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REMOTE SENSING OF FOREST CANOPIES

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ABSTRACT. Remote sensing provides information about forest canopies through a sensor signal resulting from the interaction of electromagnetic energy with canopy components. The information gained about the canopy structure is highly dependent on the frequency received by, as well as the spatial resolution of, the sensor. Currently, there are numerous types of remote sensing devices that utilize various regions of the electromagnetic spectrum and cover a range of spatiotemporal scales. This paper is designed as an introductory overview of how remote sensing can be used to assess canopy characteristics at the crown, stand and landscape levels. Examples from passive (e.g., optical multispectral imagers) and active (e.g., synthetic aperture radar and lidar) systems are presented.

INTRODUCTION

For forest canopy researchers, who pride themselves on gaining access to their study sites through the skillful use of a variety of elaborate mechanisms, such as tree climbing apparatus, cranes, towers and blimps, remote sensing may provide a less dangerous (and perhaps less enjoyable) method to gather certain types of biophysical information. In relation to forests, remote sensing is a technique to collect quantitative data through a sensor signal resulting from the interactions of electromagnetic (EM) energy with canopy (i.e., leaves, twigs, branches, trunks) and, occasionally, ground components. It can range from the scale of a leaf via a hemispherical lens (Rich 1990) to the scale of a biome via a high-orbiting weather satellite (Justice *et al.* 1985). The emphasis of this overview will lie towards the smaller end of these two scales (i.e., ≈10–50 m resolution) focusing on digital information from airborne and satellite-based remote sensing platforms.

Beyond what may seem like the major application of remote sensing in ecological studies, that is "to show what my study site looks like from space," two more defensible uses of remote sensing are: 1) to monitor inaccessible (e.g., canopy) or spatially extensive regions and 2) to detect spatial patterns and processes (Iverson *et al.* 1989, Howard 1991). More precisely, sensors can be used to address questions concerning canopy status (Rock *et al.* 1993): What is there? What type of forest is it? Deciduous or evergreen? Young or old? Are the leaves on or off? How tall are the trees? What is the percent cover? Are there signs of disturbances (e.g., treefall gaps, fire, herbivory, cutting)? etc. With image analysis techniques, questions concerning the horizontal spatial properties of the canopy can be addressed: How are the trees arranged? Are they clumped, randomly, or uniformly spaced? Do the cover types occur in patches? How are the patches shaped and distributed? What borders the patches? What is the scale of the patches? What is the extent of edge? etc. Given a time series of calibrated images and depending on the temporal resolution (i.e., repeat time), questions concerning the dynamics of canopy processes can be explored: What is the phenology of a certain canopy type? How does succession proceed across a landscape? What is the frequency and extent of natural or anthropogenic disturbances? Are the periodicities of the signals random or predictable? etc. (adapted from Quattrochi & Pelletier 1991). Though remote sensing shows tremendous promise to assist researchers in answering these and many other questions, there is a caveat directed towards armchair ecologists: the science of remote sensing still remains in its infancy in regards to ecological applications and the sensor technology is changing rapidly (Wickland 1991; Kramer 1994); thus, there is much room for skepticism and validating or ground-truthing signals is necessary (Roughgarden *et al.* 1991). Nevertheless, the extrapolation of findings beyond the scope of the typical ecological study requires the synoptic vantages afforded by remote sensing.

METHODS

1.) Passive remote sensing—Passive remote sensing, the more traditional method for remote

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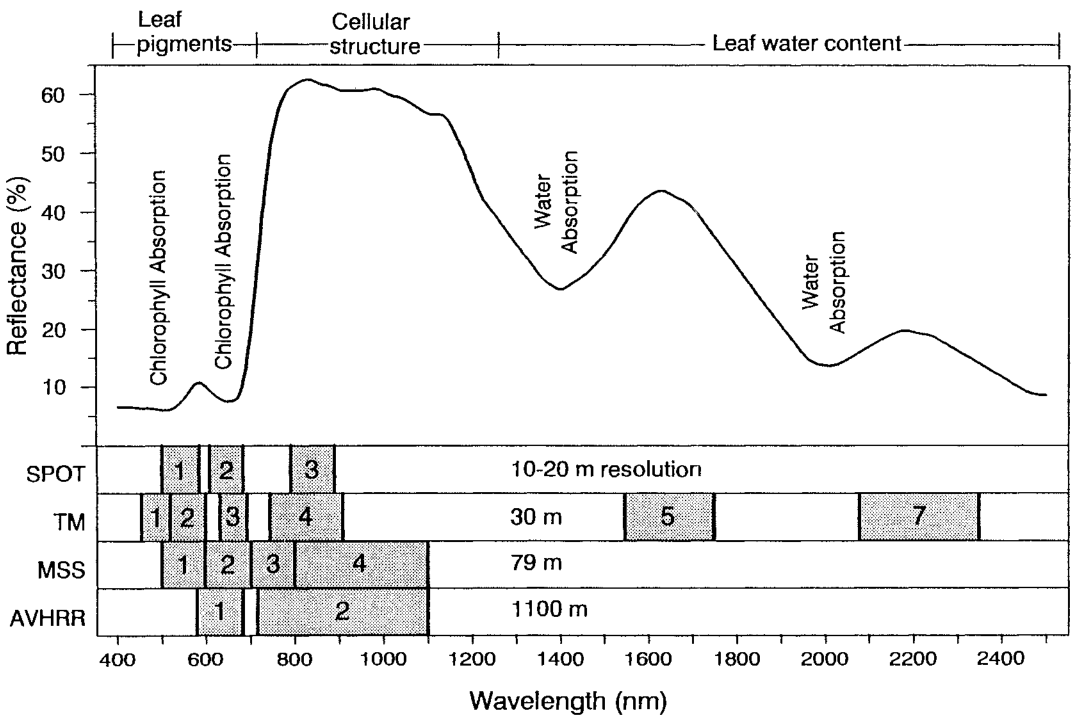

FIGURE 1. Spectral response curve for generalized green vegetation with spectral and spatial resolution of four passive satellite sensors (adapted from Iverson *et al.* 1989, Ranson & Williams 1991).

sensing vegetation, is analogous to a camera whose source of optical EM energy is the sun. Aerial photography (Howard 1970, Avery & Berlin 1992) is the most widely used form of passive remote sensing for forest canopy applications. With passive remote sensing, natural energy (i.e., primarily solar although other natural sources such as microwave emissions are also used) is absorbed, transmitted through, emitted from, or reflected off leaf, branch, or other surfaces found in the canopy or on the ground depending on the nature of the type of EM energy (wavelength) reflected and sensed (spectral resolution). Though often simply modeled as an ideal diffuse (Lambertian) reflector, where energy is scattered equally in all directions, canopy surfaces fall between ideal specular, where all incident energy is reflected in a single direction, and ideal diffuse surfaces (Lillesand & Kiefer 1994). Thus, only a portion of the energy that is reflected from the surface comprises the received signal. The magnitude of this reflected energy is influenced by the geometry of the leaf, branch, or canopy surface, the solar incidence angle and the view angle of the sensor, as well as the reflected energy's ability to penetrate the atmosphere through clouds, water vapor, aerosols, smoke, etc.

At the scale of a leaf, vegetation yields a characteristic spectral signature (Figure 1). In the visible region (400–700 nm) of the EM spectrum, absorption and reflectance is a function of leaf pigments, primarily chlorophyll, carotenoids and anthocyanins. The typical green leaf strongly absorbs blue and red wavelengths and less strongly absorbs green wavelengths; therefore leaves are largely green. Leaves also strongly reflect energy from the near infrared (NIR) region (700–1100 nm) of the EM spectrum. This property is a function of the spatial arrangement of mesophyll cells (Gates *et al.* 1965). The sharp contrast between the area of absorption in the visible red region and the area of reflection in the NIR is referred to as the "red edge." In the middle infrared region (1300–2600 nm), the magnitude of absorption and reflectance of energy by leaves is dependent on their moisture content. Absorption peaks generally occur near ≈1400 and ≈1900 nm. Reflection peaks generally occur near ≈1600 and ≈2200 nm. Remote sensing of emitted NIR has been used to estimate canopy temperatures across forested landscapes (Luvall *et al.* 1990, Luvall & Holbo 1991).

The spectral response or signature of forests is not only dependent on the spectral resolution,

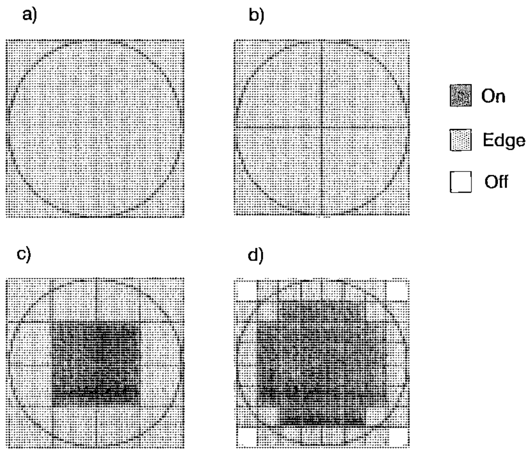

FIGURE 2. Effect of spatial resolution on sensing a circular object where a) one, b) two, c) four and d) eight pixel(s) equal(s) the object's diameter (adapted from White & MacKenzie 1986).

but also the spatial resolution of the sensor (White & MacKenzie 1986, Cohen *et al.* 1990, Weishampel *et al.* 1994). Canopies are generally sensed at resolutions above the leaf scale (FIGURE 1). Thus, a pixel represents an ensemble of reflecting components and the information garnered by a receiver becomes a function of the scale at which a canopy is sensed (Woodcock & Strahler 1987). For example, given a circular object (FIGURE 2) such as a generalized tree crown (or canopy gap) detected by a coarse resolution sensor where one or two pixels equal the feature's diameter, the entire response is comprised of reflections from crown, inter-tree space (i.e., ground or shadow) and edge features (i.e., comprised of both crown and inter-tree space). As the resolution of the sensor becomes finer, some pixels represent pure crown or pure inter-tree space responses. Thus, the spatial pattern of the objects (i.e., the degree to which trees are clumped, randomly, or uniformly spaced) can influence the overall signal. In a similar manner, Williams (1991) found spectral reflectance to decrease from the needle-, to the branch-, to the canopy-scale with the increasing presence of within-crown shadowing.

Sensors measure incoming energy in discrete regions of the EM spectrum called bands or channels (FIGURE 1). Band combinations or spectral indices have been developed to emphasize the fairly characteristic response of green vegetation, typically exploiting the high absorption in the red region and the high reflectance in the NIR. Two spectral indices commonly used by the ecologically-oriented remote sensing community are the Simple Ratio (SR = IR/red) and the Normalized Difference Vegetation Index (NDVI = (IR-red)/(IR+red)). These indices have been directly correlated with leaf area (Running *et al.* 1986), phytomass and absorbed photosynthetically active radiation (APAR) and have been used to classify vegetation types. Since these indices are a function of the vegetation greenness, they may exhibit phenological changes (Justice *et al.* 1985, Spanner *et al.* 1990, 1994) such as the timing of leaf out, autumnal pigment changes and leaf abscission, thereby providing supplemental data which can be used to further discern vegetation types (Loveland *et al.* 1991). When coupled with physiological models, these indices have been related to processes such as photosynthesis (Sellers 1985, Tucker & Sellers 1986) and evapotranspiration (Running *et al.* 1989, Sellers *et al.* 1992). Because NDVI has been used as a proxy for photosynthesis, when integrated over time, it has been used to estimate gross primary productivity (Goward *et al.* 1985).

However, these indices have their limitations. For relatively spatially homogeneous vegetation, such as agricultural crops, NDVI saturates (i.e., reaches a plateau value) near a leaf area index (LAI) of three (Asrar *et al.* 1984) and is thus an insensitive measure of moderate to dense leaf area. For more heterogeneous canopies such as those found with coniferous forests, NDVI saturates near an LAI of six (Spanner *et al.* 1990). Thus, these indices cannot be used to directly distinguish among mature forest types. But, the utilization of different bands and band combinations (Hall *et al.* 1991, Cohen & Spies 1992, Ustin *et al.* 1993) and spatial properties of pixels (i.e., scene texture; Musick & Grover 1991) may be used to further classify high-LAI forest types (Cohen *et al.* 1990).

Innovations with passive sensors—Perhaps the most data-rich approach to remote sensing involves the development of two experimental narrowband sensors: the Airborne Imaging Spectometer (AIS) and its successor, the Advanced Visible InfraRed Imaging Spectrometer (AVIRIS; Ustin *et al.* 1991, Novack 1994), to detect canopy-level chemistry. These systems of 128 and 224, 9.3 nm wide bands ranging from 900–2400 and 400–2500 nm, respectively function as airborne spectrophotometers measuring canopy reflectance at fine spectral increments. For example, the AIS was used to remotely sense the percent of canopy lignin (Wessman *et al.* 1988). A multiple regression model (R^2=0.85) related three AIS bands and percent canopy lignin for 18 forest stands in Wisconsin. In general, deciduous communities exhibited lower percent canopy lignin than evergreen communities. Corresponding laboratory analyses related percent

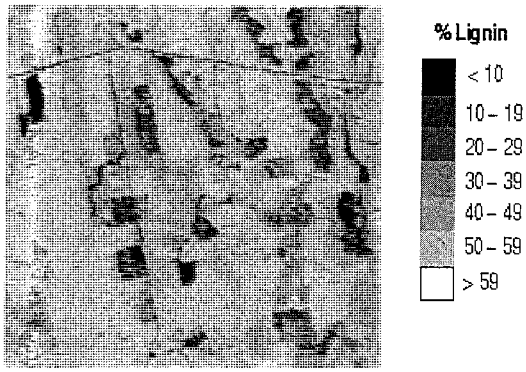

FIGURE 3. Estimated distribution of percent canopy lignin across a forested landscape in central Maine.

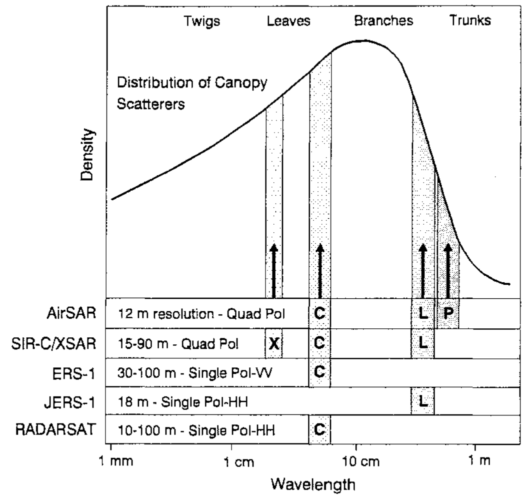

FIGURE 4. Hypothetical size distribution of canopy scatterers and the idealized region of backscatter response for various platforms (adapted from NASA 1987).

canopy lignin to soil nitrogen mineralization thereby enabling estimates of soil nitrogen availability across a landscape. To take this study a step further, if canopy palatability can be related to percent lignin, the potential for herbivory across a landscape could also be predicted with this type of instrument.

Using the relationship found by Wessman *et al.* (1988) and AVIRIS bands that corresponded to the wavelengths of the AIS bands, a percent canopy lignin cover map (FIGURE 3) was created for a forested landscape in central Maine. A description of the site composition is given in Levine *et al.* (1994). Though the validity of porting this relationship from Wisconsin forests to Maine forests is uncertain, the image shows patches of recent harvesting activity, immature stands and open bogs to have less percent canopy nitrogen than more mature, intact stands. This combination of three of the 224 bands represents a preliminary study to detect canopy-level chemistry with this instrument. The potential of these narrow-band sensors to detect concentrations of other organic consitituents found in foliar material such as pigments or structural components (e.g., cellulose, starch and proteins) which may relate to the physiological status of the canopy or its contribution to biogeochemical cycles is being explored (Ustin *et al.* 1991).

A step beyond these nadir-viewing spectrophotometers (i.e., perpendicular to the surface) is represented by the Advanced Solid-state Array Spectroradiometer (ASAS). This instrument combines a multiple narrowband sensor (62 bands ranging from 406 to 1036 nm) with a gimbaled mounting platform making possible imaging of reflected solar radiation at off-nadir angles from 72° forward to −55° backward (Dabney *et al.* 1994). Thus, ASAS can be used to sample the bidirectional reflectance (BR) of forest canopies, which is a characterization of reflectivity at all illumination and view angles (Abuelgasim & Strahler 1994, Ranson *et al.* 1994). The BR is a function of canopy structure and can be used to calculate the hemispherical relfectance (i.e., albedo) and the fraction of absorbed photosynthetically active radiation (F_{APAR}).

2.) Active remote sensing—Active remote sensing is analogous to a camera that uses a flash, thus the artificial energy source and the sensor are typically from the same platform. Hence, active sensors operate independent of solar incident angle and are generally concerned with the energy backscatter from the target at 0° phase angle (i.e., coincident illumination and view angles). Radio detection and ranging (radar or microwave) sensors (e.g., Synthetic Aperture Radar, SAR) are the most prevalent form of active sensor presently used to analyze forest canopies (Waring *et al.* 1995). As with optical energy, the reflection of microwaves by canopies is dependent on the particular wavelength as well as the spatial resolution of the instrument. However, whereas optical signals are related to the pigmentation and the water content of the canopy components, radar signals, with wavelengths on the order of centimeters respond to the structural features of the canopy (FIGURE 4). Shorter wavelength radars (i.e., X-and C-bands) are sensitive to smaller canopy components, reflecting primarily off of leaves and twigs. Longer wavelength radars (i.e., L-and P-bands) are influenced by larger features such as branches and trunks. As wavelengths increase, the canopy penetration

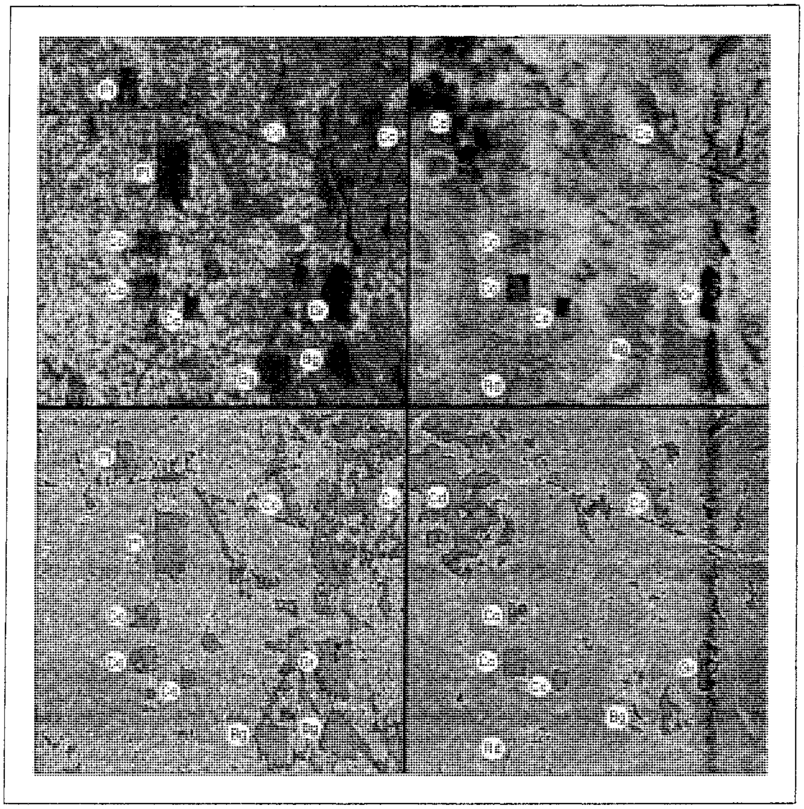

FIGURE 5. Comparison between AirSAR cross-polar (HV), P-band/C-band ratio (upper left) and SPOT NDVI (upper right) imagery for a forested landscape in central Maine. Lower panels represent filtered versions of the upper panels to accentuate edges. *Figure Abbreviations*: Bg, bog; Cc, closed canopy; Cd, cloud; Gr, grass; Pl, tree plantation; Rd, road.

depth increases. Shorter wavelengths sense the upper canopy surface, whereas longer wavelengths garner information about the geometry and density of canopy components as well as the roughness of the ground surface at the scale of the radar wavelength (Ranson & Williams 1991).

Additionally, radar is sensitive to the dielectric properties of the target, which for applications in forest ecology primarily relates to the moisture content of the canopy and ground surface. This property has been used to demonstrate diurnal water fluctuations in trees (Way *et al.* 1991) and phenological phenomena such as freeze/thaw cycles in boreal forests (Way *et al.* 1994) and seasonal below canopy flooding in tropical (Stone & Woodwell 1988, Imhoff & Gesch 1990) and temperate forests (Ustin *et al.* 1991). Hence, this sensitivity requires a combination of groundtruthing and modeling to determine what characteristics (e.g., geometric structure, size, moisture) of the target produced the received signal. Microwave transmitters and receivers can be constructed to send and receive polarized energy in the vertical (V) and/or horizontal (H) direction. Quadruple polarized (i.e., quad pol) instruments (FIGURE 4) make use of all four send/receive combinations (VV, HH, HV and VH). Polarized radars can be designed to emphasize objects of characteristic orientations such as vertically standing boles as might be found in recently burned (Kasischke *et al.* 1994) or cut (Stone & Woodwell 1988) sites. These polarized signatures can be generated to provide information about the composition and structural orientation of canopy components (Durden *et al.* 1991).

Radars have several other capabilities which make them desireable to the canopy scientist. As demonstrated by FIGURE 5, which represents a direct comparison between a radar and an optical image of the aforementioned forest in central Maine, radar is unaffected by clouds (Cd) as well as other atmospheric conditions (e.g., smoke) that typically distort or render regular optical sensing of tropical canopies impossible. And because ra-

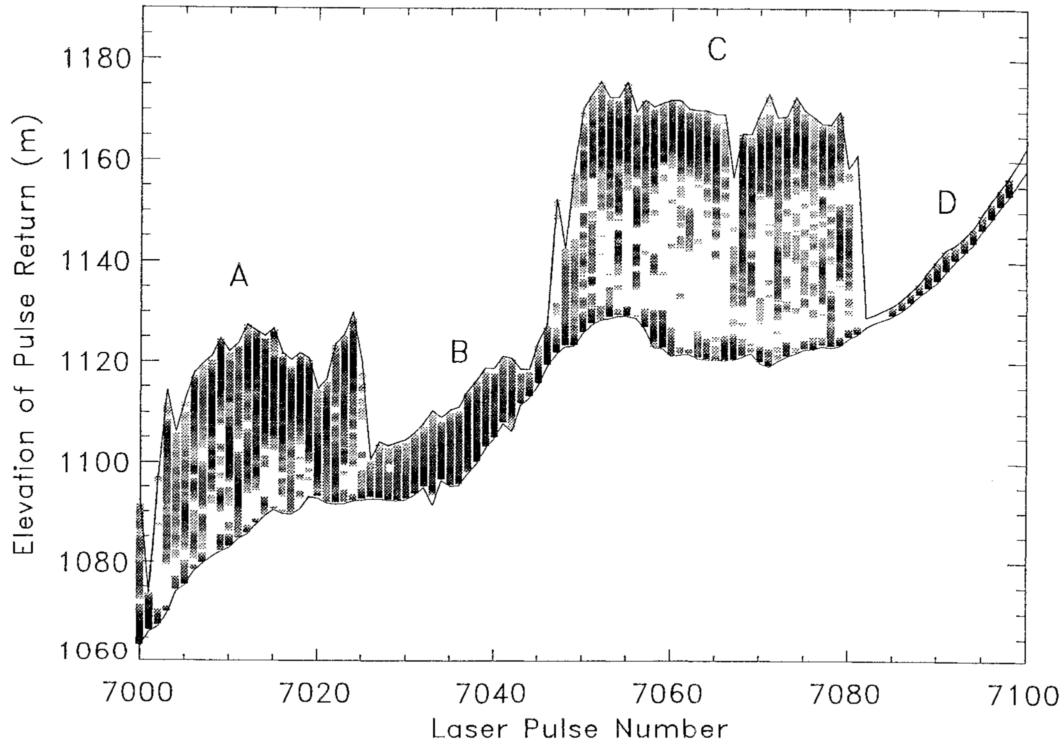

FIGURE 6. Example of lidar-derived height and vertical structural density data for a 1 km transect from the Gifford Pinchot National Forest, Washington, USA.

dar is sensitive to biomass rather than greenness, younger, low biomass plantations (Pl in FIGURE 5) which may appear as green can be differentiated from more mature, higher biomass, green stands. However, the ability to distinguish among older stands is limited as backscatter from longer wavelengths (i.e., P-band) and ratios that involve longer wavelengths (P-band/C-band) saturates at biomass levels of 150–200 Mg/ha (Dobson *et al.* 1992, Ranson & Sun 1994, Ranson *et al.* in press). Textural information may be able to increase classification accuracy among higher biomass types.

Innovations with active sensors—Light detection and ranging (lidar) systems represent another type of active instrument that is being used to detect canopy properties. With the early versions of lidar, fine resolution (footprint diameter ≈0.75 m) pulses of laser energy were directed from a low-flying aircraft over forest canopies (Nelson *et al.* 1984, 1988). By measuring the roundtrip time for pulses reflecting off the canopy and ground surfaces, tree heights could be estimated over a region, yielding height profiles of the forest stands. These profiles have been correlated, with varying degrees of success, to forest properties such as: biomass, percent canopy cover, species composition and aerodynamic roughness length (see references in Harding *et al.* 1994). However, this fine-resolution, narrow-profiling methodology has its limitations when trying to discern canopy characteristics. This approach tends to only reveal ground returns in regions of low percent canopy closure and to understimate canopy height due to a biased sampling of crown shoulders (i.e., crown regions other than the apex).

New instrumentation developed by Blair *et al.* (1994) optimizes the lidar system to consistently produce ground returns, even under conditions of high canopy closure, and vertical canopy profiles of aboveground surface area. By increasing the footprint diameter to equal roughly the average crown width (≈10 m), the instrument records the time and magnitude of backscatter from the canopy top, the ground and the intervening forest structure (comprised of leaves, twigs, branches and boles) at 22 cm vertical resolution in order to produce vertical canopy profile diagrams (Harding *et al.* 1994) which bear a striking resemblance to those measured using ground-based techniques (MacArthur & Horn 1969, Aber 1979).

FIGURE 6 shows a 2-dimensional slice through a 1 km transect of the landscape of Gifford Pinchot National Forest, Washington, USA. The top line represents the location of the first return, the elevation of the canopy top. The bottom line represents the location of the last return, the elevation of the ground surface. By subtracting these two returns, the forest height can be determined for each laser shot location. Between these lines, the gray-scale pixels represent the location and magnitude of the return at 10 m resolution in the horizontal and 22 cm resolution in the vertical directions. Higher magnitude returns are depicted by darker pixels. Four patch types can be discerned along this portion of the data: a mature stand 30–40 m tall with a fairly even distribution of canopy components in the upper 20–30 m (A); a ≈10 m tall Douglas-fir plantation with an even distribution of canopy components along the bole (B); a 40–50 m tall possibly 'old-growth' stand with the majority of canopy components concentrated in the upper 10–15 m, although there is substantial vertical heterogeneity and perhaps an understory (C); and a recently clearcut region (D).

Future development of this instrument includes increasing the swath width from a single 10 m pulse to 20, 10 m pulses and doubling the number of channels from one to two. Visible and near IR channels will yield a quasi-NDVI vertical canopy profile in order to distinguish the height distribution of chlorophyll-bearing (e.g., foliage) from non-chlorophyll-bearing tissue (e.g., twigs and branches). Thus, this sensor shows promise for generating information concerning the 3-dimensional nature of forest canopies, which heretofore has been an unknown quantity at the landscape scale.

CONCLUSIONS

This paper has outlined the types of forest canopy-related questions that can and are being addressed with the assistance of remotely-sensed data and described the basic theory behind the two types of remote sensing instruments, passive and active. Although some of the more promising instruments for detecting canopy properties are in the experimental stage and hence their coverage is limited, the availability of data from the more established forms of passive and active systems is increasing, while at the same time the costs of computing involved for the necessary image processing and data management is decreasing. Thus, the use of these tools for characterizing canopy-related patterns and processes at a variety of spatiotemporal scales has been steadily increasing over the last decade. The development of more refined sensors in terms of spectral, spatial and temporal resolution is permitting revolutionary views of chemical and structural features of forest canopies which will alter how forests are perceived across a landscape. But before these means of data collection become a regular part of the canopy-researchers toolbox, substantial amounts of field- and laboratory-based research remain in order to validate these new techniques. And although there may be a time when those fabled license-plate reading sensors become declassified, it is unlikely that they will ever be used to identify a new Coleopteran species.

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