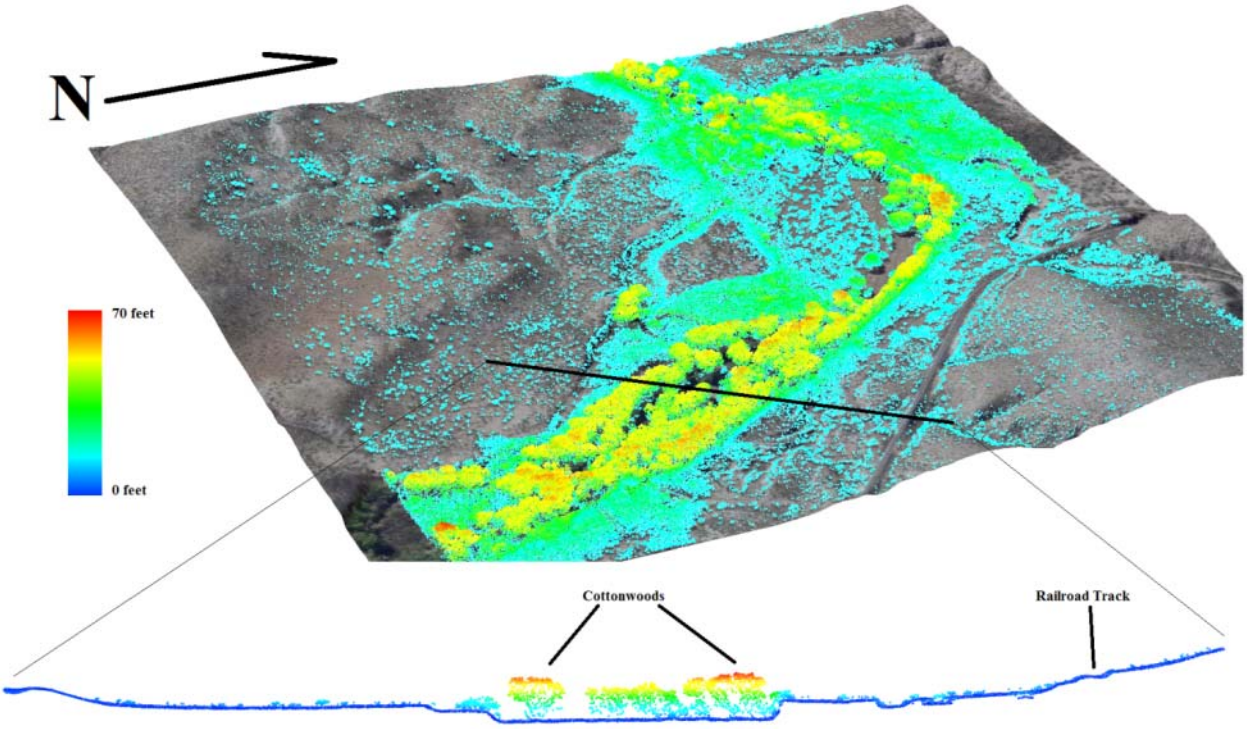

Figure 1: Example of 3-D LiDAR over Cienega Creek showing riparian areas with cottonwood and mesquite. 3-D 81ft^2 (3yd) Bare Earth surface with 2008 PAG 1ft image draped underneath 3-D point cloud of vegetation heights. Virtual transect through riparian zone, showing cottonwood heights.

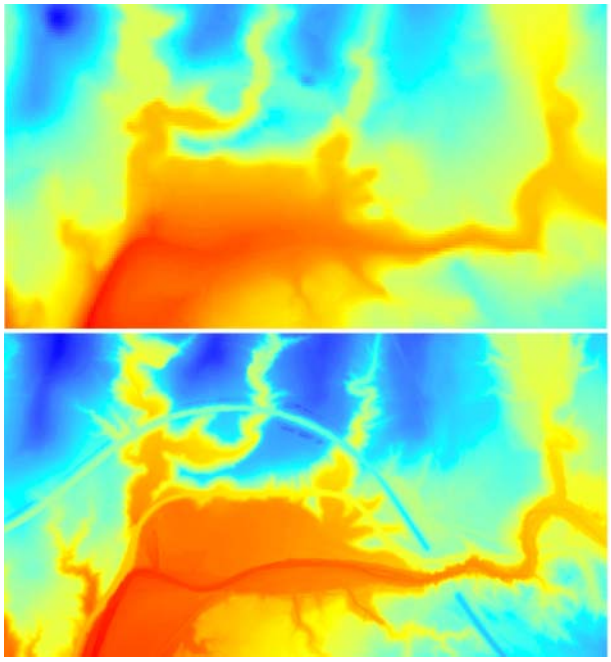

Figure 2a(left): USGS 10m standard DEM (left-top) versus 3yd LiDAR derived Bare Earth DEM (left-bottom). Red = lowest, Blue = highest elevations.

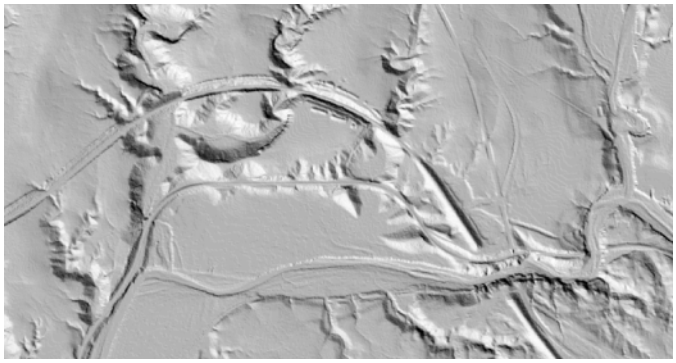

Figure 2b(above): Hillshade from 81ft^2 (3yd^2) Bare Earth DEM generated from LIDAR. Paved and dirt roads, train tracks, and ATV trails are visible.

2.5 Software

Proprietary LiDAR software can be quite expensive, ranging from $5,000 to $30,000. Such software is used by the vendor and high-end users to manipulate the 'raw' point data collected by the sensor. Municipalities and federal agencies may not be interested in—or have the resources (personnel and time)—to manipulate raw flight line data. Most data contracts include the LiDAR vendor post-processing the data into 'tiles' of 'point clouds' (the discrete laser pulse measurements). The tiled data files are necessary because of the volume of the raw LiDAR point cloud; a 1^2 mile tile (640 acres) is typically 100-500 megabytes. The 2008 PAG data contains 1,797 1^2 mile tiles arranged along Township and Range subsections. These 'raw' post-processed data are saved in a .LAS (Log ASCII Standard) format. Vendors will also convert .LAS files to .TXT files which can be loaded into common GIS applications like ESRI ArcGIS.

Free LiDAR software and viewers are available online, but most lack the support and documentation that proprietary often comes with. For this project we used a US Forest Service developed LiDAR software called FUSION (McGaughey et al. 2007), freely available at www.fs.fed.us/eng/rsac/fusion/. We ran a combination of FUSION batch functions (Catalog, GridSurfaceCreate, CanopyModel, CanopyCover, and CanopyMaxima) and loaded the outputs into ArcGIS 9.3 (ESRI, 1999-2009). FUSION can process the .LAS tiles (the 'raw' LiDAR data) into many different metrics, dependent upon a user's specifications. Data tiles can be exported from FUSION for either image classification or GIS uses.

3 Results and Discussion

3.1 Quality Assurance (QA) and Quality Control (QC)

Ensuring the accuracy of a delivered dataset is critical to validation of consistency of projects based off the LiDAR data. QA/QC should be done independently by the primary consumer for all LiDAR projects. We ran a basic QA/QC 'Catalog' batch process in FUSION on the Cienega Creek LiDAR area. The analysis was run using a 98.43x98.43ft (or 10m^2) cell size to derive whether the values meet USFS specifications (Table 2, Figure 4). The colors in Figure 4

Table 2: Cienega Creek Preserve point return densities.

	Points / Meter^2	Density	Percent of Area
Minimum	**0**	**<2 p/m^2**	**22.21%**
Maximum	**33.08**	**>4 p/m^2**	**11.64%**
Average	**2.67**	**2-4 p/m^2**	**66.14%**
Standard Deviation	**1.17**		

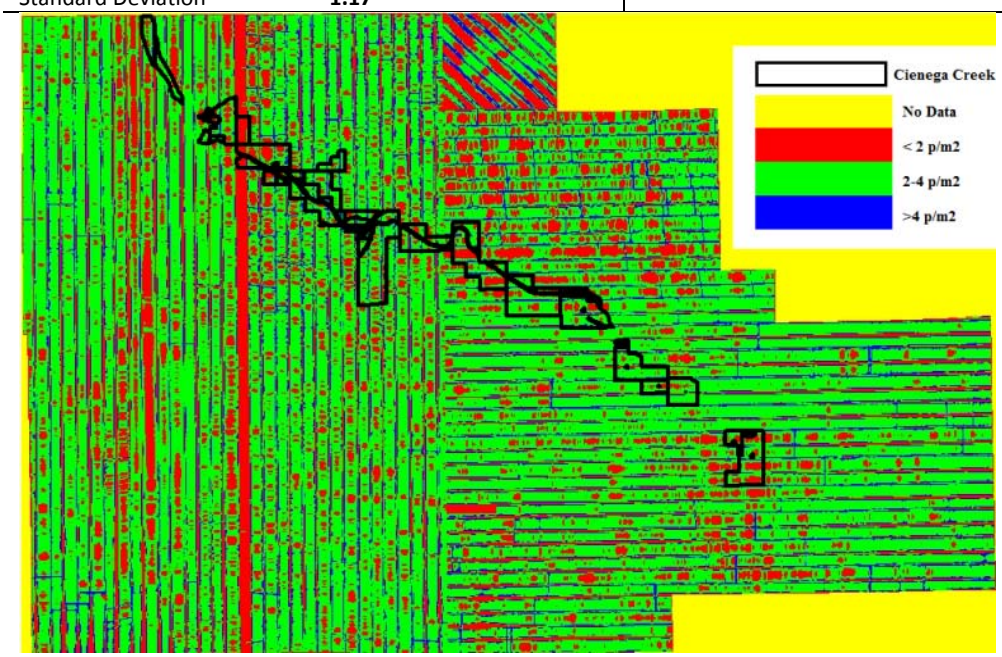

Figure 4: The Catalog image shows point density along Cienega Creek Preserve. Areas of red represent a single flight line coverage, green likely represents at least 2 flight lines overlapping, and blue represents +2 flight lines overlapping. The more points in an area the greater the inference that can be made about that site.

3.2 Example of Vegetation Field Protocol Measurements

There is no one standard protocol of validating a LiDAR flight for vegetation (due to the extreme variability of vegetation types across the planet), but many studies (e.g., Anderson

et al. 2006, Erdody and Moskal 2009, Kane et al. 2010) have used sample plot inventories with 40-70 plot locations. Many studies use either existing Forest Inventory and Analysis (FIA, Bechtold and Patterson 2005) plots or some derivation (Laes et al. 2009). Inference can be limited to the plot scale, or if the resources are available, individual plant inventories within plots can be mapped by field crews, thus making the smallest level of inference a plant instead of a plot.

Typical observations made to validate LiDAR at a plot location include:

- Differentially Corrected GPS coordinate (in UTM units, ±0.1m precision).
- Landform Type: Summit/Ridge/Plateau/Upper Slope/Lower Slope/Toe Slope/Drainage/Flat
- Slope
- Aspect
- Ground Cover
- Fuel Type
- Soil Type
- Species/individual plant counts, height metrics (total height, base height, canopy radius)
- Plot Size (Radius or Side)

Individual plant observations may include:

- Distance (nearest 0.1m) and Bearing (degree) from plot center
- Species
- Total height
- Base Height
- Canopy Radius
- Live/Dead class

3.3 Combining LiDAR with Aerial Photography (Orthophotography)

Along with the 2008 LiDAR data, PAG also obtained 1ft^2 aerial imagery over the Cienega Creek Preserve. Pima County has access to aerial flight imagery over Cienega Creek for 2007, 2005, and 2002. Multiple parameters can be created from 3-D LiDAR structural data from their spectral intensity; in addition 2-D orthophotographic bands (red, green, blue, and near-infrared[NIR]) can increase possible inference. This coupled model incorporates both orthophotography and LiDAR, with the potential to generate accurate vegetation maps at landscape scales (Hudak et al. 2007). The result would be a map that has characteristics of vegetation structure from the LiDAR data and vegetation greenness from the aerial imagery.

Most remote sensing data are a multi-spectral (including near-infrared) and can assist in species identification. However, most satellite data do not have the spatial or spectral resolution to map individual plants. Vegetation classification maps are available from LANDSAT ETM+ data (Rollins and Frame 2006), which can serve as a useful tool for finer-scale mapping

3.4 Vegetation parameters derived from the 2008 LiDAR

The LiDAR data collected in 2008 have a number of useful applications:

3.4.1 Canopy Height Model

We generated a canopy height model (highest hit point returns) for the PAG LiDAR layer at the stand level (Figure 5). This model can be used to determine vegetation heights (for individual large trees, as well as large stands of continuous cover). Kane et al. (2008, 2010) used LiDAR to derive vegetation characteristics from the rugosity or 'rumple index' of canopy models. The 2008 PAG data show LiDAR point penetrations into the canopies of Cottonwoods (Figure 1), possibly in their leaf off phase. Future field validation may be required to estimate true height errors, however we assume those errors to be small and relative to accuracies obtained by Farid et al. (2006) in a nearly identical vegetation type, with a similar LiDAR point density, and Root Mean Square Error (RMSE).

3.4.2 Canopy Cover

Canopy cover can be parameterized from leaf-on and leaf-off conditions. A LiDAR point penetration cover analysis (Figure 6) shows that in the Cottonwood riparian zone, cottonwoods maintain a near 100% cover over the surface. This has the potential to explain micro-site feedbacks on soil moisture and surface water evaporation rates, and may be correlated to riparian bird and amphibian habitat.

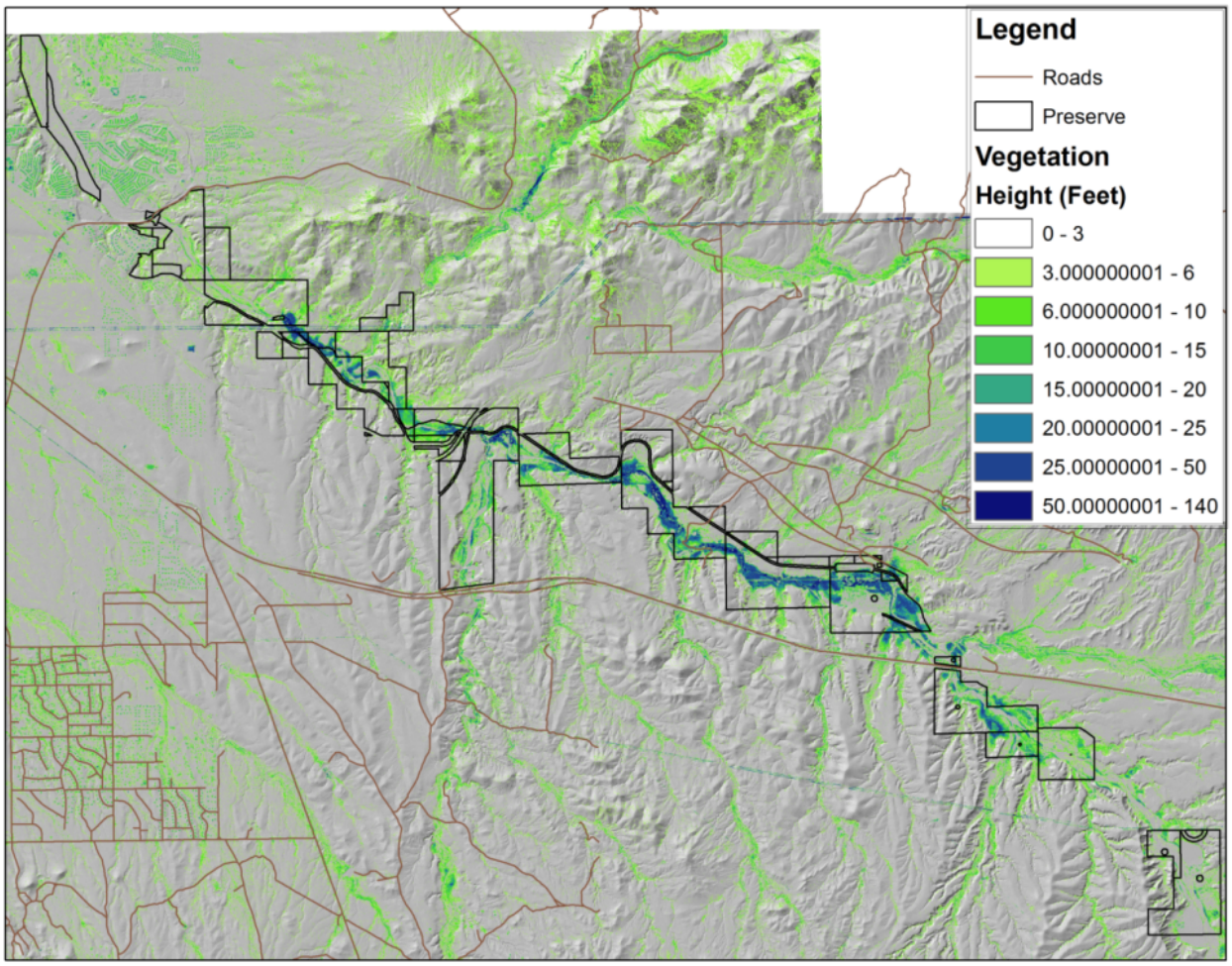

Figure 5: Map of Cienega Creek Preserve in relation to LiDAR flight area (Hillshade surface).

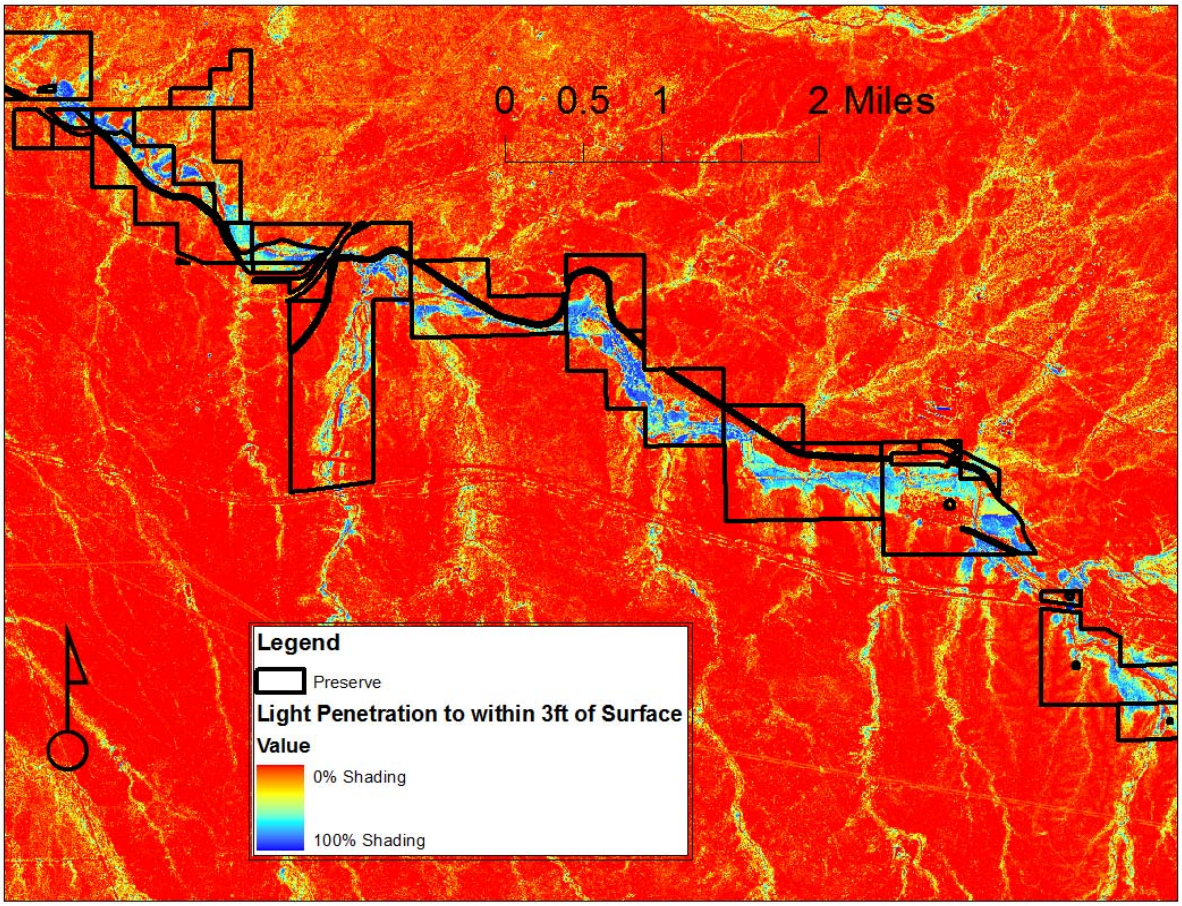

Figure 6: LiDAR point penetration proportion through canopies. Cottonwoods intercept nearly 100% of LiDAR points in dense stands.

3.4.3 Leaf Area Index

Zhao and Popescu (2009) demonstrated that LiDAR is useful for estimating Leaf Area Index (LAI) by tree species in a temperate forest in the Southeast United States. LAI may be characterized by leaf off conditions, as it is related to species canopy height, radius, and canopy base height. The use of multispectral orthophotography can strengthen this inference with a Normalized Difference Vegetation Index (NDVI) estimate.

3.4.4 Spatial distributions

A local maximum, or peak tree height (Popescu et al. 2002, McGaughey et al. 2010) can be applied to derive individual tree stems. With these we can explore individual large (>2m^3) plant-species interactions, as well as spatial distributions (Figure 7):

- Clustering - the spacing between plants, potentially related to water resource availability/competition
- Cohorts - plants of the same age, growing near each other, e.g. mesquite bosque, cottonwood grove.

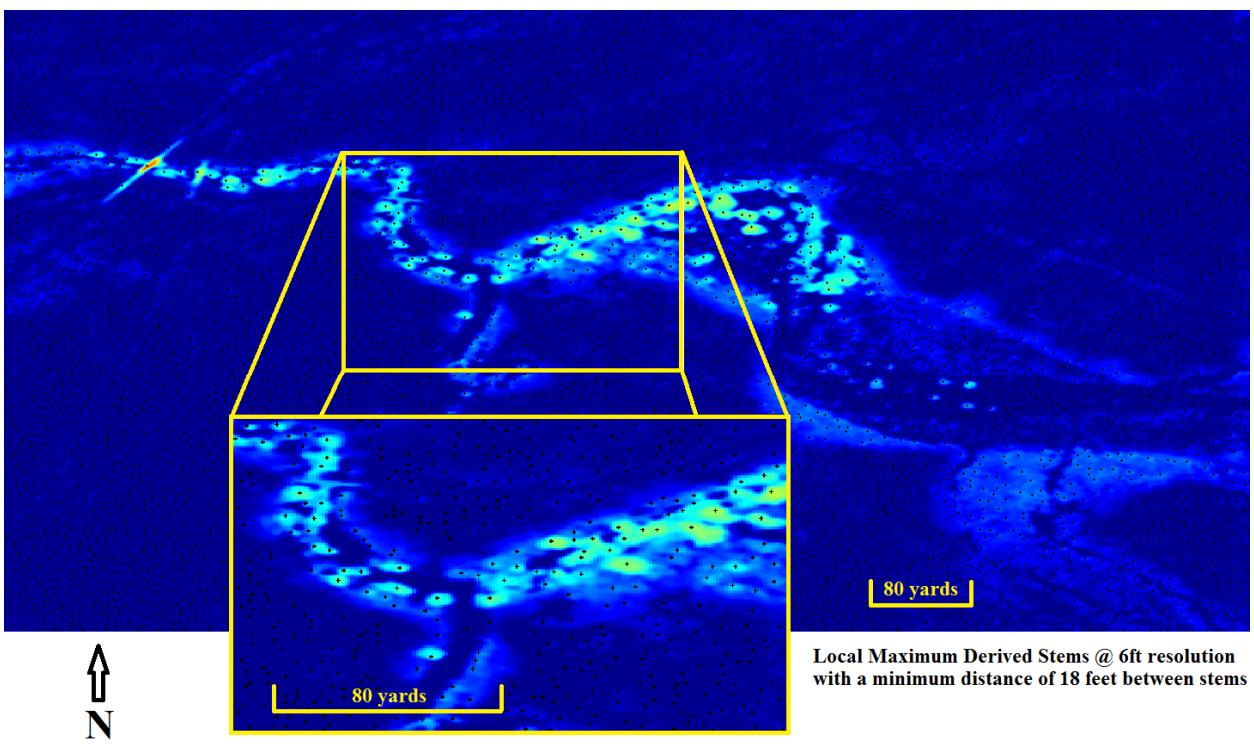

Figure 7: Example of stem detection using a local maximum in Matlab2010a (Mathworks 2010). The base canopy height model was a 6^{2}ft raster layer; we tuned the algorithm to accept no more than 1 point within 18 feet of another point to limit multiple points being attributed to individual trees (with multiple high crown points). This algorithm will need to be tested with field data to find the optimal distance variables, and a higher resolution canopy image (2-3^{2}ft) could be generated from the 2008 data.

3.4.5 Human Impacts

The smallest scale the bare earth layer derived from the LiDAR can be processed at is ~1m^2, although a smoother surface can be obtained with a 2-3m^2 surface, to avoid 'dimpling', because the data are in feet We selected a cell size of 3^{2}yd (Figure 2). Some human induced impacts we might be able to observe in a bare earth surface layer:

- Roads, Railways
- ATV trails
- Hiking Trails
- Grazing/Agricultural Impacts
- Power Lines
- Structures

3.4.6 Widlife Habitat

LiDAR does not directly measure 'habitat', however characteristics such as canopy base height, canopy cover, vegetation species, and topographic position are major factors in determining habitat suitability. Vierling et al. (2008) offer a compelling review of the uses of LiDAR for wildlife management. The potential to apply 2008 LiDAR to identify and begin monitoring species habitat in the Cienega Creek is includes classifying riparian bird, fish, and amphibian habitat features, as was noted to be of importance for the PCEMP (see main body of the report).

3.5 Vegetation measurements we cannot derive from the 2008 LiDAR

3.5.1 Complete, individual plant-level inventory

The 2008 data captured large plants (>1m^3), but smaller desert plants may not detected due to the sparseness of the point spacing from the sensor (Table 2, Figure 7) as well as the timing of the flight. A general estimate of observed vs predicted stems could be determined using a field-based inventory. It should be mentioned that while the structural parameters of the vegetation might be used to characterize a species, the LiDAR does not directly measure species diversity.

LiDAR tends to underestimate total plant stems due to the size of smaller plants, as well as their position in the view of the LiDAR sensor. In very dense vegetation only the overstory will be scanned, and deciduous trees with multiple high branches can be miss-classified with more than one parent stem (Figure 6).

3.5.2 Inside canopy measurements

The PAG LiDAR may not be dense enough to make accurate inner tree-canopy measurements (Table 2) at the individual tree scale for much of the data set. USFS (Laes et al. 2008) standards for individual tree level canopy metrics calls for ≥4 p/m^2 densities, with ≥8 p/m^2 for dense vegetation. While the data may be significant in areas with open cover a field based inventory may be needed to determine overall accuracy.

4 Considerations for Future LiDAR flights

The application of this technology to the habitat monitoring objectives of the PCEMP will be better served if future LiDAR flights collect data differently than was done in 2008 for PAG. Here we suggest the benefits of increasing accuracy versus the cost tradeoffs of doing so.

4.1 USGS LiDAR specifications

USGS (2010) LiDAR flight specifications are designed to generate bare earth layers. Because these specifications are focused directly at collecting vegetation data the density of the point cloud can be sparse, flight overlaps may not need to be greater than 50% side over-lap, and only first and last returns (1 and 2) are necessary. When vegetation is dense however, LiDAR point density must be increased to penetrate the vegetation to locate the bare earth. If a contract specifies '1 p/m^2 bare earth return', then the corresponding point cloud of raw points may likely include 2-30 p/m^2 to ensure lowest hits are made.

4.2 USFS LiDAR specifications

USFS (Laes et al. 2008) LiDAR flight specifications meet or exceed all USGS specifications. For dense vegetation point density of ≥4-8 p/m^2; >50% sidelaps; and 1-6 returns are recommended. This current specification is best used as a 'general rule of thumb' when contracting a LiDAR flight, and considerations should be made for specific flight mission planning.

4.3 Full Waveform LiDAR

Besides discrete point return LiDAR, there is also 'full waveform' LiDAR which returns data for all distances along a pulse; the wave changing amplitudes as it passes through vegetation, until it impacts the surface and reflects back. These data are very dense and require a large amount of post-processing to become useful for vegetation characterization. The potential of full waveform is great, but collection of such data is likely to increase costs. Full waveform data if available should be acceptable and welcomed, however these should be considered as supplemental to the available discrete returns.

4.4 Temporal research

The addition of new LiDAR flights over the same location will allow for repeat analysis of the site. A few potential uses of this new data are:

- Change is also an interesting and potentially useful temporal aspect, capturing the:
    - Vegetation growth and mortality
    - Clearing of vegetation by humans, grazing, or the effect of recent fire
    - ATV trails
    - Channel Morphology due to flooding and erosion
    - (at landscape scales) sinking of the basin due to ground water extraction.

4.5 Benefits of increased point density

By parameterizing the 2011 PAG flight to meet USFS vegetation specifications for the Pima County Ecological Monitoring Program could realize several metrics for vegetation that are currently unobtainable with the lower resolution 2008 data set, namely: canopy bulk density, accurate canopy base height, and percentile or quantile based canopy metrics. Increased point density would in addition likely capture small (<0.25m) plants found on the more xeric hillslopes surrounding Cienega Creek, which when coupled to 1ft orthophography could be used for community/species identification.

4.6 Costs of increased point density

Increasing the point density means the aircraft flying the LiDAR must travel slower, closer to the surface, and increase the number of 'flight lines'; this will increase the collection time, and therefore the cost per acre of the LiDAR. The cost increase is however not linear to the increase in point density, as the greatest cost to the vendor is getting the instrument here to Tucson for its initial spin-up. Also, data processing and storage will increase marginally. The costs of the 2008 Pinaleño USFS vegetation specified LiDAR (μ=7.66 p/m^2) was ~$1.40/acre from the vendor for post-processed raw .LAS data (that rose to ~$2.00/acre with USFS RSAC support for vegetation models) as opposed to the 2008 PAG flight (μ=2.66 p/m^2) cost of <$0.70/acre (no post processing). Consideration of cost should also include the size of the flight area, vendors often offer a discount for large collections >500,000 acres, which PAG likely received for 2008.

Increased point densities do not have to occur over an entire flight area if cost is a concern. Striping of the flight area with interspersed high density scan lines, or targeted scanning of priority areas could modify the costs of the overall flight.

Computer processing and storage are also increased by point density increases. The 2008 PAG data are approximately 347 GB of raw .LAS (all points), 271 GB of bare earth .TXT, 311 GB first return .TXT, and 311 GB of last return .TXT, requiring a large (>2TB) hard drive. Analysis of these layers should be conducted with Desktop PC, Workstation, or Server based computing with large (>3GB) RAM banks. New x64-bit processors and software, as well as CUDA© (NVIDIA Inc.) based GPU processing (i.e. desktop-supercomputing) are becoming more affordable, and increases in RAM (x64-bit: 4-128GB) and memory read times (Solid-State Drives (SSD) promise to make processing times irrelevant.

5 Conclusion

This report used LiDAR collected along Cienega Creek to investigate the application of this technology to the PCEMP in general and the habitat-monitoring component in particular. Though far from perfect for these needs, the 2008 PAG LiDAR provide adequate baseline data upon which we could monitoring vegetation structure if follow-up LiDAR data are collected. As the PCEMP moves into the implementation phase, this report provides much clearer understanding of data needs and costs that can be evaluated if Pima County decides to extend the program outside of the 2008 flight zone and into other parts of the County's reserve system, most especially the ranch properties that will form the foundation of the mitigation program.

6 Acknowledgements

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