Frontiers in Ecology and the Environment

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Front Ecol Environ 2008, 6, doi 10.1890/070001

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Lidar: shedding new light on habitat characterization and modeling

Kerri T Vierling[1*], Lee A Vierling[2], William A Gould[3], Sebastian Martinuzzi[2], and Rick M Clawges[4]

Ecologists need data on animal–habitat associations in terrestrial and aquatic environments to design and implement effective conservation strategies. Habitat characteristics used in models typically incorporate (1) field data of limited spatial extent and/or (2) remote sensing data that do not characterize the vertical habitat structure. Remote sensing tools that directly characterize three-dimensional (3-D) habitat structure and that provide data relevant to organism–habitat interactions across a hierarchy of scales promise to improve our understanding of animal–habitat relationships. Laser altimetry, commonly called light detection and ranging (lidar), is a source of geospatial data that can provide fine-grained information about the 3-D structure of ecosystems across broad spatial extents. In this review, we present a brief overview of lidar technology, discuss recent applications of lidar data in investigations of animal–habitat relationships, and propose future applications of this technology to issues of broad species-management and conservation interest.

Front Ecol Environ 2008, 6, doi 10.1890/070001

Habitat structure often strongly influences animal–habitat associations (eg MacArthur and MacArthur 1961; Brokaw and Lent 1999), and habitat data are necessary for ecologists to develop effective conservation and management strategies. The ideal tool for characterizing potential habitat would provide data about the three-dimensional (3-D) architecture of habitat in great spatial detail, yet also across broad extents. However, habitat models are currently based upon (1) field data of limited spatial extent and/or (2) remote sensing data that are unable to characterize vertical habitat structure. Remote sensing tools that directly characterize 3-D habitat structure and that provide data relevant to organism–vegetation interactions across a range of spatial scales from fine ($< 1\ m^2$) to coarse (ie regions $> 104\ km^2$) may substantially advance species–habitat modeling (Mason *et al.* 2003; Figure 1).

Laser altimetry, commonly referred to as light detection and ranging (lidar), is a technology that strikes close to the "ideal" habitat mapping tool described above. Lidar is a relatively new source of geospatial data that can provide fine-grained information about the 3-D physical structure of terrestrial and aquatic ecosystems (see review by Lefsky *et al.* [2002]). Over the past decade, lidar data have been increasingly used in geomorphology, silviculture, and forest ecosystem sciences, and have allowed several fundamental advances to be made in those disciplines. Although some studies discuss the *potential* for lidar to be used in exploring wildlife–habitat relationships (eg Davenport *et al.* 2000; Lefsky *et al.* 2002; Mason *et al.* 2003; Hyde *et al.* 2005), studies that directly relate empirical wildlife data with lidar-derived data on habitat structure have been few. Therefore, our objectives here are (1) to give a brief overview of the technology of lidar as it applies to animal–habitat modeling, (2) to review recent advances made in peer-reviewed studies that have explicitly used lidar to examine animal–habitat relationships, and (3) to discuss potential future applications (and limitations) of this technology in animal–habitat modeling.

In a nutshell:

- The three-dimensional arrangement of habitat is fundamental to how animals interact with the environment
- Lidar remote sensing is a tool that can characterize three-dimensional habitat structure of terrestrial and aquatic environments in fine detail across broad areas
- Lidar data may replace many labor-intensive, field-based measurements, and can characterize habitat in novel ways
- Incorporating lidar data into studies of animal–habitat relationships will help to improve models used for species management and conservation

■ Lidar: a moment in the short life of a laser pulse

Lidar is an "active" remote sensing technique, because the sensor both emits and records the radiation signal in the form of frequent, short-duration laser pulses. This is in contrast to traditional, "passive" image acquisition systems, which record radiation reflected by the surface from a source external to the sensor (such as the sun). Lidar

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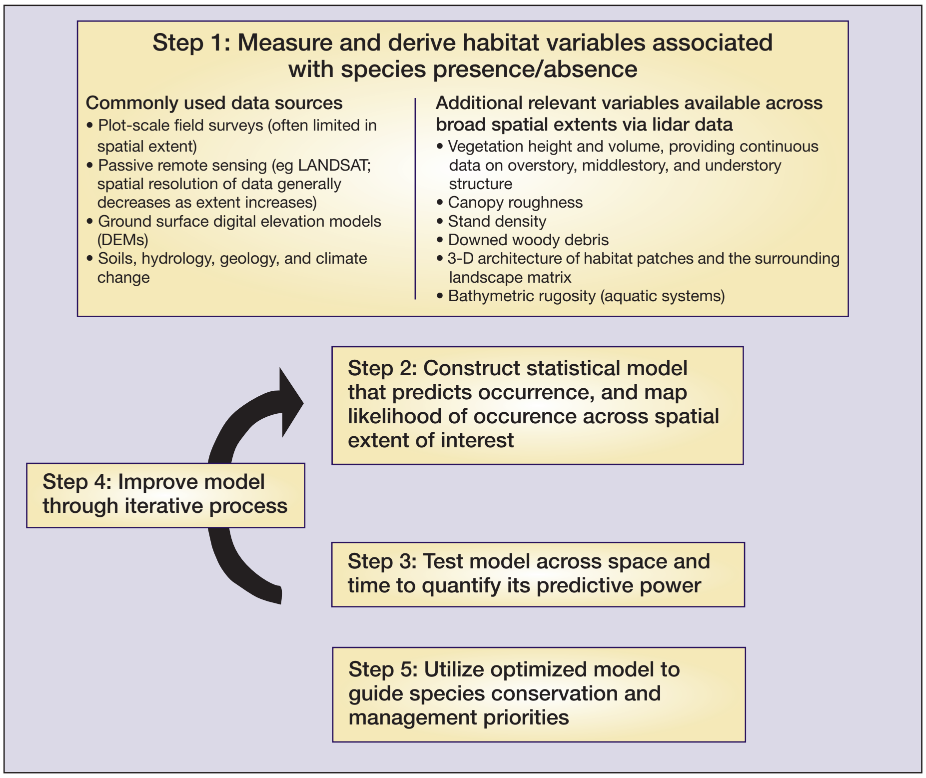

Figure 1. *Conceptual diagram of an inductive approach to creating species–habitat models. While deductive approaches to species habitat modeling differ in structure from the inductive approach shown here, the potential for lidar-derived information to aid the modeling process is similar in both cases. See papers such as Pressey (2004) and Brooks* et al. *(2004) for more information regarding approaches to species–habitat modeling.*

instruments can measure the location of objects in x, y, z space when an emitted laser pulse strikes a target surface and returns a portion of that laser energy to the sensor. The elapsed time between pulse emission and detection (when multiplied by the speed of light) produces the round-trip distance between the sensor and target, and the vertical distribution of surfaces can be recorded on either discrete point-by-point or continuous bases. Discrete point return systems typically operate at a very high spatial resolution, with the laser illuminating a very small spot (footprint diameter < 1 cm to tens of cm, depending upon the distance between the sensor and target), and record up to four points per laser pulse. Continuous “waveform” systems that digitize the energy of the full-return laser signal typically integrate information over a larger (5–70 m) footprint (Dubayah and Drake 2000). Because each emitted laser pulse is aimed toward a different footprint location, aggregating the billions of pulse-return signal records produces a 3-D map of surface structure that can be used to characterize potential habitat (Figure 2a).

Lidar systems can be mounted on ground-based, airborne, or spaceborne platforms. Ground-based lidar systems are typically mounted on a tripod, and allow rapid collection of dense (< 1 cm resolution) 3-D spatial datasets of ecosystems (Figure 2 b,c). “Point clouds” of laser returns obtained from multiple scanning positions can be co-registered in space to provide more detailed views of objects from multiple vantage points. Use of ground-based lidar systems has recently expanded from its origins in engineering analysis of built structures (Lichti *et al.* 2002) to investigations of plant canopy structure (eg Chasmer *et al.* 2006; Clawges *et al.* 2007). In aircraft, real-time data collected by onboard Global Positioning and Inertial Navigation Systems allow the 3-D position and attitude (roll, pitch, and yaw) of the lidar sensor to be calculated with a precise time reference. Encoding each emitted laser pulse with this time reference yields the information necessary to derive the absolute position of the reflecting surface or surfaces that have returned energy from the signal (Wehr and Lohr 1999). The electronics are designed and calibrated such that some current airborne sensors can resolve laser information fired and returned at rates of up to 167 000 pulses per second. A spaceborne lidar system (Geoscience Laser Altimeter System [GLAS]; http://glas.gsfc.nasa.gov/) is currently orbiting the Earth; however, its design is geared toward coarse-scale assessments of surface elevation and atmospheric properties. While GLAS can be used to derive some forest structural information (Lefsky *et al.* 2005), the data it provides are not collected in a contiguous manner across the landscape, so their usefulness in characterizing habitat is currently unknown.

The laser wavelength employed in a particular lidar instrument largely determines its interaction (or lack thereof) with various surface types, and therefore dictates how the 3-D structure of potential habitat is recorded by the sensor. For example, while near-infrared wavelengths are readily reflected by vegetation and soil (thus making them useful for recording canopy and ground signals), these same wavelengths are almost wholly absorbed by water and do not provide enough “return” energy for point detection by the instrument. To map bathymetric habitat features in marine and freshwater environments, therefore, a higher energy blue–green laser, that can transmit through water and enable subsurface point detection is required. Lefsky *et al.* (2002) provide additional details about lidar technology for a general audience.

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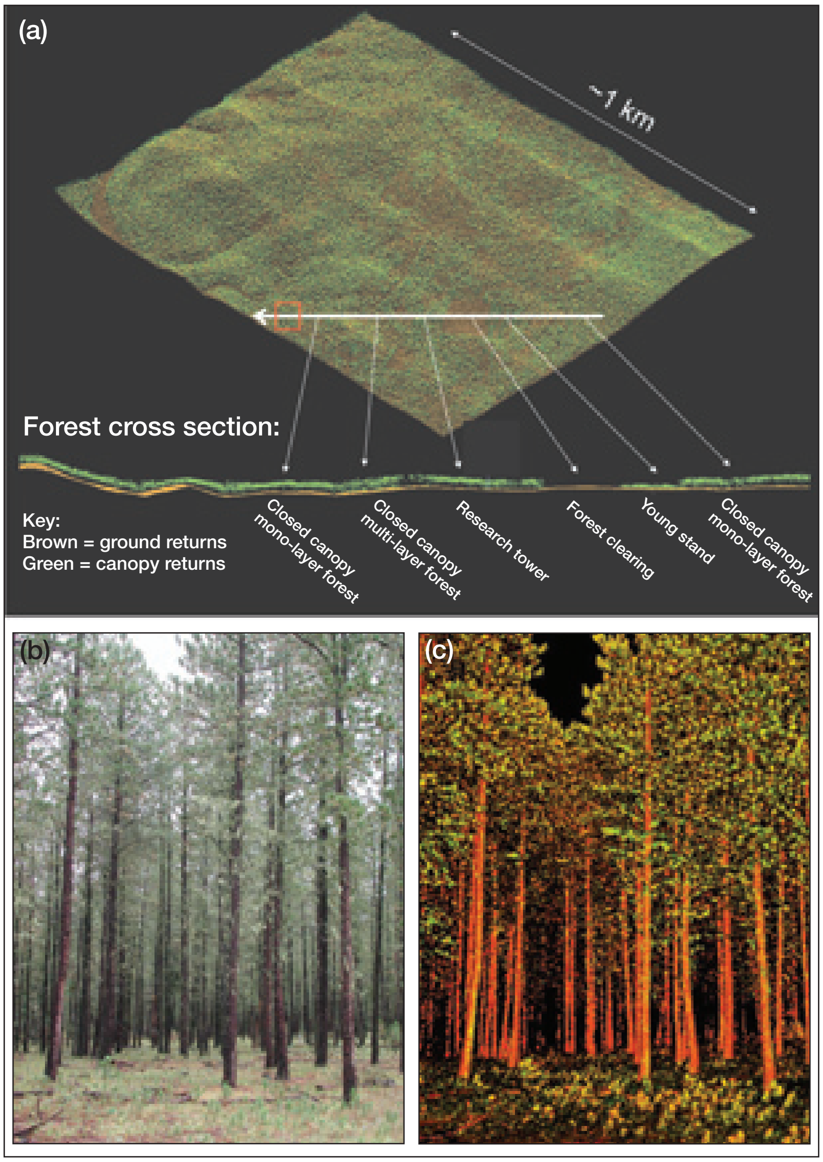

Figure 2. Examples of (a) airborne-derived lidar, (b) ground-based digital photography, and (c) ground-based lidar data collected at a ponderosa pine-dominated forest ecosystem in the Black Hills of South Dakota. (a) Ground points are colored orange, while vegetation canopy points are green. The transect at the bottom represents a 10-m wide ground swath. The highest canopy points in the transect are approximately 17 m high. The red square denotes the approximate area shown in (b) and (c). (c) Woody vegetation points are colored orange with foliage points colored green

Applications of lidar to animal–habitat modeling

A growing number of studies mention the potential for lidar to advance understanding of animal–habitat associations, yet, to date, few have actually used the data to quantitatively address these relationships (Table 1). The majority of refereed papers discussing the use of lidar to address ecological issues have appeared within the forestry and remote sensing literature. Only recently has the technology bridged disciplines to facilitate habitat modeling.

Lidar can be employed to examine species distributions in two distinct yet complementary ways. First, lidar data can be used as a predictive tool to seek out given species distributions, based on what is known about the natural history of the species. For example, the endangered Delmarva fox squirrel (*Sciurus niger cinereus*) is endemic to tall, dense forests with an open understory. Nelson *et al.* (2005) note that potential Delmarva fox squirrel habitat might be identified across extensive areas using lidar in conjunction with other sampling methods. A similar approach, using lidar-derived structural metrics, is currently underway to guide field-survey efforts for the highly endangered ivory-billed woodpecker (*Campephilus principalis*; R Dubayah pers comm). Alternatively, lidar data can be used as an exploratory tool to better understand resource selection by species of known distributions. For example, Broughton *et al.* (2006) evaluated detailed territory maps of marsh tits (*Poecile palustris*) using airborne lidar data and found substantial differences between the vegetation structure within marsh tit territories and that of adjacent locations not occupied by the bird. In particular, marsh tits were found to occupy sites comprised of mature trees with a subcanopy shrub layer, and to avoid sites containing many small, young trees (Broughton *et al.* 2006). This study is an initial confirmation of the observations made by Bradbury *et al.* (2005), who described lidar as an important tool for evaluating bird–habitat models. Bradbury *et al.* (2005) note that lidar provides (1) a combination of fine resolution data and broad spatial extent and (2) data with better vertical resolution and sampling density than can be achieved by workers in the field. These characteristics make lidar a powerful tool for examining ecological issues at multiple scales using previously unmeasurable habitat features.

In addition to studies of animal distributions, lidar data hold great promise for addressing relationships between vertical forest structure (Figure 3) and animal diversity. Recent studies have found strong positive correlations between lidar-derived measures of vegetation structural diversity and bird species diversity in both deciduous forests (Goetz *et al.* 2007) and mixed conifer/aspen forests (Clawges *et al.* in press). Hyde *et al.* (2005, 2006) also found a significant correlation between measures of vegetation structure derived from lidar and on-the-ground field observations, indicating that lidar-derived data can, in some instances, replace field-derived vegetation data traditionally used to characterize avian habitat. If this

Table 1. Current and potential uses of ground-based and airborne lidar data in studies of animal–habitat relationships and modeling

	Ground-based lidar	*Airborne lidar*
Spatial extent	~1 ha	Varies; some region-wide acquisitions currently exist
Themes of refereed studies exploring animal–habitat relationships	None to date	**Terrestrial** Creation of habitat maps to guide endangered species survey efforts (Nelson *et al.* 2005) Creation of habitat maps to guide management of common species (eg Hyde *et al.* 2005, 2006) Assessment of terrestrial habitat quality (Hinsley *et al.* 2002, 2006; Hill *et al.* 2004) Quantification of insect defoliation events (Solberg *et al.* 2006) Relating avian species territory (Broughton *et al.* 2006) and diversity (Clawges *et al.* in press; Goetz *et al.* 2007) to lidar-derived vegetation structure **Aquatic** Prioritization of restoration efforts for salmonid spawning habitat (Jones 2006) Relating fish diversity to lidar-derived coral rugosity (Kuffner *et al.* 2007)
Example future research areas relating to the use of lidar data for terrestrial and aquatic habitat modeling	Investigations of small organisms (eg insects) with fine spatial scale habitat requirements Development of novel habitat structure indices not attainable using traditional field observation Implementation of studies across numerous habitat types and geographic areas around the globe	Evaluation of resource utilization for individuals across a hierarchy of spatial scales Evaluation of habitat structural connectivity for metapopulations across a hierarchy of spatial scales Incorporation into spatially explicit databases to assist with conservation planning and prioritization Examination of relationships between animal biodiversity and habitat structure Development of novel habitat structure indices not attainable using field observation Expansion of studies across numerous habitat types and geographic areas around the globe

finding holds true across a variety of ecosystems, lidar data could become a viable complement (or surrogate) for field-based habitat assessment, and may be particularly important for mapping habitat in remote, rugged, inaccessible, or otherwise dangerous terrain.

Aside from habitat availability assessment, lidar data have also been used in conjunction with field data to estimate habitat quality across broad spatial scales. Hill *et al.* (2004) and Hinsley *et al.* (2002) employed an airborne lidar system to map forest structure across 157 ha of deciduous woodland in the United Kingdom, and related laser-based canopy height to nestling chick body mass (a surrogate for breeding success and territory quality) for two different bird species. By using the relationship between nestling body mass and lidar-derived woodland canopy height, this aspect of habitat quality was extrapolated across the entire forest (Hill *et al.* 2004). Hinsley *et al.* (2006) recently extended these analyses by investigating how climate variability over a 7-year period influenced relationships between habitat quality and canopy structure. Interestingly, the relationships between chick mass and canopy height varied according to spring-time temperature, with chick mass declining relative to canopy height during cold springs, yet increasing relative to canopy height in warm springs (Hinsley *et al.* 2006). Indeed, this study by Hinsley *et al.* (2006) provides an exemplary glimpse of the fine nuances in animal–habitat relationships that may be explored when using lidar-derived vegetation structure information in conjunction with field-collected wildlife data. As lidar-derived vegetation characterization continues to expand into more diverse habitat types (eg to map structural characteristics of low-lying shrubland systems with varying disturbance histories; Streutker and Glenn 2006; Figure 4), these ani-

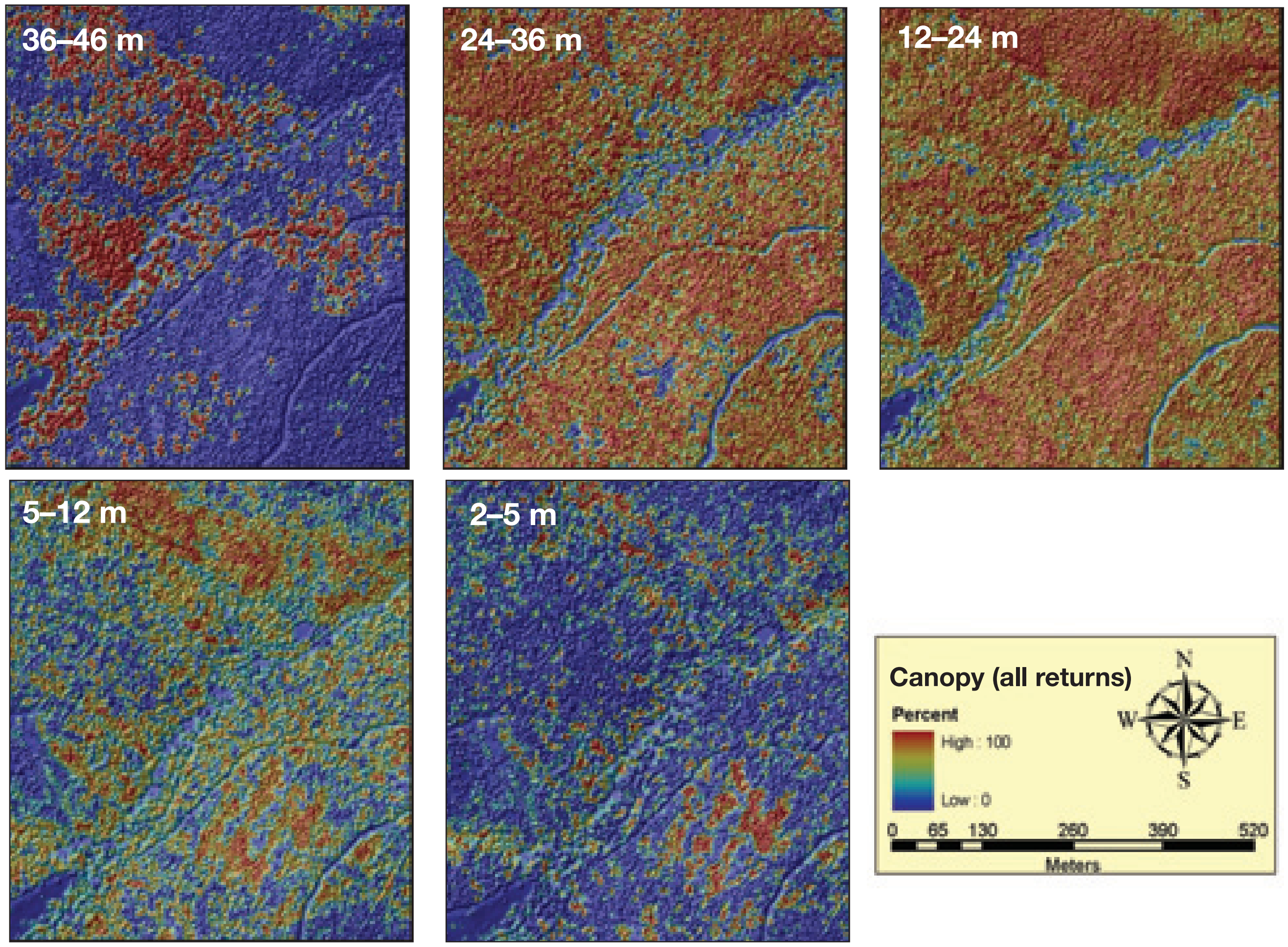

Figure 3. Lidar-derived vertical biomass distribution plots within the St Joe Woodlands of northern Idaho, consisting of ~ 10 coniferous tree species. Each pane shows the percentage of laser pulse hits that occurred within a particular height classification. From this figure, it can be seen that the majority of the vegetation across this landscape is located between 12–36 m above the ground. Heights can be ascribed to progressively finer resolution bins or used to construct near-continuous histograms of height distribution over a given area in order to more fully understand the 3-D structure of vegetation.

Courtesy of J Evans and A Hudak

mal–habitat relationships can be explored across increasingly wider ranges of ecosystems and taxa.

Many of the broad applications used in the aforementioned terrestrial-based studies are relevant in aquatic environments. For instance, Jones (2006) utilized lidar in conjunction with aerial photography to map the structure and elevation of abandoned stream channels and overflow channels, identifying the sites that would be most suitable for salmonid spawning if higher stream levels were to be restored. Below water, topographic variability (or rugosity) is a prime component of habitat complexity, and can be related to aquatic ecosystem biodiversity (eg Luckhurst and Luckhurst 1978). NASA scientists recently developed the Experimental Advanced Airborne Research Lidar (EAARL), a blue–green wavelength lidar designed to measure the morphological complexity of shallow bathymetric features at sub-meter resolution (Wright and Brock 2002; Figure 5). The first application of this sensor, in Florida's Biscayne National Park, demonstrated that it is capable of detecting overall rugosity differences across reef systems (Brock *et al.* 2004; Figure 6). Brock *et al.* (2006) also used EAARL data to map massive stony coral colonies forming patch reefs in Biscayne National Park and found that topographically complex regions within these colonies occurred in specific locations (eg around patch reef margins, where rates of mortality, bioerosion, and physical decomposition were high). The first attempt to link lidar-derived reef rugosity data with reef biodiversity was reported by Kuffner *et al.* (2007), who found that, within a contiguous reef, EAARL-derived rugosity was significantly correlated with both fish species richness and fish abundance. While this relationship was confounded when comparing results across numerous reefs, the initial results from this study were promising and highlighted the need for further investigation of marine species–habitat relationships across wider spatial and temporal scales. Expanding efforts to delineate bathymetric habitat characteristics adds an exciting and complementary dimension to the maturing field of mobile aquatic organism detection (fish

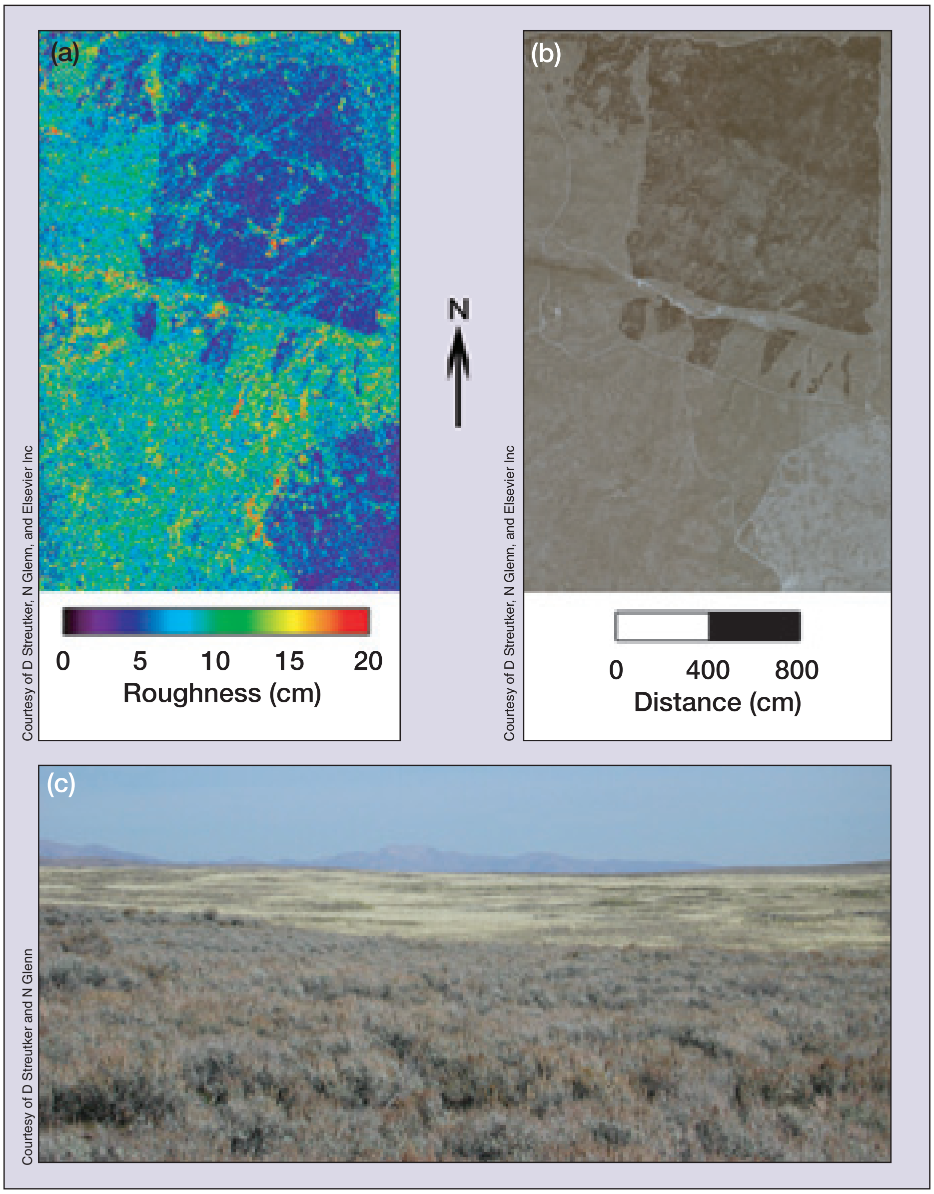

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Figure 4. *A comparison of (a) a lidar-derived map of surface roughness and (b) a true-color Quickbird scene of a sagebrush-steppe ecosystem of southern Idaho (Streutker and Glenn 2006). Linear features within the images show transitions between areas containing shrubs and recently burned areas containing fewer shrubs. (c) A pictorial example of the surface vegetation difference between unburned (foreground) and burned (background) locations.*

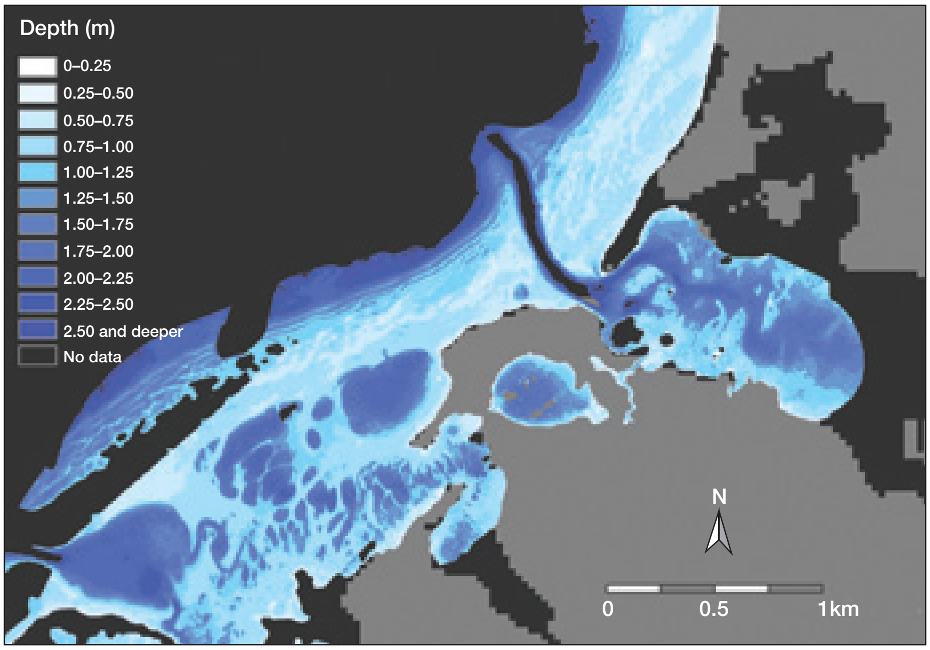
in Churnside and Wilson [2001] and zooplankton in Churnside and Thorne [2005]) using lidar.

Recent studies using lidar to examine animal–habitat relationships have only scratched the surface of the technology's potential application across the wide spectrum of taxa and habitat types occurring on the planet (Table 1). Indeed, in order to fully address species' conservation status, it is necessary to study species–habitat relationships spanning a hierarchy of spatial scales that correspond to processes relevant to individuals, populations, and metapopulations (Kristan and Scott 2006). The majority of terrestrial studies to date involve examination of bird–habitat associations; a smaller number of studies examine mammal–habitat associations; to date, no studies have examined such relationships for entire taxonomic groups (eg amphibians, reptiles, terrestrial invertebrates). Furthermore, the majority of published studies use airborne lidar data acquired for terrestrial systems in the US and the UK. Similarly, lidar utilization for management and conservation applications in aquatic environments is greatly limited in geographic extent. There is tremendous potential in using airborne and ground-based lidar data to characterize habitats and model species occurrences around the globe.

■ Future directions and applications

Remote sensing measurements used to model and extrapolate animal distributions should ideally be related to the scale at which animals discriminate habitat characteristics (Scott *et al.* 2002), as well as the scale at which managers make conservation priority decisions (Riitters *et al.* 1997; Peterson and Kluza 2003). While these decisions are, at present, largely based on datasets derived from other remote sensing platforms, advances made by the use of lidar in conjunction with existing remote sensing data are likely to have wide-reaching policy and management implications. For instance, the US Geological Survey's (USGS) Gap Analysis Program (GAP) assesses habitat protection for native animal and plant species and helps to prioritize areas for conservation at a national scale (Scott *et al.* 1993). Incorporation of lidar-derived habitat metrics into such a database is currently underway, and may allow for a greater ability to predict species distributions and, ultimately, more effective conservation planning involving habitats used by a variety of species assemblages.

There are multiple advantages to using lidar data when studying animal–habitat associations. First, a variety of terrestrial habitat characteristics, such as canopy height, roughness, volume, stand density and age, number of snags and downed trees, number of large trees, understory/middlestory height and density, ground surface texture, patch and edge characteristics, and the matrix in which a habitat occurs, can be obtained by combining lidar remote sensing and ancillary data (Lefsky *et al.* 2002; Turner *et al.* 2003). The potential to develop such vegetation structure datasets with continuous rather than categorical data (ie data that is partitioned into discrete categories) could allow for more gradient-based analyses of landscape architecture, yielding more realistic representations of landscape heterogeneity to better predict ecological processes and organism–habitat relations (McGarigal and Cushman 2005). Using lidar in this way would also enrich our current understanding of relationships between overall species diversity and satellite-derived greenness indices that have been observed across broad scales, and spanning a number of ecoregions (eg Hurlbert and Haskell 2003; Hawkins 2004).



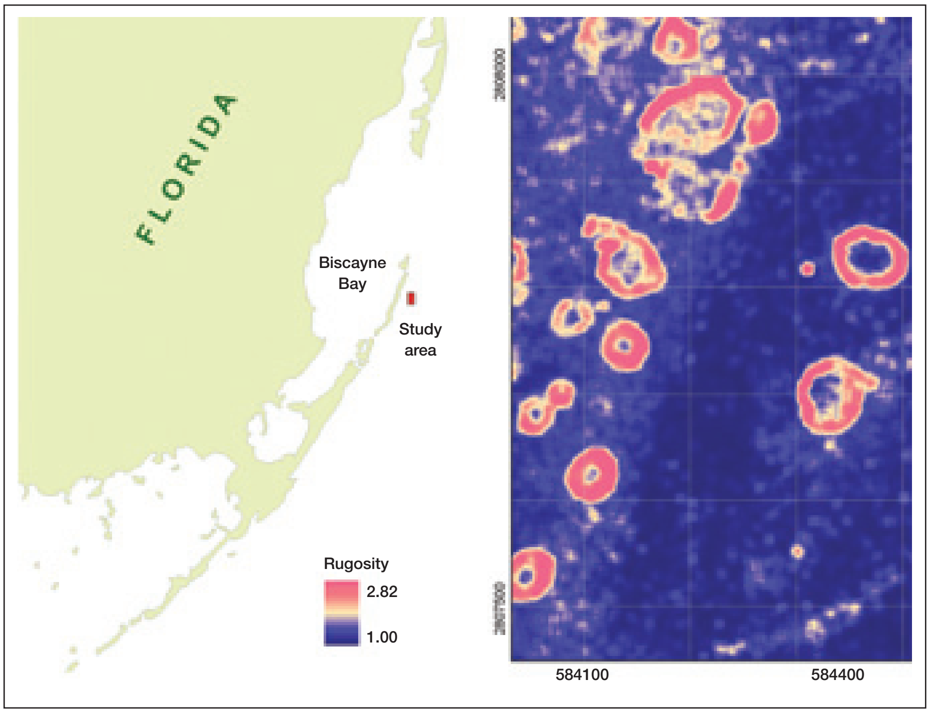
Courtesy of J Brock and A Nayegandhi

Figure 5. *Bathymetric map of an area of Terra Ceia Bay, a small bay within Tampa Bay, FL, derived from the NASA EAARL instrument. The various subsurface morphological characteristics mapped here in high detail may comprise habitats of potential importance for a variety of marine species. Gray denotes land surfaces.*

Second, the use of lidar data allows us to examine animal–habitat relationships at a level of 3-D habitat detail not previously possible across broad extents. For instance, Bradbury *et al.* (2005) used lidar to examine heterogeneity in crop height and ground cover at a fine scale and over large areas that would have been difficult, if not impossible, to assess using traditional methods.

Third, lidar data allow for a post-hoc analysis of habitat variables as they relate to the examination of animal–habitat relationships. For instance, data collected manually to quantify understory heights are generally limited in scale, due to the labor-intensive and seasonal nature of data collection. However, lidar data can be used to examine a variety of understory height metrics at spatial scales that might not otherwise have been addressed.

Finally, multiple studies report a strong agreement between field-collected data and lidar-derived data (eg Hyde *et al.* 2005, 2006; Clawges *et al.* in press); airborne lidar may therefore be a viable means of (1) obtaining habitat structure data in remote environments/rugged terrain, and/or (2) serving as a surrogate for ground-based data collection. It should be noted that, particularly because lidar systems are currently limited in their spectral sampling capabilities, complementing lidar data with passive remote sensing data (eg Hyde *et al.* 2006) can be very helpful for discerning spectrally distinctive habitat characteristics, such as those that relate to plant species phenology and other non-structural aspects of ecosystem function.



Courtesy of J Brock and A Nayegandhi

Figure 6. *Rugosity maps of coral structures off the Florida coast, as derived from the NASA EAARL instrument.*

Working with lidar data does present some logistical challenges. For example, data acquisition and processing costs can be high relative to other remote sensing data. However, in North America, airborne lidar datasets are becoming increasingly available; for instance, a growing number of states (eg Iowa, Louisiana, Ohio, Pennsylvania, North Carolina, Texas, and Florida) currently have or will soon have full lidar coverage, and an effort has begun to organize a nationwide collection for the US (J Stoker pers comm). Because lidar data are often obtained for a variety of purposes (eg for flood hazard mapping, to map elevations, to assess silvicultural practices), the potential for establishing collaborative partnerships for data sharing and acquisition is growing. (For more information, visit the USGS Center for Lidar Information Coordination and Knowledge [CLICK] website at http://lidar.cr.usgs.gov/.) While acquiring datasets in developing countries might currently pose challenges from logistical and financial standpoints, airborne lidar instruments are becoming increasingly portable and modular. Therefore, these instruments can be flown on a variety of aircraft types, increasing the ease of using local rather than dedicated aircraft. In addition, while some level of specialization is required to analyze lidar data, processing is becoming increasingly accessible to a broad range of scientists via open-source and commercial, off-the-shelf software. In sum, lidar-derived data provide truly unique habitat information, unattainable through other sampling approaches, and will therefore transform habitat modeling to support management and conservation activities worldwide.

■ Acknowledgements

We thank J Brock, J Evans, N Glenn, A Hudak, M Johnson, A Nayegandhi, E Rowell, D Streutker, Horizons Inc, and Lamp, Rynearson, and Associates Inc for providing the data and/or images that were used to develop figures for this manuscript. We also thank J Michael Scott, G González, J Aycrigg, and J Rachlow for discussions and insightful comments that improved earlier versions of the manuscript. This work was made possible through funding by the National USGS Gap Analysis Program, National Science Foundation Grant DEB-054815, and NASA grant NCC5-588. KTV and LAV are equal first authors on this paper.

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