Remote sensing of vegetation 3-D structure for biodiversity and habitat: Review and implications for lidar and radar spaceborne missions

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[1] Biodiversity and habitat face increasing pressures due to human and natural influences that alter vegetation structure. Because of the inherent difficulty of measuring forested vegetation three-dimensional (3-D) structure on the ground, this important component of biodiversity and habitat has been, until recently, largely restricted to local measurements, or at larger scales to generalizations. New lidar and radar remote sensing instruments such as those proposed for spaceborne missions will provide the capability to fill this gap. This paper reviews the state of the art for incorporatinginformation on vegetation 3-D structure into biodiversity and habitat science and management approaches, with emphasis on use of lidar and radar data. First we review relationships between vegetation 3-D structure, biodiversity and habitat, and metrics commonly used to describe those relationships. Next, we review the technical capabilities of new lidar and radar sensors and their application to biodiversity and habitat studies to date. We then define variables that have been identified as both useful and feasible to retrieve from spaceborne lidar and radar observations and provide their accuracy and precision requirements. We conclude with a brief discussion of implications for spaceborne missions and research programs. The possibility to derive vegetation 3-D measurements from spaceborne active sensors and to integrate them into science and management comes at a critical juncture for global biodiversity conservation and opens new possibilities for advanced scientific analysis of habitat and biodiversity.

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1. Introduction

[2] The science and conservation of biodiversity is concerned with life on Earth at levels of organization from genes to species, communities, and ecosystems [*Wilson*, 1992]. Globally, biodiversity has faced increasing pressures due to human and natural influences that alter the structure and function of vegetated landscapes [*Sala et al.*, 2000] and, more recently, the interaction of vegetation changes with climate change [*Jetz et al.*, 2007]. Global species extinction estimates vary, but range up to 25,000–50,000 species lost per year [*World Conservation Monitoring Centre*, 1992]. Habitat loss and biodiversity extinctions are sufficiently critical that strategic decisions are being debated as to what biodiversity and habitat can be maintained on the landscape [*Brooks et al.*, 2006].

[3] Conservation planning efforts increasingly rely on spatial data of land cover and vegetation derived from remotely sensed data sets [*Gillespie et al.*, 2008; *Turner et al.*, 2003; *Kerr*, 2001]. Information on Earth's vegetation cover provides a combination of direct and indirect information on biodiversity and habitat. Multispectral passive optical sensors such as Landsat TM/ETM+ or MODIS are useful for discriminating vegetation type and horizontal landscape structure. However, both the horizontal [*Haila*, 1999] and vertical dimensions of vegetation structure are important for biodiversity [*Brokaw and Lent*, 1999], as is the change in these structures through time [*Spies and*

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Turner, 1999]. Newer active radar and lidar sensors can quantify vertical and volumetric dimensions of vegetation structure, and have been shown to have considerable efficacy as applied to biodiversity and habitat characterization [*Bergen et al.*, 2005; *Goetz et al.*, 2007; *Turner et al.*, 2003; *Vierling et al.*, 2008]. In this paper we review the science and measurement requirements for lidar and radar data in biodiversity and habitat assessments.

[4] The remainder of this paper is organized as follows. First we provide definitions of key concepts, followed by examples of the relationships of vegetation three-dimensional (3-D) structure to habitat and biodiversity for different taxonomic groups, and a brief review of traditional measurement methods and identified needs. Section 2 of the paper focuses on capabilities of lidar and radar sensors plus their application to date in biodiversity and habitat assessments. Section 3 of the paper further defines requirements for specific lidar- and radar-derived vegetation 3-D structure variables which are important for biodiversity and habitat. We conclude with implications of the topics reviewed in this paper for spaceborne lidar and radar remote sensing and for biodiversity and habitat science and management.

1.1. Definitions

[5] In this paper we focus on terrestrial woody vegetation (shrubs, trees), but also land-cover matrices of intermixed woody and herbaceous vegetation. The two distinguishing components of vegetation are its taxon (floristics) and its physiognomy (structure). Vegetation 3-D structure is defined as having both horizontal and vertical components. The horizontal component, or landscape structure, is defined as the spatial heterogeneity of an area composed of interacting patches, forest stands or habitat types [*Turner et al.*, 2001], and is often described by patch metrics or other spatial statistical methods [*Gustafson*, 1998; *Riitters et al.*, 1995]. Vegetation vertical structure is defined as the bottom to top configuration of aboveground vegetation [*Brokaw and Lent*, 1999], including for example, canopy cover, tree and canopy height, vegetation layers, and biomass or volume. Most definitions of biodiversity include some focus on the number and abundance of different plant or animal genes, species, communities or ecosystems. Biodiversity is often quantified as species richness and abundance, and sometimes characterized spatially as species richness within ecosystems (alpha diversity), species richness between ecosystems (beta diversity), and species affinities among ecosystems (gamma diversity) [*Magurran*, 1988]. Habitat is defined as the environmental conditions (i.e., suitable or unsuitable) required by a species for survival and reproduction [*Verner et al.*, 1986], and is also defined in terms of micro- ($\sim$m^2 scales) or meso- to macrohabitat ($\sim$100 s m^2 – km^2) scales. Spatial scale pervades considerations of habitat and biodiversity [*Riitters et al.*, 1997] as well as requirements for measurements and maps derived from remotely sensed observations.

1.2. Links Among Vegetation 3-D Structure, Habitat, and Biodiversity

[6] Species may fall on a continuum from generalists to specialists with respect to floristic and structural habitat requirements but many appear to have structural preferences, particularly birds [*Buchanan et al.*, 1995; *Morgan and Freedman*, 1986; *Siegel and DeSante*, 2003; *Villard et al.*, 1999]. At about one-third of the total number of studies in the literature [*Tews et al.*, 2004], birds have been the most frequently studied taxon in the context of habitat preferences. However, there are other taxa for which structural habitat relationships have been documented, including primates, reptiles, amphibians and arthropods [*Halaj et al.*, 2000; *McGraw*, 1994; *Salter et al.*, 1985; *Shine et al.*, 2002; *Welsh and Lind*, 1996].

[7] Patterns of biodiversity are affected by climate at the scale of biomes [*Wright*, 1983]; topography shapes biodiversity at regional to landscape scales [*Burnett et al.*, 1998; *Thompson and Brown*, 1992]; and vegetation composition and structure influence biodiversity patterns at scales of landscape to patch and stand [*Tews et al.*, 2004]. These different scales of biodiversity are interrelated, e.g., topography and climate affect the type of vegetation that can grow in a given site, and hence the vegetation structure. However, vegetation structure is also affected by land use, soil type, species interactions, and many other factors. Vegetation structure has a strong local effect on biodiversity beyond that which can be explained by climate and topographic position.

[8] Although debated, one general hypothesis regarding structure is that greater structural complexity creates more "niches" and thus greater species diversity. A relationship between vegetation vertical complexity and biodiversity was one of the first to be hypothesized and was captured as a positive relationship between foliage height diversity (FHD) and bird species diversity (BSD) [*MacArthur and MacArthur*, 1961]. The FHD statistic is intended to explain both the density and height distribution of foliage in a vegetation profile and is given as

$$\mathrm{FHD} = -\sum p_i \log_e p_i, \tag{1}$$

where p_i is the proportion of horizontal vegetation coverage in the ith layer, summed over the number of layers. Subsequent studies defined more specific patterns of bird-structure relationships [*James and Wamer*, 1982]. Not all studies agree with the general positive relationship between biodiversity and structural complexity, although scale may be a factor. For example, in a chronosequence of northern hardwood forests, bird species biodiversity increased after new clear cuts to a maximum at a midsuccessional stage where there is a mixture of open and closed canopy-dependent bird species; with further succession, diversity decreased as species typical of younger stands are eliminated [*Morgan and Freedman*, 1986].

[9] As with habitat, biodiversity patterns of birds are most widely studied with respect to vegetation structure, but relationships exist for other taxa as well, including small mammals, primates, arthropods and amphibians [*Aguilar-Amuchastegui and Henebry*, 2007; *Carey and Wilson*, 2001; *Gardner et al.*, 1995; *Petranka et al.*, 1994; *Sorensen and Fedigan*, 2000; *Tanabe et al.*, 2001]. Vegetation structure can also influence other plants. Simplification of overstory structure may have negative effects on understory vegetation diversity in temperate forests [*Leniere and Houle*, 2006]. Biomass removal results in complex influences on tropical forests [*Kumar and Shahabuddin*, 2005]. The above

are just a few key examples of the relationships between vegetation 3-D structure, habitat and biodiversity across a range of taxa.

1.3. Traditional Measurement of Vegetation 3-D Structure

[10] Many of the vegetation 3-D variables cited above (i.e., canopy cover, height, vertical layers, volume/biomass) have a basis in traditional, field measurement methods. Almost all field-based measurements rely on sampling because complete censuses are too costly. This typically includes aggregating individual tree measurements by sample plot, and then across sample plots by stand, where a stand is defined as a spatially continuous group of trees and associated vegetation having similar structure and growing under similar soil and climatic conditions [*Oliver and Larson*, 1990]. In addition to direct field measurements, aerial photographs can be used to measure forest cover, tree height, and tree density, but air photo interpretation typically still requires reference field data sets.

[11] At the tree level, basic measurements important for habitat and biodiversity studies include species composition, diameter (or basal area (BA)), and height. Volume or biomass is not directly measured, but estimated via allometric equations. At the plot level, measurements of individual trees are used to estimate tree density, BA, height, and tree volume or biomass per unit area. Vegetation diversity can be calculated at the plot level as species richness (or size class distributions, etc.), and by summarizing these measures with diversity indices, such as Shannon's Index (H') [*Shannon and Weaver*, 1949] or extensions of this index [*Staudhammer and LeMay*, 2001]. Field plots are then typically summarized by stand, and this enables calculation of diversity by comparing measurements among plots, and by summarizing plot-level measures into stand-level metrics. Stands (or patches) in turn can be analyzed in regards to their heterogeneity, and extended through landscape metrics [*McGarigal and Marks*, 1995], which are typically based on land-cover maps derived from air photos or optical satellite imagery.

[12] A rich array of statistics are available to describe vegetation structure with field measurements [*McElhinny et al.*, 2005], but it is important to note that vegetation 3-D structure can only be measured using these methods for relatively small areas. Landscape-scale measurements are generally limited to horizontal structure, and field measurements do not permit "wall-to-wall" (spatially continuous over the area of interest) measurements of vegetation structure for any sizable area. Therefore a tradeoff has existed between richness of vertical detail and horizontal extents. Furthermore, field measurements are not always standardized, are lacking for many remote areas that are difficult to access, and are inefficient in capturing change. Thus there is great need for remotely sensed direct estimates of vegetation 3-D structure over landscapes in order to obtain information for biodiversity and habitat assessments anywhere on the globe. Lidar may meet this need in the form of sample data (i.e., lidar footprints) and radar and optical imagery as wall-to-wall coverage. Next we focus specifically on lidar and radar, illustrating on how each brings different capabilities to remote sensing applications for biodiversity research as well as their potential to be used together.

2. Lidar-Radar Vegetation 3-D Structure in Habitat and Biodiversity Studies

[13] The application of lidar and radar to biodiversity science is relatively young, but there have been several studies that have used these sensors to map and quantify vegetation 3-D structure specifically for habitat and biodiversity applications.

2.1. Lidar

[14] Light Detection And Ranging (lidar) is based on the use of laser light emitted from a source and reflected back to a sensor as it intercepts objects in its path, including vegetation elements and the ground [*Dubayah and Drake*, 2000; *Lefsky et al.*, 2002b]. The round-trip travel times are directly related to the distance of the reflecting vegetation elements. Discrete return lidars can capture several distances (heights) over a small footprint diameter, the first near the top of the canopy and the last near the ground, and are thus particularly useful for measuring height and height variation, if the location of the ground is known or distinguishable. Multiple-return (multistep) systems, typically record on the order of four to six discrete ranges per pulse and provide some indication of within-canopy vertical structure. Full waveform lidars retrieve a continuous vertical profile of the magnitudes of lidar reflections from within a forest canopy on each pulse over a large footprint diameter (10–100 m). This vertical profile of vegetated surfaces, referred to as a waveform, is produced by measuring the strength or brightness of the lidar return as the pulse progresses from top to bottom through the forest canopy. The sequential, vertical height bins in a lidar waveform typically integrate laser light returns on the order of 1–2 ns, corresponding to a vertical distance of 15–30 cm within the canopy. Various height and canopy cover metrics derived from either waveform or discrete returns can be used to measure/estimate canopy height, biomass, basal area, canopy height vertical profiles, and canopy cover [*Dubayah and Drake*, 2000]. When lidar footprints are contiguous along an imaged transect, they capture the variation of vertical profiles as well as any edges that occur along that transect. It is this vertical profiling, or full waveform, capability that holds the greatest interest for vegetation 3-D studies related to biodiversity and habitat.

[15] Discrete return laser scanners have been used to estimate canopy height and structural data indicative of the territories and breeding success of several types of bird species [*Bradbury et al.*, 2005; *Broughton et al.*, 2006; *Clawges et al.*, 2008; *Hinsley et al.*, 2006] and the endangered Delmarva Fox Squirrel [*Nelson et al.*, 2005]. Additional discrete return lidar analyses of aspects of biodiversity are reviewed by *Vierling et al.* [2008].

[16] Full waveform lidar has been used to extract canopy height, topography and the vertical distribution of canopy elements for the Pautuxent National Wildlife Refuge, and when these structural attributes were compared to bird survey data, canopy vertical distribution information was consistently found to be the strongest predictor of species richness [*Goetz et al.*, 2007]. Separate consideration of the different guilds dominated by forest, scrub, suburban and

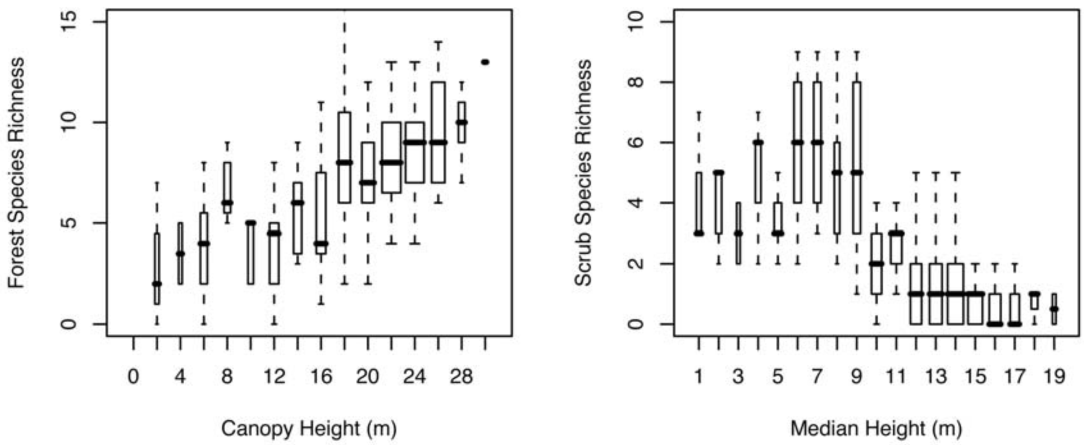

Figure 1. Box plots show range of response variable (species richness) values relative to key habitat predictor variables for richness of (left) forest species and (right) scrub species. Predictor variables were derived from airborne LVIS full waveform lidar at a 7 km altitude with a 12 m footprint diameter. Each box shows the median (horizontal line), quartiles (upper and lower extent of box), and range (dashed vertical lines) for each binned range within the predictor variables. The width of the boxes is proportional to the sample size. (Reprinted from *Goetz et al.* [2007] with permission from Elsevier.)

wetland species also improved predictions (Figure 1). Lidar energy height metrics were also consistently better predictors than traditional remotely sensed variables such as canopy cover, indicating that with new measurement technology new metrics may be developed that will improve upon the traditional variables described earlier. Full waveform airborne lidar (Laser Vegetation Imaging Sensor (LVIS)) is also being employed to map potential Ivory-billed woodpecker habitat based on known niche discriminating characteristics [*Swantantran et al.*, 2007]. These studies show that lidar holds promise for detecting habitat because it can directly measure the organization of vegetation material in space.

2.2. Radar

[17] Radar (Radio Detection And Ranging, using microwaves) sensors are attractive tools for habitat analysis because of their ability to penetrate cloud cover, characterize vegetation geometry volumetrically and to generate images across a swath width. Synthetic Aperture Radar (SAR) system parameters include frequency (or wavelength), polarization (e.g., HH is horizontal transmit and horizontal receive, HV is horizontal transmit, vertical receive), incidence angle, and spatial resolution (hereafter we use radar to refer to the sensor type generally and SAR when reporting on specific sensors). Radar backscatter (i.e., reflection) at a given wavelength and polarization is a function of (1) structural or geometric properties and (2) dielectric properties. Structural properties of vegetation canopies are (1) size distribution of scatterers (main stem, branches, and foliage) relative to wavelength, (2) orientation of scatterers, and (3) number of scattering elements [*Bergen and Dobson*, 1999; *Ulaby et al.*, 1986]. Dielectric properties are a function of volumetric water content, the phase of water (liquid or frozen), and the specific dry density of the scatterers. In very dense vegetation canopies shorter wavelengths (i.e., X or C band) tend to saturate within the crown, and longer wavelengths (i.e., L or P band) penetrate through the canopy and backscatter from branches and stems [*McDonald et al.*, 1990]. Numerous studies have now demonstrated the relationship between vegetation structure, biomass, and radar backscatter across a broad range of forest types [*Dobson et al.*, 1995; *Le Toan et al.*, 1992; *Saatchi and Moghaddam*, 2000]. A wealth of historical SAR data now exist and acquisitions using new systems are in the planning stages [*Houghton and Goetz*, 2008]. In addition to SAR backscatter methods, interferometric SAR (InSAR) can be used to directly estimate forest height and there is a growing body of evidence that multibaseline polarimetric InSAR (Pol-InSAR) is capable of retrieving some information on the vertical distribution of woody biomass [*Florian et al.*, 2006; *Papathanassiou et al.*, 2008; *Treuhaft and Siqueira*, 2004].

[18] While the first study using SAR to assess biodiversity patterns was carried out as early as 1997, few studies exist overall. Bird species diversity, abundance and habitat use were studied over different vegetation structural and floristic zones in northern Australia [*Imhoff et al.*, 1997]. When P, L, and C band SAR data were analyzed along with floristics and bird data, the SAR data discerned structural differences relevant to bird habitat quality within floristically homogeneous stands, and abundances of individual species were observed to change significantly across both floristic and structural gradients of the site (Figure 2). Habitats of forest bird species in northern Michigan were modeled using SAR-derived biomass data, Landsat-derived vegetation cover type and landscape structure, field observations of birds, and the GARP (Genetic Algorithm for Rule-Set Production) modeling methodology. Model results showed that inclusion of biomass improved the accuracy of bird habitat prediction over vegetation type alone, and that the inclusion of neighborhoods and biomass together usually produced the greatest accuracy improvement. The maps that included structure were also interpreted to be a more precise depiction of a particular species habitat when compared with those using vegetation type only [*Bergen et al.*, 2007]. In addition to studies of habitat and biodiversity of birds, radar-derived data has been used to infer spatial distributions of forest diversity in the tropics, such as distinguish-

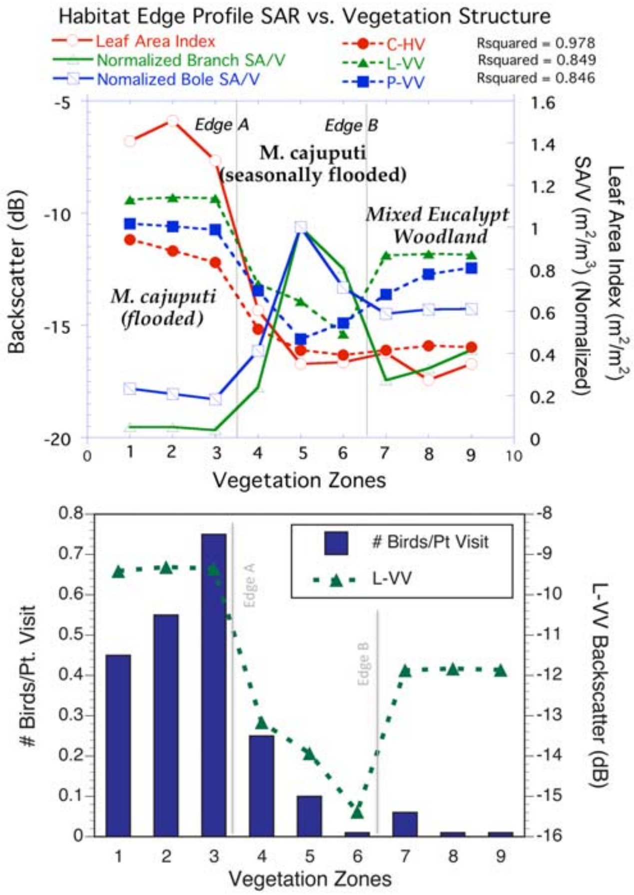

Figure 2. (top) SAR response to vegetation structure and biomass along nine habitat zones in northern Australia. All changes in vegetation structure parameters except stem density were significant across edge A and at zone 5 despite their nearly monospecific composition. Few structure changes were statistically significant across edge B except Branch SA/V (ratio of vegetation surface area to volume). The SAR channels shown responded significantly to changes in crown parameters at edge A, zone 5, and edge B. (bottom) Yellow oriole abundance showed significant changes across habitat edges A and B where significant vegetation structural transitions occurred. These transitions were also detected by the SAR (line) illustrating the relationship between SAR L band backscatter, bird abundance, and floristics. (Reprinted from *Imhoff et al.* [1997] with permission from Elsevier.)

ing between structural characteristics of swamp and lowland forests in the African Congo basin [*De Grandi et al.*, 2000] and mapping tropical tree species diversity in Central South America [*Buermann et al.*, 2008; *Gillespie et al.*, 2009; *Saatchi et al.*, 2008].

2.3. Synergy

[19] A number of studies have used radar and lidar together, and some also with passive optical remote sensing data. For example, *Clawges et al.* [2008] used discrete return lidar to map relationships between birds, FHD, and vegetation volume; whereas multispectral IKONOS data provided information on distribution of general habitat types. Full waveform lidar was used in synergy with SAR/InSAR, Landsat ETM+ and Quickbird to characterize forest structure and wildlife habitat in the Sierra Nevada Mountains of California [*Hyde et al.*, 2006], although wildlife data per se were not analyzed as part of this study. Results of this study indicated that maps based on extrapolation of lidar achieved the best estimates for canopy height and biomass, and the combination of all sensors was more accurate than lidar alone, and marginally better than the combination of lidar and Landsat imagery. Landsat data was used to supplement airborne SAR data and describe floristic gradients in the aforementioned study of bird diversity in Australia [*Imhoff et al.*, 1997]. The importance of floristics as shown by early habitat studies [*Rotenberry*, 1985] motivated the inclusion of Landsat-derived vegetation type in the study to otherwise examine the influence of incorporating vegetation volumetric (radar-derived biomass) and horizontal structure on avian habitat models [*Bergen et al.*, 2007] (Table 1 and Figure 3). In the Amazon Basin, vegetation surface properties of moisture content, leaf size and branch orientation and canopy roughness were obtained from monthly composite active radar scatterometer image data (i.e., QuickSCAT). These data were fused with other habitat measurements extracted from MODIS and SRTM (Shuttle Radar Topography Mission) topography data to ascertain the factors determining the occurrence of three high economic value timber tree species [*Prates-Clark et al.*, 2008].

3. Requirements for Vegetation Structure From Spaceborne Radar-Lidar

[20] Recently the National Research Council's (NRC) decadal survey on Earth observations from space identified needs for the quantification of vegetation 3-D structure and biomass [*National Research Council*, 2007]. The NRC suggested that this be accomplished through the combination of lidar and SAR/InSAR. Applicable spaceborne missions proposed by the NRC included the DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice) mission employing multibeam lidar and L band SAR/InSAR; and the ICESAT-II (Ice, Cloud, and land Elevation Satellite) lidar-only mission. These recommendations, other potential missions, plus the growing science community interest in acquisition of vegetation 3-D data from space, prompted recent workshops which assessed science and measurement requirements for (1) biomass/carbon, (2) disturbance monitoring, and (3) biodiversity and habitat [*Bergen et al.*, 2005; *Saatchi*, 2008; *Zebker et al.*, 2007]. The results of these assessments for biodiversity/habitat are summarized in this paper (Table 2). In section 3.1 we define more specifically the variables and requirements for spaceborne lidar and radar vegetation 3-D data for biodiversity and habitat science and management. Variables are stratified into local scale measurements generally obtained from single pixels (radar) or pulses (lidar) versus those that rely on collective, landscape-scale measurements involving two-dimensional arrays of radar observations or linear segments of lidar observations and/or their fusion.

3.1. Local Scale Biodiversity and Habitat Variables

[21] Several required and technically feasible biodiversity and habitat variables have been identified (Table 2) at the lidar footprint diameter (pulse) and radar pixel resolution.

Table 1. Multidimensional Vegetation Structure in Modeling Avian Habitats and Interpretation of Mapped Habitat and Structure[a]

Structure Data	Training/Testing Accuracy	P Value
Pine Warbler		
Vegetation type only	62/59	0.002
Vegetation type and biomass	73/64	0.035
Vegetation type, biomass and neighborhoods	82/80	0.000
All vegetation structure data	84/81	0.000
Chipping Sparrow		
Vegetation type only	77/77	0.000
Vegetation type and biomass	83/79	0.000
Vegetation type, biomass and neighborhoods	85/80	0.000
All vegetation structure data	85/84	0.000
Red-Eyed Vireo		
Vegetation type only	63/60	0.083
Vegetation type and biomass	69/61	0.081
Vegetation type, biomass and neighborhoods	71/63	0.015
All vegetation structure data	75/66	0.007

Species	Habitat and Structure
Pine warbler	The most realistic maps used all three structure data layers. Pine warbler prefers mature (high biomass) conifers but nonconiferous pixels are selected for suitable habitat as long as surrounded by neighboring high biomass conifer pixels.
Chipping sparrow	The most realistic maps used vegetation and biomass data layers. The chipping sparrow inhabits low biomass, disturbed areas; it is thus sensitive to biomass levels but inclusion of neighboring pixels in majority and variety statistics eliminated some suitable habitat when modeled with neighborhoods.
Red-eyed vireo	The most realistic maps used all vegetation structure data layers. Red-eyed vireos inhabit understories, preferring deciduous understory of mature, high biomass conifer and mixed forest overstories. Area sensitive, they will not typically inhabit small isolated patches of preferred habitat.

[a]Training/testing accuracies, significance, and interpretations of presence/absence maps predicted from bird species locations and different vegetation structure spatial data. Vegetation structure data were derived from synergistic Landsat (vegetation type and neighborhoods) and radar (biomass) and used with the geolocated bird field observations in the GARP modeling methodology to produce the multiple output habitat maps. (Reprinted from *Bergen et al.* [2007], with permission from Elsevier.)

Assumptions are based on a ~25 m full waveform lidar pulse and a ~30 m or better radar nominal pixel. In addition to requirements for measurement variables, there are requirements for accuracy and precision which in turn are related to these pixel resolutions, and footprint diameters (lidar) as well as other mission characteristics.

3.1.1. Canopy Cover

[22] Canopy cover is well correlated with habitat suitability or biodiversity for many taxa including birds [*Hansen et al.*, 1995; *Willson*, 1974], mammals [*Carey and Wilson*, 2001], reptiles [*Shine et al.*, 2002] and amphibians [*Welsh and Lind*, 1996]. The emergence of local gaps in a canopy can have significant impacts on habitat and diversity [*Aguilar-Amuchastegui and Henebry*, 2007; *Carey and Wilson*, 2001], thus knowledge of canopy "gappiness" engenders understanding disturbance regimes as they may affect structure. Canopy cover, defined as percent cover by area, can be measured with lidar sensors, and we suggest that an accuracy of ±10% is both feasible and necessary for biodiversity assessments (Table 2; unless stated otherwise uncertainties expressed as one sigma). Forest interior habitat, including the midstory (e.g., 3–10 m) and understory (e.g., 1–3 m), are habitat for birds and other animal species, thus canopy cover is a desired variable at multiple vertical levels. Accurate canopy cover measurements from lidar are sensitive to topographic slope effects, and larger footprints will exacerbate slope-related accuracy limitations; a 25 m footprint diameter is thus probably the maximum that is preferred for biodiversity studies. Radars may be indirectly sensitive to degree of canopy cover, due to its influence on backscatter [*Green*, 1998], however precision is not known and fusion with lidar needs to be more thoroughly explored.

3.1.2. Canopy Height

[23] Canopy height (or forest height) has been directly and indirectly correlated with the suitability of habitat for birds [*North et al.*, 1999], mammals [*Nelson et al.*, 2005] and other taxa, and used as a management tool for biodiversity planning. Canopy height is, along with volumetric measures, a surrogate for the important habitat characteristics of successional stage and age [*Morgan and Freedman*, 1986]. Lidar systems can provide a variety of canopy height metrics, including the maximum canopy height, HOME (Height Of Median Energy), and some aspects of the within-canopy height distribution (discussed under canopy vertical height profile, below). For biodiversity studies, a lidar-derived absolute canopy height accuracy of ±2 m is required, and ±1 m is desired. The fairly stringent requirement in terms of the accuracy of height measurements is in part related to young forest or shrub vegetation, where an absolute error of ±1 m, may represent a very high relative error. Researchers have reported 3–4 m height errors between field measurements and heights derived from the Geoscience Laser Altimeter System (GLAS) instrument onboard ICESAT-I [*Lefsky et al.*, 2005, 2007]. The ICESAT-1 GLAS has a 6 ns pulse width and a 1 ns digitization capability at the receiver, yet its ability to accurately capture boreal or arid vegetation structure is limited [*Hilker et al.*, 2008; *Nelson et al.*, 2009]. As discussed for canopy cover, a lidar footprint diameter not in excess of 25 m is preferred for height analyses, and annual repeat measurements during the same leaf on season are desirable to measure change.

3.1.3. Canopy Vertical Height Profile

[24] In addition to measures of canopy overstory heights, canopy vertical height profiles are essential to estimate stand structural complexity [*McElhinny et al.*, 2005], and are found to be good predictors of biodiversity and habitat for birds [*Goetz et al.*, 2007; *MacArthur and MacArthur*, 1961], insects [*Humphrey et al.*, 1999] and other taxa. In addition to enabling metrics such as FHD, vertical canopy height profiles make possible the measures of quantile heights (Table 2). Quantile heights may enable studies of individual layers, which are thought to be as or more important than

FHD [*Willson*, 1974], but have been difficult to measure and study. For canopy vertical height profiles, a lidar vertical resolution of ±2 m would be required, and ±1 m is desired. Desired footprint diameter is again 25 m resolution, with repeat observations taken annually and during the same leaf on season each year.

3.1.4. Biomass

[25] Biomass is one of the indirect indicators of age, density, successional stage, and productivity – important factors known to influence habitat selection and biodiversity [*Petranka et al.*, 1994; *Sorensen and Fedigan*, 2000; *Reinkensmeyer et al.*, 2007; *Martinuzzi et al.*, 2009b]. Recently, radar-derived biomass has been used to improve species habitat models [*Bergen et al.*, 2007]. Radar L band backscatter has been shown to be related to trunk and branch biomass and to total aboveground biomass in several different types of forests [*Dobson et al.*, 1995; *Lucas et al.*, 2006; *Saatchi and Moghaddam*, 2000], including relatively low-biomass forests [*Patel et al.*, 2006]. At high-biomass levels, saturation may begin around 60–100 t/ha [*Dobson et al.*, 1992; *Imhoff*, 1995], and estimates for high-biomass areas from radar alone are unlikely to meet required precisions for biodiversity and habitat applications. The fragmented and variable nature of many landscapes worldwide levies a fine spatial resolution requirement for useful biomass data for biodiversity and habitat applications and a nominal radar sensor pixel resolution no coarser than 30 m is required. Again, a lidar footprint not larger than 25 m is preferred for biomass for biodiversity and habitat. Results from the coarser resolution ICESAT-1 GLAS showed a trend toward weaker height-biomass models in short-statured, sparse boreal forests [*Goetz et al.*, 2009; *Nelson*, 2009]. At the landscape to global scales, standard output biomass and biomass change products from radar and lidar fusion ranging from 1 ha to 1 km (depending on biomass levels/saturation plus final missions configurations) are under discussion and precisions of ±20% or ±10 tC/ha, whichever is larger are desired [*Houghton*, 2009].

[26] Closely related to biomass (and canopy cover) is basal area (BA). BA is a common measure of tree cover used in wildlife habitat studies [*Cade*, 1997] and correlates with stand age and productivity. BA is difficult to sense directly, but radar measurements correlate well with low to middle levels of BA, although like biomass, at higher-BA radar signals may saturate. Multifrequency polarimetric SAR has been successfully correlated with BA in temperate forests [*Dobson et al.*, 1995] and profiling lidar has obtained estimates of BA in temperate [*Anderson et al.*, 2008] and tropical [*Nelson et al.*, 1997] forests.

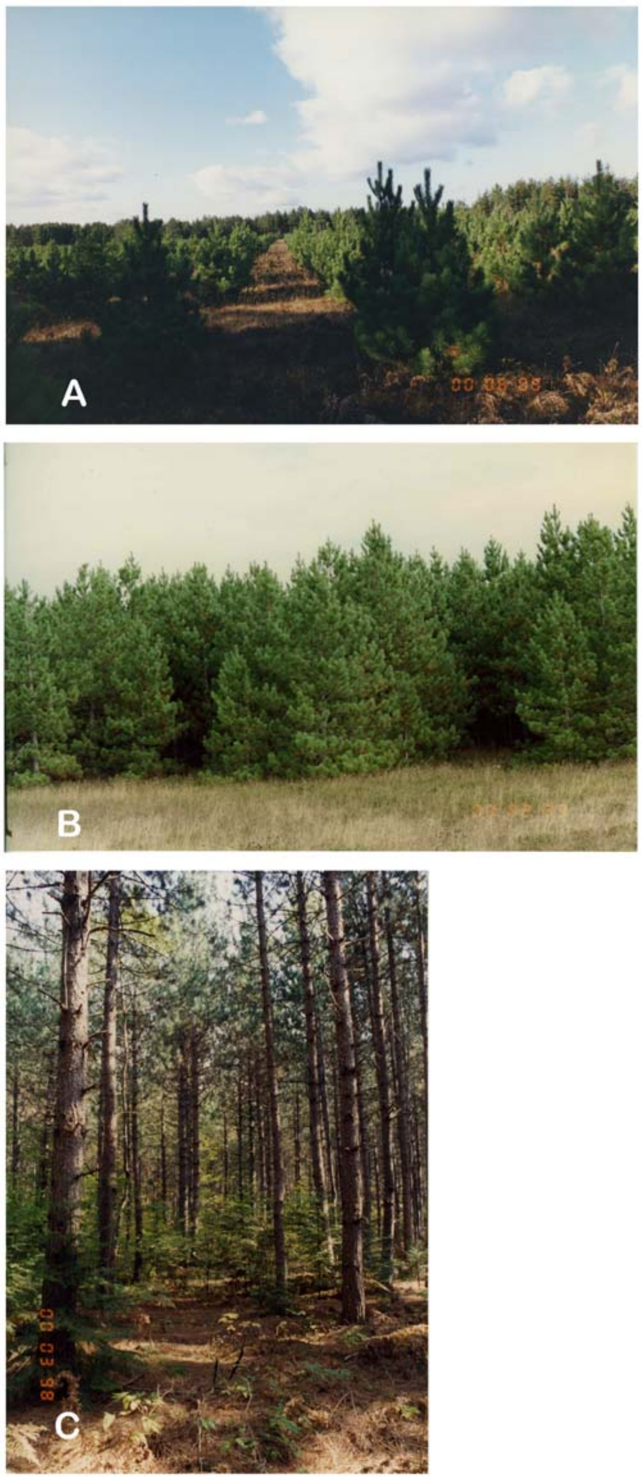

Figure 3. Three forest areas within 10 km of each other in northern Michigan are all classed as upland conifer or red pine (*P. Resinosa*) on available Landsat- and airphoto-derived classifications. Field photos show very different vegetation 3-D structure, as do statistics for canopy cover, height, biomass, vertical profile, and other variables important to biodiversity and habitat. Bird observations for three common species (pine warbler, red-eyed vireo, and chipping sparrow) showed that (c) pole-mature/high-biomass upland pines and large patch sizes provided the primary habitat for pine warbler; these same forests provided secondary habitat for deciduous-preferring red-eyed vireo when they had a deciduous understory. (a) Low-biomass, short-stature open seedling canopies provided habitat for chipping sparrow only. (b) Dense sapling red pines were less frequently selected by pine warbler which prefers more mature conifer forest structures [*Bergen et al.*, 2007]. (Photos courtesy of University of Michigan Radiation Laboratory.)

Table 2. Vegetation 3-D Structure Variables Important for Biodiversity and Habitat

Variable[a]	Radar[b]	Lidar[c]	Precisions/Comments[d]
Variables From Single Radar Pixels or Single Lidar Pulses			
Canopy cover (includes canopy cover along the continuous vertical profile and at desired heights) (%)	no	yes	10–20% M, 5% D
HOME (m)	yes	yes	2 m M, 1 m D
Maximum canopy height (m)	no[e]	yes	2 m M, 1 m D
Canopy height profile	no[e]	yes	1 m quantile heights, within canopy relative accuracy of ±5%[f]
Dry biomass (t/ha)	yes[g]	yes	±20% or 10 tC/ha
Basal area (approximates diameter × density)	yes	yes	
Stem density[h] (stems/ha)	no	no	±20%
Diameter (cm)	no	no	±20%
Physiognomy	yes	no	(hardwood versus conifer)
Species	no[i]	no	
Snags, standing dead wood (snags/ha)	no	?	
Landscape-Scale Variables			
Canopy cover	?	yes	10–20% M, 5% D
Canopy texture (standard deviation of heights) (m)	?[j]	yes	±20% M, ±10% D
Height size class distribution	no	yes	
Diameter size class distribution	no	no	
Edge identification/mapping	yes	yes[k]	within limits of pixel/pulse size
Landscape pattern (mapping/measuring patch size and other landscape patterns)	yes	yes[l]	within limits of pixel/pulse size, many calculated by patch metrics or spatial statistics
Surface (topographic) roughness (m)	no	yes	±20% M, ±10% D

[a]Based on the assumption of individual 30 m L band radar pixels or 25 m lidar footprints.
[b]A "yes" indicates that researchers believe that useful information associated with a particular variable can be gathered by the radar or lidar. A "no" indicates it is unlikely that useful measurements would be forthcoming. A "?" indicates capabilities not known to date.
[c]Assuming low slopes (<10°). Steeper slopes will compromise the ability to identify the ground return in the waveform.
[d]When known, the "Precisions/Comments" entries characterize the minimum (M) and desired (D) accuracy and/or precision with which that variable should be measured to be most useful. All uncertainties (±) expressed as one sigma unless otherwise indicated.
[e]May be possible to derive canopy height and profile from single-pass InSAR; however, the method is experimental with unknown precisions.
[f]At any height under conditions of 99% canopy cover on flat terrain.
[g]L band SAR estimates saturate between 100 and 200 t/ha; InSAR may increase this upper limit.
[h]This refers to traditional stem density; volumetric density would be considered biomass density and measured by the biomass variable.
[i]Unless monospecific forest stands in which case species may be determined.
[j]May be possible with single-pass InSAR.
[k]Along transects only given contiguous lidar pulses; no edge information in between transects.
[l]Some landscape pattern metrics can be calculated with the lidar transect information, e.g., average distance between forested patches or correlation length, others cannot.

3.1.5. Physiognomy

[27] Physiognomy refers to structure (morphology and growth form) and life form (i.e., coniferous or deciduous) of the dominant species of a forest, and is increasingly used in vegetation classifications [*Grossman et al.*, 1998]. In addition, physiognomy refers to characters of seasonality, leaf shape, phenology, duration, etc., and may be as or more relevant than floristics to influencing presence-absence of species in a habitat [*Morrison et al.*, 1998]. Physiognomy is expected to be retrievable from radar to at least the level of hardwood versus conifer given their different crown shapes and growth forms (arrangements of trunk, branch and leaf structures) [*Pierce et al.*, 1998], which are in turn fundamental biophysical factors underlying SAR backscatter [*Ulaby et al.*, 1986].

3.2. Landscape-Scale Habitat and Biodiversity Variables

[28] Some key variables including canopy cover, biomass, and height are both pixel-based and landscape-scale measurements. Only those unique to the landscape scale are discussed below.

3.2.1. Canopy Texture

[29] Variation in the form of image texture has been correlated with age and complexity of forest canopies, which in turn has been shown to be related to biodiversity and habitat. Strong correlations have been found between radar texture measures and standing biomass in tropical forests using the L-HH JERS-1 SAR [*Kuplich et al.*, 2005]. Mapping of variation in the height and texture of the outermost canopy surface using waveform lidar has been demonstrated [*Harding et al.*, 2001], and canopy texture has been further described as canopy rugosity, measured in meters as the standard deviation of heights between a set of lidar returns [*Lefsky et al.*, 2002a]. Lidar estimates of texture or rugosity are desired at ±10% but may also be useful up to ±20%.

3.2.2. Height Size Class Distribution

[30] A large diversity of tree sizes can indicate a wide range of habitat for wildlife and thus stand variation in tree height and diameter is an important consideration in biodiversity conservation in forested landscapes. For example, the variation in tree diameters is one part of several indices of complexity and of old growth forests. Traditionally the domain of field measurements, aerial photography or high-resolution optical data [*Lahde et al.*, 1999], further research with waveform lidar at sufficient spatial resolutions is needed to advance reliable estimates of height-size class distributions in order to use these retrievals for describing and quantifying habitat. Capturing variation in tree crown sizes by measures such as canopy rugosity as discussed above might provide similar information.

3.2.3. Edge

[31] Edge refers to landscape transitions between distinctly different forest structures (e.g., mature and young) or between forest and nonforest. Edges provide habitat for many organisms and the amount, variety and structural characteristics of edges thus have a positive relationship with habitat and biodiversity. However, for interior dwelling species or species that may find edge dwellers to be competitors, the influence of increased edge density on biodiversity is one of the most significant negative consequences of forest fragmentation [*Matlack and Litvaitis*, 1999]. Edge-related metrics derived from contiguous along-transect lidar plots are discussed below. Direct quantification and mapping of forest edge for biodiversity studies will require additional work on radar and lidar edge detection algorithms which are still in the early stages of development [*Wu and North*, 2001].

3.2.4. Patch Metrics and Other Approaches to Landscape Pattern

[32] Landscape pattern metrics (e.g., shape, size, contiguity, edge density, etc.), based on land cover and other geospatial data and calculated via programs such as FRAGSTATS [*McGarigal and Marks*, 1995], are now standard in vegetation and wildlife management. Contiguous along-transect lidar plots will enable unprecedented sampling of canopy vertical profiles, including detection of edges and estimation of correlation lengths for overstory and understory habitats. These contiguous samples will also enable metrics such as canopy and topographic roughness of landscape parcels intercepted by the laser transect vertical profiles, and average crossing distances between and across patches with particular height and/or canopy cover characteristics. However, a fuller complement of landscape metrics would require the more synoptic coverage provided by radar and lidar fusion. Moving beyond a patch-centric perspective, these data may used to quantify functional connectivity using morphological operators [*Vogt et al.*, 2007], landscape covariates using geostatistical techniques and lacunarity [*Henebry and Kux*, 1995], and imputation of stand level characteristics using recursive partitioning algorithms [*Hudak et al.*, 2008].

3.3. Geographic and Temporal Coverage

3.3.1. Spatial Scale

[33] For biodiversity and habitat applications, selection of spaceborne sensor pixel/footprint resolutions must consider the spatial scale of species' relationships with vegetation 3-D structure. A radar pixel resolution of 25–30 m and a lidar footprint diameter of 25 m meet these requirements [*Zebker et al.*, 2007]. Habitat science and management most frequently occurs at local to regional scales and thus this fine nominal spatial resolution data is required for describing habitat and associated biodiversity patterns. It is, however, important to distinguish between sensor nominal resolution requirements and the coarser pixel sizes (e.g., 1 ha to 1 km) of standard data products, such as biomass and biomass change, likely to be compiled as a result of lidar and radar fusion and targeted for a global level of precision [*Houghton*, 2009].

3.3.2. Global Coverage

[34] Complete coverage of Earth's vegetation 3-D structure and biomass is needed. Without such a scientific baseline, change in habitat and biodiversity cannot be directly quantified. Global coverage is also important because biodiversity assessments and conservation strategies differ between taxa and between agencies and organizations, resulting in different global geographic priorities for habitat conservation [*Brooks et al.*, 2006]. Given a global spaceborne mission and the heterogeneity of Earth's terrestrial ecosystems, a prudent option is to sample using transects formed by contiguous lidar pulses along orbital tracks and to acquire wall-to-wall radar coverage. It will be important to fuse lidar with radar data along transects and then interpolate between lidar transects.

3.3.3. Temporal Coverage

[35] A global perspective makes demands on lidar-radar sensor temporal acquisition configurations. Certain kinds of events that may affect biodiversity and habitat [*Spies and Turner*, 1999] are periodic and a mission could be programmed to observe them, whereas others such as fire, hurricane, pest outbreaks etc., are essentially random where chance controls how the mission might observe them. Seasonality of forested ecosystems varies widely across the globe and phenologies of tree species are linked to climatic variation, ranging from nearly synchronous at mid and high latitudes to asynchronous in the tropics. Given seasonal objectives, a temporal resolution of 91 days between radar repeat coverage would be optimal, and 180 days would be minimum acceptable. In order to capture the effects of disturbance events on canopy structure and of landscape pattern soon after the disturbance event, augmenting a 91 day repeat for the radar with the ability for it to target specific events off repeat, is desired.

3.4. Variables Not Currently Retrievable From Spaceborne Lidar and/or Radar

[36] As summarized above, spaceborne lidar and radar sensors have tremendous potential to provide vegetation 3-D measurements that are crucial for biodiversity and habitat assessments. However, it is important to note that some important attributes of vegetation 3-D structure cannot be or are difficult to directly measured from space. Among these attributes are tree diameter size class distributions, stem densities, tree species (unless monocultures), and densities of snags and coarse woody debris on the forest floor and other microhabitat characteristics. However, structural attributes that a spaceborne lidar could measure well, such as tree height, are often strongly correlated to vegetation attributes that are not directly detectable, such as tree diameter. Work with small footprint lidar has shown understory shrub and snag cover can be estimated, even when aggregated to a 20 m spatial resolution [*Martinuzzi et al.*, 2009a], although this could be more challenging with a spaceborne sensor having a larger nominal footprint diameter. Spaceborne radar and lidar could also be combined with other satellite measurements, and some of the vegetation attributes that are difficult to ascertain via the active sensors (e.g., tree species or health) may be estimated with other new passive spaceborne sensors, such as hyperspectral instruments.

3.5. Fusion and Further Synergy

[37] In order to extend measurements at lidar transects across continuous areas, fusion and interpolation using radar or other spatial data is needed. A relatively straightforward approach makes use of radar or optical imagery to stratify

the landscape and assess lidar metrics within strata [*Goetz et al.*, 2009]. A similar approach that can be applied at finer spatial resolution is to segment the radar images into polygons of like radar response and then assess lidar metrics (e.g., of canopy height, canopy cover, and estimates of aboveground woody volume) at transects within those segments. Several novel fusion methodologies to accomplish this objective are evolving rapidly [*Slatton et al.*, 2001]. Geostatistical modeling coupled with aspatial regression to interpolate lidar retrieved canopy height across a region has demonstrated utility, as do recursive partitioning algorithms [*Hudak et al.*, 2008]. Additional wall-to-wall information is available from synergy with optical sensors (e.g., MODIS or Landsat ETM+) suitable for landscape regional scales, and in more localized areas, SPOT and Quickbird may help remove some of the ambiguities when predicting swath-wide biomass and other variables from radar and lidar. For example, airborne lidar integrated with Landsat ETM+ data provided stable estimates forest height and of spatial variability in coniferous forests of the Pacific Northwest [*Hudak et al.*, 2002].

4. Summary and Conclusions

4.1. Implications for Spaceborne Missions

[38] The recent NRC decadal survey on Earth observation from space has called for the launch of L band SAR/InSAR and multibeam full waveform lidar missions with capabilities for measuring vegetation 3-D structure and biomass. Based on this call, along with our review of biodiversity and habitat science discussed in this paper, the following criteria emerge.

4.1.1. Lidar

[39] We suggest that the lidar mission consider the following in order to best meet biodiversity and habitat science and measurement requirements.

[40] 1. A 20–25 m lidar maximum pulse size is recommended. This relatively small footprint diameter will mitigate the effects of topographic slope on accurate vegetation 3-D structure estimates.

[41] 2. A post spacing equal to (or nearly equal to) footprint diameter is desired so that profiles are contiguous along track. Contiguity allows landscape-scale assessments of edge as well as tracking the ground beneath forest canopies to enable better estimates of forest canopy height.

[42] 3. Waveform data should be collected equal to ~15 cm vertical bins.

[43] 4. Within technological limits, maximizing the number of parallel, contiguous transects/profiles equally spaced is desired. A transect spacing of 500 m or less at the equator is desired.

[44] 5. A 91 day orbital repeat cycle designed to facilitate comparable leaf on height measurements year to year is required. A 91 day repeat cycle mitigates snow contamination (which changes canopy height measurements) and mitigates problems associated with changing phenology, i.e., leaf on/leaf off issues and senescence.

[45] To the extent that lidar pulse width affects accurate within and top of canopy height retrievals, we recommend that the laser transmitter and receiver be designed to ensure that height measures are accurate to within ±1 m of accurate ground measures, with ±2 m desired. The relatively small recommended footprint size will do better than a coarser one (i.e., that currently available through the ICESAT-1 GLAS) with respect to capturing the vegetation signal, particularly in heterogeneous landscapes with fine-grained spatial structure and/or those of short and sparse stature, and most importantly in areas of topographic relief. Continuous lidar plots along transects would permit vegetation and biodiversity scientists to find and measure (vertically) edges, assess patch crossing lengths and improve height estimates. An increased sampling density available from a lidar with, e.g., five rather than three beams would significantly enhance the habitat characterization capability.

4.1.2. Radar

[46] We suggest that the radar mission consider the following in order to best meet biodiversity and habitat science and measurement requirements.

[47] 1. Wall-to-wall global coverage is required.

[48] 2. Fully polarimetric (HH, HV, VH, VV) capabilities are desired. If full polarimetry is not an option, then a dual polarimetric L band system with acquisition of HH, HV polarimetry is a minimum requirement.

[49] 3. Tandem (single pass) SAR interferometry is desired and strongly preferred over repeat-pass interferometry due to rapid decorrelation associated with the latter.

[50] 4. A nominal scene area of 75 km × 75 km is suggested.

[51] 5. A nominal pixel spatial resolution of 30 m in range and 27 m in azimuth or finer after a minimum of three looks in the range direction is desired. The effective number of looks (to reduce SAR speckle) should be three or greater. An output square pixel that is map oriented and system geocorrected so that it can be readily integrated into GIS databases would be desirable for more applications oriented end users.

[52] While spaceborne radar sensors exist, the radar parameters proposed by the NRC which include cross polarimetric or fully polarimetric L band and InSAR are expected to be more optimal for deriving information on vegetation 3-D structure and biomass. Because cross polarization has been shown to be useful in canopy cover and biomass retrievals, this configuration is a minimum requirement for an L band SAR. Higher saturation thresholds may be possible using fully polarimetric L band SAR and polarimetric ratios [*Castro et al.*, 2003]. Although InSAR is warranted for this application, relatively less is known to date about InSAR capabilities to retrieve the range of variables and precisions required for biodiversity and habitat. Repeat-pass InSAR configurations (two observations separated by a span of days) are likely to result in unacceptable levels of interferometric decorrelation. Single-pass tandem configurations do not have the latter issue and therefore are a more robust InSAR solution. InSAR and polarimetric InSAR (PolInSAR) should continue to be an active area of consideration and development [*Papathanassiou et al.*, 2008].

4.2. Future Considerations

[53] A vegetation 3-D mission will provide measures of vegetation structure from space. The remotely sensed data collected by lidar and radar satellite missions will help infer relationships with habitat, as characterized by vegetation

structure metrics. These data in turn, will be used to predict suitable (or preferred) habitat associated with specific species or other aspects of biodiversity (such as species richness and abundance). The examination of extant research carried out for this review shows that the biodiversity and habitat application of lidar and radar sensors has advanced substantially, but much remains to be done.

[54] We suggest three equally important areas related to this topic upon which to focus additional research. First, comprehensive empirical field studies focused on quantifying and analyzing relationships between habitat and biodiversity of taxonomic and ecological groups (species, guilds, populations etc.) and vegetation 3-D structure and biomass should be a high priority. While much research exists, new work is needed to develop and test specific relationships given the suite of measurements that will result from spaceborne lidar and radar sensors. Second, additional work needs to be done to better understand the biophysical relationships and uncertainties between sensor parameters and configurations (e.g., SAR\InSAR frequencies and polarizations, lidar number of beams and distinctions between discrete return and full waveform lidars, fusion of SAR-lidar, etc.) and the 3-D physical structures of vegetation, in particular as they concern the high-priority measurements, resolution and accuracies defined in this paper. Those presented here are best estimates to date based on extant studies, community input and knowledge of sensor capabilities and limitation; undoubtedly they can be further refined with additional quantitative study. Third, once new sensors are in place and a wealth of new data are available, these data should be used to rigorously test scientific hypotheses and explore the multifaceted relationships between vegetation 3-D structure, habitat and biodiversity, and to use this research to inform conservation management. Measurements from spaceborne active sensors and their integration into science and management heralds new possibilities for advanced considerations of multidimensional relationships of habitat and species diversity, and come at a critical juncture for global biodiversity conservation.

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