**Abstract:**

The identification of small habitat features embedded within forest ecosystems is a challenge for many wildlife inventory and monitoring programs, especially for those involving rock outcrop specialist taxa. Rock outcrops are often difficult to remotely detect in dense Appalachian hardwood forests, as most outcrops remain hidden under the forest canopy and therefore invisible when relying on aerial orthoimagery to pinpoint habitat features. We investigated the ability for light detection and ranging (LiDAR) point cloud data to identify small rock outcrops during the environmental assessment phase of a proposed management project on the Jefferson National Forest in Virginia, USA. We specifically compared this approach to the visual identification of rock outcrops across the same area using aerial orthoimagery. Our LiDAR-based approach identified three times as many rock outcrop sites as aerial orthoimagery, resulting in the field-verification of four times as many previously-unknown populations of green salamanders *Aneides aeneus*, a rock outcrop specialist amphibian of high conservation concern, than would have been possible if relying on aerial orthoimagery alone to guide surveys. Our results indicate that LiDAR-based methods may provide an effective, efficient, and low-error approach that can remotely identify below-canopy rock outcrops embedded within Appalachian forests, especially when researchers lack pre-existing knowledge of local terrain and the location of habitat features.
Light Detection and Ranging (LiDAR) Assisted Detection of Rock Outcrops in Appalachian Hardwood Forests

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Abstract

The identification of small habitat features embedded within forest ecosystems is a challenge for many wildlife inventory and monitoring programs, especially for those involving rock outcrop specialist taxa. Rock outcrops are often difficult to remotely detect in dense Appalachian hardwood forests, as most outcrops remain hidden under the forest canopy and therefore invisible when relying on aerial orthoimagery to pinpoint habitat features. We investigated the ability for light detection and ranging (LiDAR) point cloud data to identify small rock outcrops during the environmental assessment phase of a proposed management project on the Jefferson National Forest in Virginia, USA. We specifically compared this approach to the visual identification of rock outcrops across the same area using aerial orthoimagery. Our LiDAR-based approach identified three times as many rock outcrop sites as aerial orthoimagery, resulting in the field-verification of four times as many previously-unknown populations of green salamanders *Aneides aeneus*, a rock outcrop specialist amphibian of high conservation concern, than would have been possible if relying on aerial orthoimagery alone to guide surveys. Our results indicate that LiDAR-based methods may provide an effective, efficient, and low-error approach that can remotely identify below-canopy rock outcrops embedded within Appalachian forests, especially when researchers lack pre-existing knowledge of local terrain and the location of habitat features.

Keywords: LiDAR; remote sensing; rock outcrops; green salamander; amphibian

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**Introduction**

Species with restricted ranges and highly-specialized habitat requirements are priorities for many wildlife monitoring and management programs. Habitat specialists are often used as indicator species in conservation efforts (Roberge and Angelstam 2006; Caro 2010; Butler et al. 2012), with past work highlighting declines of specialist species in response to global change, such as habitat and climate disturbances, across a broad taxonomic spectrum (Clavel et al. 2011). Similarly, range-restricted species are frequently at risk of declines due to habitat loss and are therefore the target of many conservation management programs (Casazza et al. 2014; Januchowski-Hartley 2016; Scriven et al. 2020).

Species associated with rock outcrops are frequently those with high degrees of habitat specialization and restricted ranges, especially in hardwood forests of the eastern United States. Numerous outcrop-specialized plant species have been found to exhibit both low levels of
genetic diversity and population size across portions of the Appalachian Mountain region of
North America (Godt et al. 1996), while outcrop-specialized vertebrate taxa from the same
region have been recognized as harboring cryptic, microendemic diversity (Patton et al. 2019).
Such species are accordingly receiving an increasing focus in regional conservation monitoring
and management efforts (Wiser and White 1999; Corser 2001; Ford et al. 2006; Ulrey et al.
2016). In particular, researchers across multiple states are currently in the midst of efforts to
survey rock outcrops for outcrop-specialist amphibians, such as green salamanders Aneides
aeneus (Figure 1A), that are undergoing review for possible listing as threatened or endangered
pursuant to the US Endangered Species Act (ESA 1973, as amended; Giese et al. 2012; Smith et
al. 2015; Newman et al. 2018; John et al. 2019).

A challenge related to surveying and monitoring rock outcrop specialists in forest
ecosystems is the identification of individual outcrops during the planning phase of management
projects. Outcrops may be small and isolated depending on local geology (Figure 1B), with rock
outcrops in mature eastern hardwood forests often occurring beneath a thick forest canopy
(Smith et al. 2017; Hinkle et al. 2018). In addition, even large rock outcrops and cliff systems
may still be obscured in leaf-off orthoimagery due to the presence of conifers or other dense
evergreen vegetation, further limiting these datasets’ applicability to the remote sensing of rock
outcrops. These attributes can render aerial orthoimagery useless in remotely sensing potential
habitat features at the landscape scale, with researchers and managers often forced to rely on
historic occurrence data, citizen science reports, or personal knowledge of the terrain within a
given area when selecting survey locations (Smith et al. 2015; Newman et al. 2018; Smith et al.
2019; Williams et al. 2020). Surveys for rock outcrop specialists in areas with few to no historic
records or little preexisting knowledge of local terrain may therefore underestimate both the
prevalence and abundance of focal taxa.

Light detection and ranging (LiDAR) datasets provide one possible avenue for advancing
the remote sensing of rock outcrops beneath thick forest cover. Datasets using LiDAR rely upon
pulsed lasers and associated sensors to generate a “point cloud” of elevation or distance
observations across a given area, including for vegetation, built structures, and the ground
surface (Devereux et al. 2005; Omasa et al. 2007; Dong and Chen 2017). Ground points (e.g.,
points reflecting the ground surface) from airborne LiDAR datasets can then be rendered into
high-resolution elevation models that visualize terrain features beneath thick forest cover and at a
resolution sufficient enough to identify microhabitat features associated with the forest floor,
including ground cover characteristics, fine-scale hydrology and terrain, and variability in forest
soils (Liu 2008; Akay et al. 2009; Murphy et al. 2011). In fact, high-resolution terrain and
vegetation height information derived from LiDAR data have recently been used to improve
occupancy and abundance modeling for some lungless salamander taxa within the central
Appalachian region (Contreras et al. 2020). Such LiDAR datasets, which are becoming more
widely available via state-level geospatial programs, may therefore provide researchers with an
ability to remotely identify rock outcrops within forest ecosystems more effectively than more
traditional methods, such as visual inspections of aerial orthoimagery. To date, however, no
attempts exist in the literature to assess the ability of LiDAR datasets to achieve these goals for
surveys of outcrop specialists in forested regions of the eastern United States.

We initiated an effort in early 2020 to survey rock outcrops within a densely-forested
portion of the Jefferson National Forest in southwest Virginia, USA for green salamanders – a
rock outcrop specialist of high conservation concern (Giese et al. 2012) – as part of the
environmental assessment of an area proposed for timber management activities by the USDA Forest Service. Green salamanders have been given high conservation priority across their range, especially in terms of public forest management activities, due to their high degree of habitat specificity (Gordon 1952; Petranka 1998), past observed population declines (Snyder 1983), and ongoing threats to existing populations (Corser 2001; Hinkle et al. 2018). As a result, multiple state wildlife agencies and federal land management agencies are engaged in inventory and monitoring for green salamanders throughout the species’ range (Newman et al. 2018; Rossell et al. 2019; Smith et al. 2019). The proposed timber management project that formed our study area lacked any historic records of green salamanders that could be used to guide survey site selection, with most rock outcrops located on steep slopes beneath thick mixed mesophytic forest cover that made the identification of rock outcrops via aerial orthoimagery difficult. We therefore used LiDAR data to remotely identify the location of putative rock outcrops across this study area in order to understand if the use of orthoimagery versus LiDAR data makes a difference for salamander monitoring. Here we detail this remote screening approach, present its results relevant to improving upon surveys of green salamanders, and discuss its potential applicability to surveys of other rock outcrop specialists in forest ecosystems.

**Study Site**

Our study area was centered around the Devil’s Hens Nest section of the Jefferson National Forest, a 50 km² region across Wise and Scott counties in Virginia, USA. The study area is located across relatively high elevations (approximately 500-1100 m asl) encompassing the headwaters of the Stock and Cove Creek watersheds along Powell and Cliff Mountains. The study area contains forest types common across much of the Dissected Appalachian Plateaus
Physiographic Province (Braun 1942; Muller 1982), featuring predominantly mixed mesophytic forests with riparian vegetation characterized by eastern hemlock *Tsuga canadensis* and great rhododendron *Rhododendron maximum* within stream gorges. Stream valleys in the study area are largely dissected gorges containing large cliff and boulder systems comprised of sandstone, with some limestone outcrops occurring across the lower, southern portion of the study area near the northern boundary of the Valley and Ridge Physiographic Province. Rock outcrops within the study area include the aforementioned cliff systems along stream gorges and isolated collections of sandstone boulders that occur as erosional remnants along higher-elevation ridgelines.

**Methods**

**Identification of rock outcrops using orthoimagery**

We first identified the location of rock outcrops within the study area using digital orthoimagery. Specifically, we used 0.3 m resolution, leaf-off orthoimagery publicly available from the Virginia Base Mapping Program (VGIN 2020; imagery data identifier s03_24.2019) to identify the location of putative rock outcrops in management units within the study area, as defined by USDA Forest Service personnel (Data S1). These management units encompassed 11.5 km², or approximately 23% of the study area (Figure 2). We first overlaid management unit polygons over orthoimagery in ArcGIS v.10.3, visually inspecting orthoimagery for indications of rock outcrops (e.g., visible cliffs or outcrops protruding through the forest canopy or linear banding of outcrop-associated, evergreen vegetation such as great rhododendron and mountain laurel *Kalmia latifolia*). Putative rock outcrop sites were marked with points in ArcGIS v.10.3. Since exposed rock microhabitats in our study area often occur in collections of closely-spaced rock
features along clifflines or in discrete outcrops derived from the same eroded and exposed surface strata (Smith et al. 2017; Hinkle et al. 2018), we defined rock outcrops in our orthoimagery surveys and the LiDAR-based screening described hereafter as those locations having one or more discrete outcrops spaced closely (<10 m) together and separated from other such locations by at least 50 m.

Identification of rock outcrops using LiDAR data

We also downloaded 0.75 m resolution, 1 cm vertical accuracy LiDAR point cloud data for the study area using publicly available data provided by Virginia Geographic Information Network (VGIN 2020; Table S1). Point cloud data were collected in December 2016 at a nominal pulse density of 1.746 pulses per square meter. We used the “LAZ to LAS” protocol in the LASTools extension (Hug et al. 2004) in ArcGIS v.10.3 to extract point cloud data, rendering ground points into a digital elevation model (DEM; 1 m spatial resolution and 0.1 m vertical resolution) using LASTools’ “blast2dem” protocol. We then stitched individual DEMs derived from separate point cloud coverages into a single DEM covering the entire study area using the Mosaic tool in ArcGIS v.10.3.

We then sought to classify the slope of terrain rendered on our resulting DEM to visualize high-slope locations representing putative rock outcrops. Past habitat data collected as part of green salamander assessments near our study area have indicated that rock outcrops generally contain near-vertical surfaces exceeding 80% slope and bounded by more gently-sloping hillsides (Smith et al. 2017; Hinkle et al. 2018). We therefore used the Slope tool in ArcGIS v.10.3’s Spatial Analyst extension to visualize slope across our LiDAR-derived DEM,
classifying resulting slope values into two groups: a high-slope category (>80%) and a low-slope
category (<80%; Figure 3).

We then used ArcGIS v.10.3’s Raster to Polygon tool to convert our classified DEM
slope raster into a polygon shapefile, selecting all high-slope polygons across the study area. We
exported this selection as a new shapefile, which indicated the location of putative rock outcrops
across our study area. This shapefile was trimmed to all management unit polygons and was then
used to guide field surveys. We excluded polygons from our LiDAR dataset that were co-located
with the shoulders of forest management roads, as these cut-banks may mimic the steep slopes of
vertical or near-vertical habitat features (White et al. 2010; Prendes et al. 2019). We identified
forest management roads using visual interpretations of data provided by USDA Forest Service
personnel, who had intensively surveyed the study area earlier in the project planning and
environmental assessment process.

Organismal surveys and comparisons of remote detection methods
We performed field surveys for both rock outcrops and green salamanders at all proposed
management units across the study area from March-October 2020, corresponding to the local
active season of green salamanders as observed in past studies (Smith et al. 2017). Surveys
consisted of the same two observers (the authors) walking and visually inspecting the entirety of
each management unit for rock outcrops to assess our remote sensing methods. We initially
targeted all management units where our LiDAR and orthoimagery datasets detected rock
outcrops, but we later surveyed remaining management units not highlighted by these datasets to
look for rock outcrops missed by our remote sensing methods.
We then performed time- and area-constrained visual encounter surveys at all rock outcrops identified in the field. Surveys consisted of the same two observers (the authors) visually inspecting all accessible crevices and rock surfaces for green salamanders with an LED headlamp. Since green salamanders also exhibit temporary arboreal behavior during summer months (Wilson 2003; Waldron and Humphries 2005), we also surveyed all tree surfaces and refugia (knotholes, hollow stems) within 10 m of rock outcrops with an LED headlamp and Whistler WIC-5000 borescope. We surveyed each rock outcrop for one hour or until all available rock and tree surfaces had been searched, with the timing of surveys randomized between early morning and late evening (0700-2300 hours). Each rock outcrop was surveyed twice, with visits spaced at least two weeks apart, if green salamanders were not encountered during the initial visit. We did not perform surveys during or immediately after heavy rainfall events or during abnormally dry periods to avoid conditions locally associated with low green salamander detection, as noted by past work near our study area (Smith et al. 2017). This survey methodology has been previously used to successfully detect green salamanders in numerous previous studies near our study area (Smith et al. 2015; Smith et al. 2017; Hinkle et al. 2018).

Since the USDA Forest Service’s goals for this inventory effort were to detect the presence of green salamanders in management units throughout the study area, we limited our survey data to the presence of the species at a given rock outcrop, as opposed to estimating abundance or other demographic parameters.

Following the completion of field surveys, we sought to compare the ability for our two remotely-sensed datasets (orthoimagery and LiDAR) to identify the location of rock outcrops in the field. Since all of our putative rock outcrops identified remotely via orthoimagery (n = 8) verified as having outcrops present in the field, we used these sites as control points to compare...
against LiDAR-identified outcrops. Specifically, we compared the following: (i) the number of field-verified rock outcrops detected via orthoimagery that were detected by our LiDAR dataset, (ii) the number of field-verified rock outcrops detected by LiDAR data but not by visual examination of high-resolution orthoimagery (Figure 4), and (iii) the number of false-positive rock outcrops detected by LiDAR data (e.g., locations identified by our screening approach as having putative outcrops present that did not verify during field surveys). We also inventoried the number of rock outcrops that we identified during field surveys that were not detected by either orthoimagery or LiDAR data. In order to demonstrate the utility of our methodology for monitoring rock outcrop-dwelling salamanders, we then repeated these comparisons for rock outcrops where green salamanders were detected during field surveys.

**Results**

We verified the presence of 24 rock outcrops in management units across our study area during field surveys (Table S2). Eight outcrops (33% of all field-verified outcrops) were identified by high-resolution aerial orthoimagery, while our LiDAR dataset identified all 24 outcrops (100% of field-verified outcrops). Sixteen additional high-slope locations were identified by our LiDAR dataset that were associated with cut-banks along forest management roads and were removed from subsequent analyses (Table 1). All rock outcrops identified by inspection of aerial orthoimagery were large outcrop and cliff complexes associated with riparian habitats along major stream gorges within the study area (Cove Creek and Stock Creek) and were visible protruding through the forest canopy. By contrast, rock outcrops identified only by our LiDAR dataset were either smaller linear cliff systems hidden beneath the forest canopy or isolated, erosional remnant outcrops in ridgetop or midslope positions also beneath the forest canopy.
We encountered no false positives or negatives when using our LiDAR dataset, following our methodology to remove high-slope locations co-located with cut-banks along forest management roads.

We encountered green salamanders at 13 (54%) rock outcrops surveyed during field visits (Figure 2). We could not perform surveys at six (25%) of our rock outcrops due to their locations along excessively steep or unstable slopes that prevented safe access. Three (23%) outcrops with confirmed green salamander observations were identified during visual inspections of orthoimagery, while all 13 of these rock outcrops were identified by LiDAR data. We found green salamanders most often in rock crevices or on outcrop surfaces (n = 11 sites), with remaining animals found on tree surfaces or in hollow stems or knotholes in trees surrounding outcrops (n = 2 sites; see Table S2 for a full list of observations). All of the green salamander observations inventoried through our field surveys represent previously-unknown localities not inventoried by natural history collections or reported in other published work.

Discussion

Datasets derived from LiDAR hold promise as a tool for identifying microhabitat features embedded within the larger landscape, due to their high resolution and ability to detect fine-scale features in complex terrain. Such datasets have previously been used to identify fine-scale features such as forested wetlands (Lang and McCarty 2009), below-canopy cave openings (Weishampel et al. 2011), and even the presence of invasive plant taxa (Asner et al. 2008). Data derived from LiDAR and representing vegetation height and terrain complexity have also recently been used to improve surveys and abundance predictions for several terrestrial salamander species within central Appalachian hardwood forests (Contreras et al. 2020).
results extend this applicability to the detection of rock outcrops embedded within Appalachian hardwood forests and associated surveys of rock outcrop specialists. The use of LiDAR data allowed us to not only detect rock outcrops beneath the forest canopy but also inventory multiple new localities of a sensitive species of high conservation concern as part of the environmental assessment phase of a proposed forest management project.

Most notably, we found that LiDAR data were substantially better at detecting the presence of rock outcrops than more commonly-used aerial orthoimagery, especially for outcrops located within thick vegetation (Figure 4). In fact, LiDAR data were capable of detecting three times more rock outcrops than visual inspections of aerial orthoimagery. This was especially true for smaller outcrops not located within larger collections of grouped outcrops or large cliff systems. Such outcrops, while isolated in nature, can nonetheless be important habitat for wildlife species of high conservation concern, including green salamanders (Gordon 1952; Petranka 1998; Hinkle et al. 2018; Rossell et al. 2019). One such isolated outcrop identified by LiDAR data in our study area, for example, was later found to serve as a nesting site for our target species during follow-up field surveys (Figure 1B).

We also found that both LiDAR and orthoimagery-based datasets had zero false positives after trimming the high-slope locations identified by LiDAR data for road cuts, with neither dataset highlighting locations that did not contain outcrops during field surveys. While the identification of rock outcrops is relatively straightforward when using orthoimagery since rocks can be visually seen on image tiles, false positives may be a special concern for the detection of rock outcrops using LiDAR data, since the detection of these features is based on slope rather than visual assessments of habitat. The absence of false positives in our dataset was likely due to our use of pre-existing slope measurements at nearby outcrops to guide our selection of slope
classifications when categorizing our slope-adjusted DEM. This likely led to a more accurate
categorization of outcrop features than would have been possible without pre-existing
knowledge of the attributes of local outcrop features, and researchers adapting our method
without such pre-existing field data may want to proceed with caution if ascribing our slope
classification thresholds to habitats in study areas with differing geological and physiographic
contexts. Performing field-based assessments of a subset of known outcrops across an area of
interest and then using these data to inform the selection of slope criteria may be one way to
ensure this accuracy during work in other study areas.

It is important to note that our slope classification did initially result in several false
positives, namely constructed cut-banks along the shoulders of forest management roads
providing vehicle access throughout our study area (Figure 5). However, the remaining steps in
our methodology, namely removing high-slope locations co-located with forest management
roads, eliminated these false positives from our dataset and ensured the accuracy of our final
dataset used to guide field surveys. This may be an additional consideration for those adapting
our protocol in other study areas, especially those where the location of forest roads is not known
a priori. Specifically, older or decommissioned forest roads not visible via aerial orthoimagery
may still retain cut-banks and other graded features that may be detected by slope-adjusted
LiDAR datasets (White et al. 2010; Prendes et al. 2019), falsely presenting as linear rock
outcrops in remotely-sensed shapefiles. Similarly, other anthropogenic features – such as built
structures, ditches and drainage features, and features related to surface mineral extraction – may
also be detected in protocols relying upon the detection of high-slope locations within LiDAR
datasets (Chase et al. 2011; Rapinel et al. 2015; Moudry et al. 2019). It is also possible that the
construction of these features and other landscape changes may occur during the time lag
between the acquisition of LiDAR data and subsequent data analyses or field surveys. This was not an issue in our study area despite a substantial (four years) time lag between data acquisition and field surveys due to the location of our study area in an undeveloped national forest. However, these will likely be important considerations for the adaptation of our approach in other study areas.

The resolution of digital elevation models (DEMs) rendered from LiDAR data is also a potential consideration for the application of our methodology to other study areas. The smallest rock outcrops in our management units were generally large enough (approximately 3-5 m tall by 10 m long) to be easily detected by LiDAR data and the associated DEM rendered from those data. However, more coarse resolution datasets – or, conversely, study areas with substantially smaller microhabitat features – may pose problems for the remote sensing of potential green salamander habitat using LiDAR data by way of not sufficiently detecting all high-slope locations across the landscape. Researchers should therefore carefully consider the resolution of available LiDAR datasets, the resolution of DEMs and related spatial coverages rendered from those data, and the size of the landscape features that are of interest to a study prior to adapting our approach in other contexts.

Regardless, we found that the LiDAR-based detection of rock outcrops substantially improved our ability to identify not only microhabitat features but also localities for a sensitive wildlife species of high conservation concern. Identifying rock outcrops via LiDAR data allowed for us to inventory more than four times as many green salamander localities than we would have been able to achieve if relying on orthoimagery alone. Given that our study area occurred within an area proposed for timber harvesting activities by the USDA Forest Service, this improved knowledge is important to help apply existing forest policies, which dictate that managers must
adapt management protocols to provide enhanced protection (e.g., larger buffers around rock
faces, intact forest corridors between nearby outcrops) when green salamanders are known at a
given location (Brodman 2004; USDA Forest Service 2012). The ability for LiDAR data to more
effectively uncover both potential habitat and new target species localities allowed us to provide
much more robust information that can guide future management planning across our study area
and improve the conservation value of management actions.

More broadly, our results indicate that researchers who are relying solely on the use of
orthomagery, historic records, or personal knowledge of local terrain may be underestimating
both the prevalence and abundance of green salamanders in undersampled areas. In our study
area, for example, a reliance solely on orthomagery and pre-existing knowledge of local terrain
would have resulted in far fewer inventoried green salamander populations, as well as an
erroneous conclusion that these populations were highly disjunct and constrained only to larger
outcrop systems penetrating the forest canopy. We located green salamanders not only at these
major outcrop complexes but also at smaller, isolated outcrops hidden beneath the forest canopy
and between those locations. This species already suffers from sampling deficiency rangewide
(Smith et al. 2015; Newman et al. 2018; Smith et al. 2019), and future inventory and monitoring
methods that do not sufficiently survey available habitat may continue to underestimate this
species’ status in certain areas. Adapting tools, such as LiDAR data, that allow for researchers to
remotely screen for the location of potential habitat prior to initiating field surveys may be one
key avenue for improving upon survey techniques for both green salamanders and other rock
outcrop specialists in future work.

Supplemental Material
**Data S1.** Spatial data (keyhole markup language format) for management units in the Devil’s Hens Nest portion of the Jefferson National Forest, Wise and Scott Counties, Virginia, USA. Management units within the study area were used to identify rock outcrops using aerial orthoimagery and light detection and ranging (LiDAR) point cloud data.

**Table S1.** Raw data identifiers for light detection and ranging (LiDAR) point clouds used to generate a digital elevation model for the Devil’s Hens Nest portion of the Jefferson National Forest, Wise and Scott Counties, Virginia, USA. All point clouds were downloaded from the United States Geological Survey’s National Map geospatial download platform (http://nationalmap.gov).

**Table S2.** Rock outcrops detected using two remote sensing methods (light detection and ranging (LiDAR) and aerial orthoimagery) across the Devil’s Hens Nest portion of the Jefferson National Forest, Virginia, USA. Salamander observation data refer to the results of green salamander *Aneides aeneus* surveys of each remotely identified rock outcrop in 2020. Rock outcrops coded as “inaccessible” could not be surveyed due to excessively steep or unstable slopes that prevented access. Geographic coordinates have been obscured to two decimal places due to conservation concerns.

**Reference S1.** Brodman R. 2004. Region 9 Species Conservation Assessment for the Green Salamander, *Aneides aeneus* (Cope and Packard). Milwaukee, Wisconsin: USDA Forest Service.
Reference S2. Giese CLA, Greenwald DN, Curry T. 2012. Petition to list 53 amphibians and reptiles in the United States as threatened or endangered species under the Endangered Species Act. Tucson, Arizona: Center for Biological Diversity.

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Table 1. Numbers of high-slope locations identified by orthoimagery and light detection and ranging (LiDAR) data across the Devil’s Hens Nest portion of the Jefferson National Forest, Wise and Scott Counties, Virginia, USA in 2020, grouped by source dataset type. “After road removal” refers to high-slope locations identified by LiDAR data but co-located with forest management road cut-banks that were excluded from subsequent investigation. “Unsurveyable” refers to high-slope locations identified by LiDAR data and/or orthoimagery that were unable to
be surveyed for green salamanders *Aneides aeneus* due to the presence of excessively steep and/or unstable slopes.

| Dataset type       | Rock outcrops detected | After road removal | Field-verified | Unsurveyable | Green salamanders present |
|--------------------|------------------------|--------------------|----------------|--------------|---------------------------|
| Orthoimagery and LiDAR | 8                      | 8                  | 8              | 2            | 3                         |
| LiDAR alone       | 32                     | 16                 | 16             | 4            | 10                        |
| Total              | 40                     | 24                 | 24             | 6            | 13                        |

**Figure Captions**

**Figure 1.** Study organism and associated habitat types used in an assessment of the ability for light detection and ranging (LiDAR) data to remotely detect rock outcrops in Appalachian hardwood forests. (A) Green salamander *Aneides aeneus* traversing the vertical surface of a rock outcrop within the study area. Note dorsoventrally flattened body, which serves as an adaptation for narrow crevice refugia. (B) Typical rock outcrop habitat for green salamanders, with one of
the authors for scale. This particular outcrop feature – an erosional remnant – was isolated from other outcrops, harbored a nesting site for green salamanders, and was only detected by LiDAR data.

**Figure 2.** Location of the study area across the Devil’s Hens Nest portion of the Jefferson National Forest, Wise and Scott Counties, Virginia, USA used in 2020 to assess the ability of light detection and ranging (LiDAR) data to remotely detect rock outcrops. Polygons denote the location of management units defined by the Jefferson National Forest, with different symbols denoting rock outcrop sites identified using remote screening methods (“LiDAR/Orthoimagery” denotes sites identified by both LiDAR data and orthoimagery). “Detection” and “No Detection” denote rock outcrops where green salamanders *Aneides aeneus* were encountered or not encountered during follow-up field surveys, respectively. Red box in inset map denotes the location of the study area.

**Figure 3.** Generalized workflow for identifying putative rock outcrops from light detection and ranging (LiDAR) data across the Devil’s Hens Nest portion of the Jefferson National Forest, Wise and Scott counties, Virginia, USA in 2020.

**Figure 4.** Representative example of orthoimagery versus light detection and ranging (LiDAR) data across a portion of the study area (red box in inset map) encompassing the Cove Creek headwaters of Wise and Scott Counties, Virginia: (A) aerial orthoimagery, (B) a digital elevation model of the same area rendered from LiDAR ground points, and (C) high-slope rock outcrops (red polygons) as identified by the digital elevation model and our screening methodology.
Diagonal lines represent visual artifacts produced during rendering and did not affect the identification of high-slope rock outcrops. None of the rock outcrops highlighted in Panel C were originally identified when using aerial orthoimagery.

**Figure 5.** Representative example of cut-banks along forest roads (yellow polygons) identified as high-slope locations adjacent to rock outcrops (red polygons) in a light detection and ranging (LiDAR)-derived digital elevation model across the Devil’s Hens Nest portion of the Jefferson National Forest in Wise and Scott counties, Virginia (red box in inset map) in 2020. Yellow cut-bank polygons correspond to an active forest management road providing access to management units.
Figure 3

LiDAR Point Cloud Download

Ground Points Extraction

Render Digital Elevation Model

Slope Analysis and Categorization

Low-Slope (<80%)

High-Slope (>80%)

Putative Outcrop Layer

Roadbed Exclusion
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