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REMOTE SENSING OF RIPARIAN BUFFERS: PAST PROGRESS AND FUTURE PROSPECTS[1]

Scott J. Goetz[2]

ABSTRACT: Riparian buffer zone management is an area of increasing relevance as human modification of the landscape continues unabated. Land and water resource managers are continually challenged to maintain stream ecosystem integrity and water quality in the context of rapidly changing land use, which often offsets management gains. Approaches are needed not only to map vegetation cover in riparian zones, but also to monitor the changes taking place, target restoration activities, and assess the success of previous management actions. To date, these objectives have been difficult to meet using traditional techniques based on aerial photos and field visits, particularly over large areas. Recent advances in remote sensing have the potential to substantially aid buffer zone management. Very high resolution imagery is now available that allows detailed mapping and monitoring of buffer zone vegetation and provides a basis for consistent assessments using moderately high resolution remote sensing (e.g., Landsat). Laser-based remote sensing is another advance that permits even more detailed information on buffer zone properties, such as refined topographic derivatives and multidimensional vegetation structure. These sources of image data and map information are reviewed in this paper, examples of their application to riparian buffer mapping and stream health assessment are provided, and future prospects for improved buffer monitoring are discussed.

(KEY TERMS: geographic information systems (GIS); remote sensing; riparian buffers; stream health; watershed management.)

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INTRODUCTION

Riparian buffers have been recognized as important landscape features that provide unique habitat for many wildlife species (Iverson *et al.,* 2001) as well as filtering capabilities for removing nutrient pollutants from agricultural runoff and urbanized (impervious) areas before they reach waterways (Cooper *et al.,* 1987; Correll, 1997; Lowrance *et al.,* 1997; Weller *et al.,* 1998). As evidenced by the diversity of papers in this special issue, information on riparian buffers has become an integral part of the environmental and developmental planning process. This information has aided the advancement of more effective hydrological assessments, water resources planning, and resource management. Mapping of riparian buffer vegetation has not been systematically accomplished across many watersheds, however, partly because the traditional approach has relied on aerial photo interpretation. This approach can quickly become impractical over very large areas, even with mosaicked digital orthophotographs. For example, the federal interagency Chesapeake Bay Program (CBP) has been tasked with establishing 2,000 miles (3,300 km) of forested riparian buffers by the year 2010 across the entire 168,000 km^2 Chesapeake Bay watershed (CBP, 2003) but does not have a practical methodology to accurately assess current buffer statistics nor the success of past buffer zone tree planting.

In the past, satellite imagery was of marginally sufficient spatial resolution to adequately map riparian buffer vegetation within the narrow (approximately 30 m) widths adopted as functional buffers (CBP, 2003). In the past few years, a combination of factors has changed the prospects for remote sensing of both buffer extent and properties. These include techniques to extract additional information from moderately high resolution (20 to 30 m) satellite observations; the advancement of commercial satellite imagery at very high spatial resolution (1 to 5 m), nearly comparable to aerial photographs; and the

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[2]Senior Scientist, The Woods Hole Research Center, P.O. Box 296, Woods Hole, Massachusetts 02543-0296 (E-Mail: sgoetz@whrc.org).

advent of new types of remote sensing based on the use of three-dimensional laser imaging of the earth surface.

The objective of this paper is to provide an overview of the application of remote sensing to mapping the extent, configuration, and properties of riparian buffer zone vegetation cover in the context of their functional links to stream biotic health and to provide a glimpse of some of the future prospects conveyed by these relatively new technologies. This is addressed through a brief review of past applications of optical remote sensing, examples of the potential for combined use of very high and moderately high resolution observations, and the prospects of laser remote sensing for riparian buffer assessment.

PAST PROGRESS: TYPE CLASSIFICATIONS OF THE BUFFER ZONE

The most widely used satellite remote sensing observations are those that measure light reflectance in the optical portion of the electromagnetic spectrum (visible and near infrared), particularly the Landsat (Land Satellite) series of sensors with 30 m (100 ft) ground cell resolution (Cohen and Goward, 2004). The Landsat Project is a joint initiative of the National Aeronautics and Space Administration (NASA) and the U.S. Geological Survey (USGS) to gather Earth resource data using a series of satellites. NASA was responsible for developing and launching the spacecrafts, whereas USGS is responsible for flight operations, maintenance, and management of all ground data reception, processing, archiving, product generation, and distribution. Landsat-1 was launched in 1972, and the most recent platform in the series, Landsat-7, provides imagery from mid-1999 to the present. A Landsat Data Continuity Mission (LDCM) is being formulated to provide these essential earth observations for land cover and land use change monitoring.

The primary instrument on Landsat satellites since 1984 is the Thematic Mapper (TM), which provides imagery in spectral wavelength bands ranging from the visible to the thermal infrared over an area approximately 170 km by 180 km (100 by 110 miles). Landsat-TM provides the most widely used and generally available remote sensing data for earth science and resource management applications (Klemas, 2001; Cohen and Goward, 2004), partly because of the wide availability of the data and the moderate cost (US$475 to US$800 per 32,000 km^2 scene) relative to much higher resolution imagery.

Landsat-TM image mosaics have been generated by the Earth Satellite Corporation, with NASA funding, over the entire global land surface circa 1990 and 2000 (Tucker *et al.,* 2004). Moreover, national land cover mapping efforts rely heavily on Landsat imagery, particularly the National Land Cover Database (NLCD) (Vogelmann *et al.,* 2001). Comprehensive compiled Landsat data are distributed at low or no cost through various sources, primarily the USGS Earth Resources Observation Satellite facility in South Dakota, but also through NASA Earth Science Information Partnerships, such as those with the University of Maryland Global Land Cover Facility and the University of Michigan Center for Global Change and Earth Observations.

Land cover type maps are the most common product of Landsat and other moderately high resolution imagery and have been widely used to estimate the amount of various cover types within riparian buffer zones. For example, the amount of forest cover within a 30 m buffer of the stream edge, derived from Landsat-based maps of land cover, was found to be positively correlated with species and taxa richness of macro-invertebrate assemblages in coastal plain watersheds of the southeastern United States (Sawyer *et al.,* 2004). Conversely, the amount of urban land cover types within the 30 m buffer was negatively correlated with fish species richness.

Similar analyses in the mid-Atlantic region of the United States, based on use of Landsat derived land cover maps from the NLCD, suggest that forest cover in the riparian buffer zone was the single most important variable in explaining instream phosphorus and sediment load variability (Jones *et al.,* 2001). This observation extends to headwater streams of the mid-Atlantic region, where riparian forest cover within 120 m of the stream channel was found to be the second most important predictor of stream indices of biotic integrity (IBI), after the amount of urban land cover in NLCD maps (Snyder *et al.,* 2003). Moreover, King *et al.* (2005) found that the amount of NLCD forest cover within a 250 m buffer reduced the threshold level above which urban land cover negatively impacted water quality in small watersheds across Maryland.

A substantial amount of research on remote sensing of riparian vegetation cover and on links with stream health metrics such as IBI scores has also been conducted in the Pacific Northwest. Land cover proportions within 120 m riparian buffers across the Willamette Valley of Oregon, estimated using Landsat derived land cover maps, were consistently selected in statistical models as significant predictors of stream condition metrics (Van Sickle *et al.,* 2004). Vegetation within the local buffer zone (30 m from the stream channel) were less useful predictors, which the authors attribute to issues of the accuracy of the land cover maps within the narrower 30 m buffer zone.

Others have noted that the amount of vegetation within the 50 m to 100 m stream buffer zone was not a significant predictor of fish or macro-invertebrate IBI (Lammert and Allen, 1999; Volstad *et al.,* 2003), at least partly due to the insufficient resolution of the land cover products for narrow buffer zone assessments.

The issue of riparian buffer land cover map accuracy was directly addressed by Lattin *et al.* (2004), who compared Landsat image maps across a range of riparian buffer zones to visually interpreted aerial photographs specifically commissioned for the study of riparian buffer zones in watersheds of the Willamette Valley. Buffer zone vegetation cover within a range of longitudinal and lateral extents from the stream channel was assessed using the air photo interpretation augmented with field validation and geographic information system (GIS) analysis. Their results indicate that a Landsat derived map was, not surprisingly, less accurate than the air photo interpretations but that the differences between the maps declined as buffer width increased (up to 150 m). Forest and grass cover were consistently underestimated in the Landsat maps at narrower buffer widths, while agriculture and shrub cover were consistently overestimated. These systematic differences, if applicable to other regions, would tend to bias the importance of cover types within the buffer zone relative to stream chemical and biotic metrics.

This survey of riparian buffer research using remote sensing is not comprehensive; but as the above results suggest, use of land cover type maps for riparian buffer analysis may be limited unless the maps are specifically developed for analysis of relatively narrow buffer properties. This is particularly true if the maps are based on the use of imagery at Landsat spatial resolution (30 m) or coarser, partly because multiple images must be used and the locational accuracy of the image cells (pixels) may be misaligned even slightly between overlapping or adjacent scenes. Buffer mapping applications using land cover type classifications may be further limited by classification accuracies and generalization of cover type classes.

CURRENT POTENTIAL: BUFFER VEGETATION DENSITY AND DISTRIBUTION

Proportional Cover Estimation

Recently, new types of land cover maps are being produced which emphasize subpixel information (i.e., the proportion of each image cell that is occupied by any given land cover type). With this approach, information within each grid cell of an image can be derived using higher resolution imagery to characterize the amount of each cover type present. A common way to accomplish this is through a type of classification tree algorithm that outputs continuous estimates of a given land cover type (Hansen *et al.,* 2002; Huang and Townshend, 2003). These algorithms work by recursively dividing the image data into increasingly homogeneous partitions using nonparametric rules.

Decision trees have become popular for land cover mapping because the tree output is intuitive, with each variable threshold listed for each successive hierarchical partition. Decision rules are based on the best binary split of the data incorporating the information provided by the predictor variables (typically multispectral information provided by the imagery) and associated explained variance of the training data. Using this approach, maps of proportional forest, impervious, agricultural, grass, or wetland cover can be produced with values ranging between 0 and 100 percent for each 30 m (900 m^2) cell of Landsat imagery, provided there are local higher resolution maps of these cover types (discussed in the next section) to calibrate the subpixel estimates.

Land cover map products of this type, focused on forest and impervious cover, are being produced at the national scale by the NLCD and its collaborators (Homer *et al.,* 2002; Yang *et al.,* 2003) and will be available for nationally consistent watershed analyses over the coming years. One such proportional tree cover map was produced for the 168,000 km^2 Chesapeake Bay Watershed (Figure 1), an area encompassed by 18 Landsat scenes. This and a similar map of percent impervious surface cover are described in more detail by Goetz *et al.* (2004).

A key advantage to using these datasets for riparian buffer mapping, such as those depicting the spatial patterns and proportional density of tree cover in Figure 1, is that the spatial structure of the landscape is finely resolved, and small groups or single pixels may be depicted with just 20 percent or 30 percent tree cover. Moreover, one can relatively easily run GIS operations to overlay buffers of a stream network and calculate the amount and density of tree cover within the riparian zone. Because the density of tree cover varies along the buffer zone (see inset in Figure 1), such maps can be used for targeting buffer restoration activities, assessing the influence of buffers along individual stream reaches, or assessing the establishment of past plantings. The tree cover maps can also be manipulated to show only those areas with more than 60 percent or 70 percent tree cover, thus further focusing management goals (e.g., on areas traditionally defined as forest).

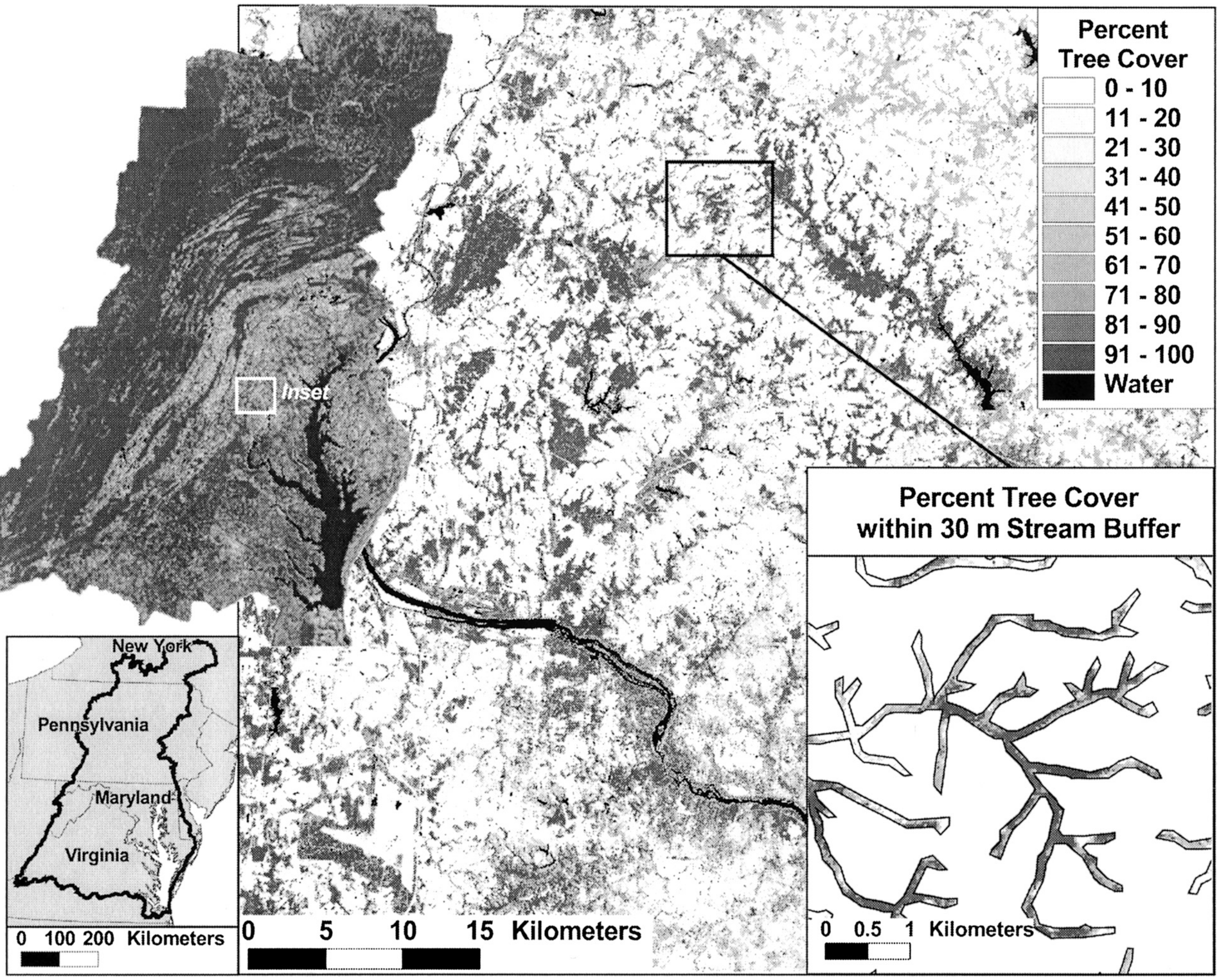

Figure 1. Landsat Map of Tree Cover as a Proportion of Each 30 m Pixel. The image on the left shows tree cover over the Chesapeake Bay watershed (after Goetz *et al.,* 2004). The background image shows greater detail on tree cover within the indicated inset area (Montgomery County, Maryland). The image on the lower right shows a portion of the map, with the density of tree cover (percent) within riparian buffers 30 m either side of the stream centerline.

The Landsat derived impervious and tree cover maps are being used in a number of resource management assessments conducted by various organizations including, among others, the CBP and the Maryland Department of Natural Resources, both of which have extensive ongoing efforts to protect and restore watersheds and monitor water quality indicators. For example, the maps are being used in strategic forest land assessments to target the prioritization of specific parcels for connecting disjunct forest patches (MD DNR, 2003), for tracking past rates and patterns of urbanization across watersheds (Jantz *et al.,* 2005), and for assessing the vulnerability of forest and other resource lands to urbanization (Boesch and Greer, 2003; Weber, 2004). The data also are being used in separate watershed characterizations and assessments across 20 counties in the state of Maryland for which stream physical and biological data have been acquired (MD DNR, 2005).

Very High Spatial Resolution Mapping of the Buffer Zone

In addition to Landsat imagery, similar satellite platforms can be used to assess riparian zone land cover, particularly the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), launched in December 1999, a cooperative effort between NASA, Japan's Ministry of Economy, Trade, and Industry, and Japan's Earth Remote Sensing Data Analysis Center (Kahle *et al.,* 1991). ASTER imagery features enhanced spatial and spectral resolution useful for resolving buffer vegetation types, but it does not acquire imagery on a continuous basis, either spatially or temporally. To produce proportional estimates of vegetation cover within each ASTER, Landsat, or other moderately high resolution image cell, finer scale information on the extent of tree, impervious, or agricultural cover is needed. This finer resolution data can be derived from digital aerial photography or any of a suite of very high resolution satellite sensors currently operating, including Space Imaging Corporation's IKONOS, launched in September 1999 (Dial *et al.,* 2003); Digital Globe's QuickBird, launched in October 2001; and Orbital Imaging's OrbView3, launched in June 2003 (OrbImage, 2005). All of these provide imagery with ground cell sizes between 0.6 and 4 m (2 to 13 ft), which is comparable in quality to aerial photographs but with the added advantage of digital multispectral information, stable geometry, and consistent viewing conditions. Several additional very high resolution satellite-based sensors are planned for launch in the near future.

These very high resolution observational datasets provide an ability to map buffer zone vegetation and allow development of maps that can be used to calibrate, validate, or refine estimates from the moderately high resolution imagery (such as Landsat and Aster) described above. Very high resolution imagery can also be used to monitor the success of tree plantings, provided that baseline conditions on buffer vegetation can be established at a given point in time, sufficient time has passed for canopy establishment to occur, and consistent image data and mapping techniques were used at each time interval. Accomplishing this over very large areas may be difficult due to differences in atmospheric, sun, and viewing conditions at the time of image acquisition and the cost of obtaining image data (which may range from US$23 to US$76 or more per km^2 depending on the data source, precision of georeferencing, and special acquisition condition requests).

Moreover, the accuracy of image-based tree cover classifications accuracies must be sufficient to assess change, which depends on the above conditions at image acquisition, as well as the quality and consistency of the data used to train the image data classifiers. This type of change detection is routinely accomplished but can be challenging (Coppin *et al.,* 2004; Jantz *et al.,* 2005; Yang *et al.,* 2003). Alternatives to full "wall to wall" mapping include stratified sampling approaches where imagery was collected across a range of conditions or political or geographic regions or by targeting areas of specific interest.

An assessment of IKONOS imagery for mapping land cover within buffer zones and surrounding landscape configuration was linked with stream health for a diverse range of watersheds in Maryland (Goetz *et al.,* 2003). The analysis was based on use of assessments conducted as part of the Maryland Biological Stream Survey (MBSS) that include physical stream properties such as pH, dissolved oxygen, and temperature as well as biological indicators such as fish and benthic macroinvertebrate IBI scores relative to comparatively undisturbed (reference) stream conditions (Roth *et al.,* 2004). These data, in turn, provided the basis for integrated stream health rankings across 246 small watersheds, approximately equivalent to a 14 digit hydrological unit code, with scores ranging from 1 to 50, which were then converted to categorical rankings of excellent, good, fair, and poor (Montgomery County Department of Environmental Protection, 2004).

Streams in excellent health represent reference stream conditions. Watersheds with overall stream health ranked as excellent had, on average, greater than 65 percent tree cover within a 30 m riparian buffer zone and less than 6 percent impervious cover distributed throughout the watershed (Table 1). The other categorical rankings (good, fair, poor) had diminishing riparian tree cover and greater impervious cover, and all differences among rankings were statistically significant. Landscape configuration and agricultural cover did not explain a significant portion of the residual variance in these watersheds, which was partly attributed to storm drains in urban areas bypassing the riparian buffer zone vegetation and more directly linking impervious areas with the stream network (Snyder *et al.,* 2005). A key advantage to the IKONOS-derived maps was the fine spatial resolution, which allowed local scale analysis to be based on a large number of samples (pixels) within the narrow riparian buffers and associated statistically meaningful results.

TABLE 1. Montgomery County Watershed Stream Health Rankings and Mean Land Cover Characteristics Derived From IKONOS Image Maps (see Snyder *et al.,* 2005).

Stream Health Ranking	Watersheds (N)	Area (km^2)	Forested Buffer (percent)	Impervious Cover (percent)
Excellent	38	272	76.8	3.6
Good	81	658	71.3	4.9
Fair	76	451	63.2	13.9
Poor	50	356	56.3	19.5

Additional studies of buffer zone land cover attributes based on very high resolution imagery are under way in various parts of the country, including Yellowstone National Park; the Lake Tahoe Basin; the

Navarro River watershed in Mendocino County, California; the Contentnea Creek watershed in Wilson County, North Carolina; and elsewhere. The results of these analyses are just beginning to enter the refereed literature.

FUTURE PROSPECTS: LASER REMOTE SENSING OF BUFFER PROPERTIES

In recent years laser remote sensing instruments have become increasingly available to the research and science applications communities. These light detection and ranging (Lidar) systems have been in development and research applications for many years; they vary, but each sends a pulse of light (from an aircraft or satellite platform) that is reflected back to the sensor as it intersects objects in its path. As the reflected light is detected at the sensor, it is digitized, creating a record of returns that are a function of distance between the sensor and the intersected object. Unlike radar systems, which emit and measure returned radiation in the microwave region, Lidar systems are optical and thus subject to interaction with clouds and other atmospheric constituents.

Lidar technology has advanced from recording just a single return of reflected light to multiple returns and, more recently, "full return" systems in which a continuous series of reflected returns are digitized at the sensor (Blair *et al.,* 1999). Lidar systems are also characterized by the size of the laser beam transmitted, with a general distinction between narrow (or pencil) beam versus broad-beam systems (Lefsky *et al.,* 2002; Nelson *et al.,* 2003). These are also referred to as small (10+ cm) or large (20+ m) footprint systems, although, in the case of aircraft-based instruments, the footprint depends on the altitude flown above the ground surface. A final distinction between systems is the density of the laser beam sampling, with imaging sensors able to characterize the surface more fully than spot sampling along a grid at regular intervals. Commercial systems, of which there are now at least 22 in the United States alone, are currently of the pencil beam, multiple return variety, and prices vary widely depending on the desired product, area coverage, and vendor. Data acquisition services are widely available and have been used in an increasingly broad range of applications, particularly to improve surface (bald earth) elevations.

The more distinctive Lidar systems, and those with the most potential for characterizing the three-dimensional structure of vegetation canopies and the earth surface, are imaging, full return, broad beam systems such as the Laser Vegetation Imaging Sensor (LVIS) (Blair *et al.,* 1999; Drake *et al.,* 2002). A satellite Vegetation Canopy Lidar mission being developed by NASA (Dubayah *et al.,* 1997) has been discontinued, but some version of the full return broad beam instrument will inevitably be operational from a space-based platform for terrestrial applications. One such Lidar sensor, the Geoscience Laser Altimeter System (GLAS), is operational onboard the Ice, Cloud, and Land Elevation Satellite. The sensor, which produces a laser shot 70 m in diameter at the earth surface with 175 m spacing between samples, was designed for analysis and monitoring of the mass balance of ice sheets. As such, it is not suitable for riparian buffer assessment, but an example of a canopy profile from the LVIS instrument (Figure 2) shows the variable return generated as light is reflected from canopy elements, followed by a strong return from the ground. This entire stream of reflected laser returns is referred to as a waveform.

Multiple return or full return Lidars can resolve subcanopy surface topography (Hodgson *et al.,* 2003) in addition to the top of the canopy. The difference between these two provides an estimate of canopy height (Harding *et al.,* 2001). In full return Lidar systems the vertical distribution of intercepted surfaces can also be estimated (Lefsky *et al.,* 2002). This latter component is useful because it can provide much-improved estimates of above ground biomass and its vertical distribution (e.g., Drake *et al.,* 2002) and can be used to better estimate parameters for ecosystem models (Hurtt *et al.,* 2004). It also has utility for improved mapping of riparian buffer zone structure, notably surface topography (Bowen and Waltermire, 2002) and vegetation density, and thus has potential for improving functional models of the buffer zone, as in the Riparian Ecosystem Management Model (Lowrance *et al.,* 2000).

Some examples of using full return Lidar products for buffer zone analyses are provided in Figure 3, based on LVIS data processed over approximately 625 km^2 of the Patuxent and Patapsco River watersheds in central Maryland (Blair *et al.,* 2006). The study area extends across the Piedmont physiographic province in the northwest to the coastal plain in the southeast. The image products demonstrate the fine spatial structure of the landscape, including the riparian buffer zone, which can be derived from the 20 m data products. Notably, subcanopy topography can be extracted well enough, even in dense vegetation (Hofton *et al.,* 2002), to improve the derivation of stream hydrological networks using standard GIS software. Note the greater detail in the LVIS derived streams, including minor tributaries, than in the USGS hydrological network map. This permits better definition of the buffer zone of relevance to the stream

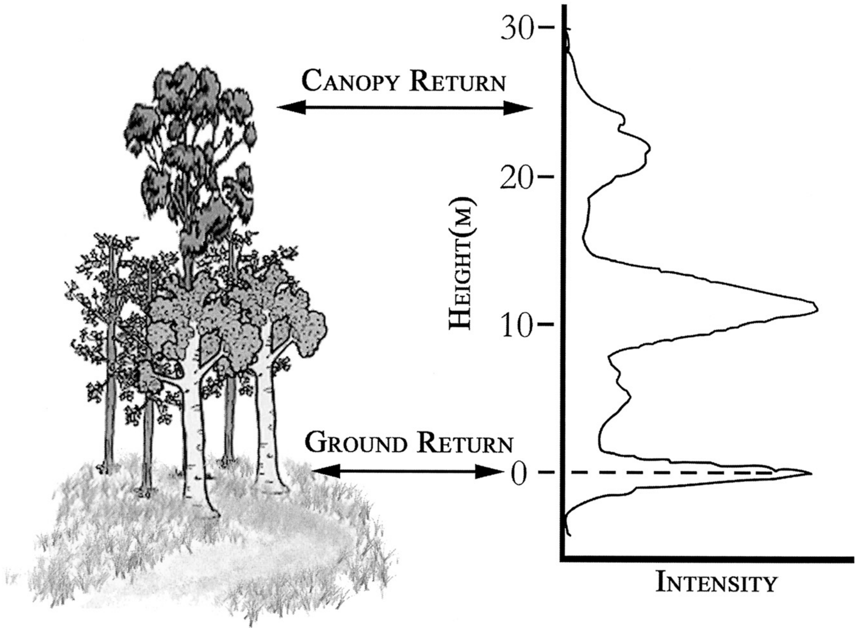

Figure 2. Diagram Depicting a Full Return Lidar Beam Through a Vegetation Canopy (after Dubayah *et al.,* 2000).

ecosystem and improved delineation of the catchment boundaries. The topographic slopes derived from the Lidar surface elevation data provide configuration and distribution information on the vertical gradients within individual stream reach buffers. The canopy height data, in turn, permit mapping of the vegetation height distribution across the watershed and within the buffer zones and clearly delineate forest patches from adjacent agricultural fields even within the narrow buffer zones (Figure 3). Canopy heights in the buffer zones can be extracted across a range of topographic slopes that in this case averaged 16.6m on slopes less than 4 degrees to 22.0 m on slopes greater than 13 degrees.

The Lidar image products and associated analysis shown in Figure 3 would differ with pencil beam systems that sample the surface at some grid spacing and beam size determined by the sensor system, sampling rate, and height and speed of the aircraft. If the data were finely sampled, one would expect results similar to those described above. Coarser sampling would be expected to introduce uncertainty in the estimates of surface properties such as elevation and tree height, although typical acquisitions with a 30 cm beam sampled at an interval of 2 m or less would be expected to capture much of the surface variability integrated by a broad beam imaging system. Dense sampling of a pencil-beam system would be required to ensure that treetops were adequately captured and enough samples penetrated to the ground surface, particularly in densely vegetated areas and in complex terrain.

Lidar remote sensing is not a panacea for mapping riparian buffer properties over large areas, but it can provide a unique view of the vertical structure of land cover within buffer zones, as well as the density of vegetation or even built structures. Unlike passive optical remote sensing systems such as Landsat, Lidar data have not yet been widely used in watershed management. This is likely to change as a result of the rapid advancement of Lidar sensors, and the substantial and growing range of Lidar service providers to ensure that data can be acquired on demand and products tailored to the end user's needs (e.g., a watershed manager). Full return Lidar products are more complex than the single-return or multiple-return systems and require substantial computing and data storage capabilities as well as processing techniques, but even these have been simplified to a substantial degree through the provision of derived data products like those depicted in Figure 3 (Blair *et al.,* 2006). Users of Lidar imagery for riparian buffer analyses will likely find multiple- and full return systems not only adequate for determining buffer properties such surface topography, canopy height, and vegetation cover density but also unique in terms of providing data that augment the more traditional estimates of land cover type categories.

CONCLUSIONS

Remote sensing imagery has become available in the past few years that allows much better characterization of riparian buffer zone properties than was previously possible, and this progress is likely to expand

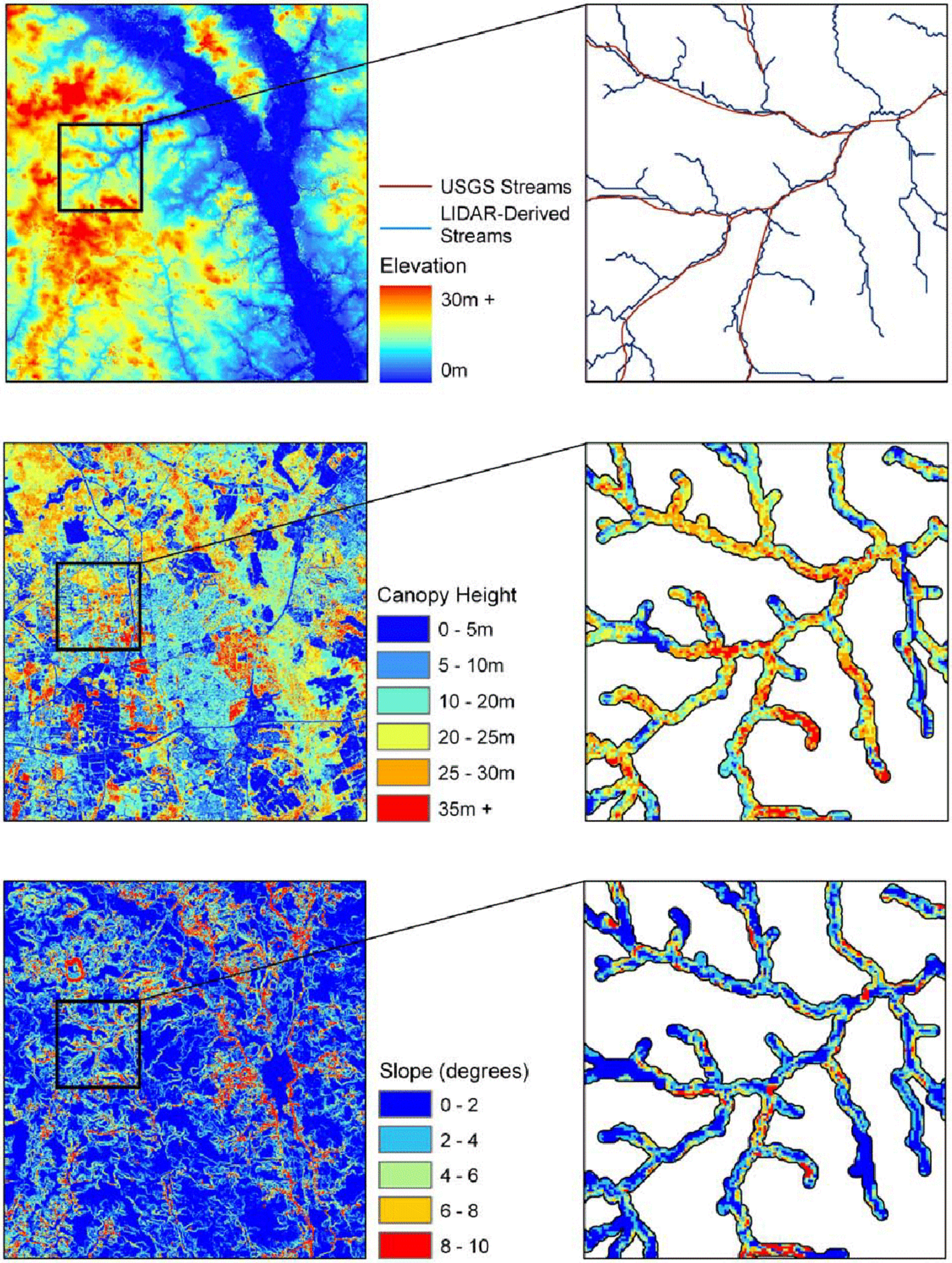

Figure 3. Lidar Derived Maps of a 625 km^2 Portion of the Patuxent and Patapsco River Watersheds in Prince George's County, Maryland. Maps of ground elevation (upper left), tree canopy height (middle left), and topographic slope lower left) were derived from LVIS imagery (Blair *et al.,* 2006). For the indicated inset areas in these images, the USGS stream network is compared to that derived from the LVIS surface elevation image (upper right), canopy height within the 50 m stream buffer (middle right), and topographic slope within the 50 m stream buffer (lower right).

rapidly in the near future. Advances have been made possible through a combination of multiscale optical imagery and relatively new laser remote sensing technology (Lidar). Very high spatial resolution image data (< 5 m) permit improved characterization of landscape structure, such as the spatial configuration of vegetation relative to the stream network, as well as improved definition of vegetation distribution and density within relatively narrow buffer zones. They also provide a means to produce maps from moderately high resolution imagery, such as widely available 30 m Landsat Thematic Mapper data, in which proportional estimates (0 to 100 percent) of forest, impervious, or agricultural cover types are generated for each image pixel (Figure 1). Once algorithms are generated using these two image data sources, they can be applied to produce consistent maps over much larger areas that would not be economically practical to map using the very high resolution imagery alone. Moreover, this approach provides much better characterization of buffer zone vegetation density than can be accomplished using generalized categorical land cover or land use type maps. These proportional (subpixel) map products provide useful information to improve management of stream biotic health and water resources.

The second advance in remote sensing relevant to riparian buffer zone management is the advent of Lidar instruments that are capable of characterizing the three-dimensional structure of the landscape, including narrow buffer zones, in terms of ground surface elevation, vegetation density, and height distributions. Lidar products permit improved definition of stream networks and catchments through refined definition of elevation grids, while topographic definition within buffer zones can be derived and used with associated vegetation information (height and density distributions) to better characterize buffer physical properties (Figure 3). These capabilities open up a range of future prospects for remote sensing of buffer properties, some examples of which are described herein.

The prospects are substantial for these technological advances in informing buffer functional assessments and for models related to the transport of nutrients and other pollutants. Recent and continued advances in remote sensing provide a means to move from the applied research realm to operational use for management purposes, but it is important to note that what is currently technically feasible for applications research is not necessarily equivalent to what is practical for management applications over very large areas. This is particularly true of Lidar data, which come in a variety of forms and are advancing rapidly both technologically and commercially.

A number of commercial firms have taken advantage of these research advances, however, and as a result laser and very high resolution optical imaging data are available from a number of commercial vendors. In the case of noncommercial Lidar systems, including those discussed here, data are being made more widely available through government and nonprofit research institutions. The primary benefits of these new sources of riparian buffer information include their consistency over areas both large and small and their potential to be used with moderately high resolution satellite imagery and traditional data sources such as aerial photos and field surveys. Together these provide a rich source of information that has the potential to substantially improve buffer zone management and associated attributes of water quality and stream health.

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