Remotely sensed data have been employed for the characterization of ecologically important variables from local through global contexts. These data may be used to generate a wide range of estimates that are valuable to ecologists, including information on land cover, vegetation cover, habitat, forest structure, and forest function (Kerr and Ostrovsky 2003), and to track changes in these variables. Recent technological developments in remote sensing have resulted in new capabilities for data capture and data processing, making it possible to generate and analyze digital images at high spatial resolution (fine grain, defined here as a pixel size of 16 square meters \([m^2]\) or less). A wide variety of options exists for using data processing and data analysis to estimate a range of ecologically important attributes. For instance, in the characterization of vegetation, applications have been developed for the estimation of stand structural attributes and leaf area. These applications have been developed for the estimation of stand structural attributes and leaf area. These applications have been developed for the estimation of stand structural attributes and leaf area. These applications have been developed for the estimation of stand structural attributes and leaf area.

The information that may be generated from remotely sensed data is directly linked to the sensor and to the related characteristics of the images it produces: spatial resolution (pixel size; table 1), spectral resolution (wavelength ranges utilized), temporal resolution (when and how often images are collected), and spatial extent (ground area represented) (Turner W et al. 2003). Thus, the most appropriate remotely sensed data may be selected for a given application (Lefsky and Cohen 2003). The sensor and image characteristics of the MODIS (Moderate Resolution Imaging Spectroradiometer) satellite, for instance, allow for regular monitoring of global vegetation productivity (Running et al. 2004) but not for spatially detailed characterization of vegetation. Rather, information at the national scale is commonly generated using remotely sensed data at coarse spatial resolution for attributes such as fractional cover, land cover and change, fire, leaf area, and productivity (see Cihlar and colleagues for overviews of methods [2003a] and applications [2003b]). In many cases, information generated to represent ecological phenomena at the global scale is too general to meet regional or local objectives. Sensors such as the Landsat series (see Cohen and

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Goward 2004), which gather images at higher spatial resolution, have a long history of use for spatial and temporal scaling in ecology. With a pixel size of 30 by 30 m and an image extent of 185 by 185 kilometers (km), the Landsat systems have generated data that are ideal for characterizing attributes at the landscape to regional level. For greater spatial detail than that offered by Landsat, data at higher spatial resolution are often sought (table 1). While satellite-based data at high spatial resolution are now available, forest inventory data, developed by generalizing the characteristics of vegetation from aerial photographs, have often been the most widely available source of detailed information.

The estimation of forest stand structure, including species composition, crown closure, stand height, stem density, age, and volume, has been the focus of forest inventories used to develop resource management plans in the quest to ensure that forests are managed on a sustainable basis. Timber growth and yield have dominated the forest inventory agenda in the past few decades (Lin and Päivinen 1999), with detailed data on the location and extent of forest resources being collected principally to meet timber planning and harvest scheduling needs (Gillis and Leckie 1993). However, management practices are now increasingly designed to maintain and enhance the long-term health of forest ecosystems while providing environmental, social, and cultural opportunities for present and future generations (Kohm and Franklin 1997). For example, conservation of biodiversity and of wildlife habitat has become a critical goal of forest management as part of an ecosystem-based approach to adaptive management of forested landscapes (Kimmins 1999). In response, systems for the classification of forest inventories are changing. New biophysical information is required, perhaps combined with a larger number of more refined classes of traditional inventory attributes (Franklin SE 2001). Forest biophysical data are related to forest structure and function (e.g., leaf area index [LAI], biomass, net primary productivity [NPP]), but these data are often not collected routinely in current programs for forest inventory and monitoring because they are poorly understood by those in operational forestry, and the feasibility of their estimation and mapping has been advanced significantly only with recent developments.

This situation has created opportunities to develop complementary methods of data acquisition with remotely sensed aerial or satellite data at high spatial resolution. New technological developments (greater spatial, radiometric, temporal, and spectral resolution), coupled with increasingly sophisticated computer processing techniques, enable biophysical remote sensing and estimation of traditional forest inventory data at reasonable cost (Wulder and Franklin 2003). A fundamental premise in using remotely sensed data to estimate or map biophysical or forest inventory data is that there is a predictable relationship between the spectral response measured by the sensor and the magnitude of the parameter of interest. To interpret such a relationship requires knowledge

<table>
<thead>
<tr>
<th>Type of instrument or photographic scale</th>
<th>Approximate range of spatial resolution (meters)</th>
<th>General level of plant discrimination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-resolution satellite images</td>
<td>1000 (AVHRR) 500 (MODIS)</td>
<td>Broad land-cover patterns (regional to global mapping)</td>
</tr>
<tr>
<td>Medium-resolution satellite images</td>
<td>30 (Landsat) 20 (SPOT-4 multispectral)</td>
<td>Separation of extensive masses of evergreen versus deciduous forests (stand-level characteristics)</td>
</tr>
<tr>
<td>High-resolution satellite images (e.g., IKONOS)</td>
<td>&gt; 1 (panchromatic) &gt; 4 (multispectral)</td>
<td>Recognition of large individual trees and broad vegetative types</td>
</tr>
<tr>
<td>Airborne multispectral scanners</td>
<td>&gt; 0.3</td>
<td>Initial identification of large individual trees and stand-level characteristics</td>
</tr>
<tr>
<td>Airborne video</td>
<td>&gt; 0.04</td>
<td>Identification of individual trees and large shrubs</td>
</tr>
<tr>
<td>Digital frame camera</td>
<td>&gt; 0.04</td>
<td>Identification of individual trees and large shrubs</td>
</tr>
<tr>
<td>1:25,000 to 1:100,000</td>
<td>0.31 to 1.24*</td>
<td>Recognition of large individual trees and broad vegetative types</td>
</tr>
<tr>
<td>1:10,000 to 1:25,000</td>
<td>0.12 to 0.31</td>
<td>Direct identification of major cover types and species occurring in pure stands</td>
</tr>
<tr>
<td>1:2500 to 1:10,000</td>
<td>0.026 to 0.12</td>
<td>Identification of individual trees and large shrubs</td>
</tr>
<tr>
<td>1:500 to 1:2500</td>
<td>0.001 to 0.026</td>
<td>Identification of individual range plants and grassland types</td>
</tr>
</tbody>
</table>

AVHRR, Advanced Very High Resolution Radiometer; MODIS, Moderate Resolution Imaging Spectroradiometer; SPOT-4, Systeme Pour l’Observation de la Terre.

of the optical properties of forests (e.g., canopy geometry, leaf spectral properties), the effects caused by the size of the viewed area (e.g., spatial resolution), and environmental and systems factors such as topography, sun elevation, haze, wind speed, and the orientation and inclination of the view axis between the surface and sensor. The spatial resolution of a remotely sensed measurement is determined by the sensor's instantaneous field of view (IFOV). With any image data, the user must consider the relationship between the ground objects of interest and the IFOV, which strongly influences the information content.

When the pixel size exceeds the size of an individual tree crown, decreasing visible and infrared reflectance has been observed in stands as trees age and become larger. As a stand ages, the areas between the tree crowns become smaller, and the effects of crown closure and shadow increase (Franklin J 1986, Gemmell 1995). As trees grow taller, foliage biomass increases, and the spectrally brighter understory is covered with shadows, reducing the overall spectral reflectance of the stand. One potential advantage of using data at medium spatial resolution (e.g., from the Landsat Thematic Mapper and Enhanced Thematic Mapper Plus sensors; see Cohen and Goward 2004) has been the ability to measure the structural properties of forests, because pixel values are an integrated measure of the overstory, understory, soil, and shadow components (Scarth et al. 2001). However, the characteristics of individual trees are difficult to determine using these data. By contrast, remotely sensed images at high spatial resolution commonly have a pixel size smaller than the size of an individual tree crown; in other words, the objects of interest (usually the trees) are larger than the spatial resolution used to measure them.

One way to understand these data is to consider that there are many pixels per object rather than many objects in a single pixel (Strahler et al. 1986). Thus, a group of pixels may be combined to characterize individual trees in a way that is impossible with medium-resolution data (Hay et al. 1996, Moskal and Franklin 2002, Culvenor 2003).

The optimal approach for processing remotely sensed images depends primarily on the definition of the output products desired (e.g., maps) and is influenced by spatial resolution and interpixel variance. Per-pixel image classifications are commonly applied at low or moderate spatial resolution but sometimes do not operate well at high spatial resolution. The spectral variability that is found for an individual tree (e.g., pixels representing sunlit crown, shaded crown, and the influence of factors such as branches, cones, and tree morphology) is not helpful in developing unique spectral signatures for tree or object classification. A spectral end-member approach may be appropriate (Asner et al. 2003, Ustin et al. 2004). Alternatively, approaches for extracting individual tree information from imagery at high spatial resolution are based on techniques that operate principally in the spatial domain (Culvenor 2003). For example, the texture of an image may be an important characteristic that can be related to forest parameters (Wulder et al. 1998), and an understanding of the expected spectral response for trees may be used to develop rules for delineating tree crowns before they are classified using a spectral signature (or other) approach (Fournier et al. 1995).

Remotely sensed data may be used to represent ecological phenomena across a range of scales (Kerr and Ostrovsky 2003). These data are most commonly applied to characterize global or landscape-level properties. The operational use of satellite and airborne data at high spatial resolution is developing quickly. The ability to use multiple spatial resolutions of imagery, in conjunction with field data, in multiscale analyses is a burgeoning area for research and applications. However, there is often a perceived mismatch between the data wanted by ecologists and the data collected with remote sensing instruments (Kerr and Ostrovsky 2003). This perception is declining, thanks to the availability of high-resolution data that can be directly linked to traditional field-based ecological measurements (Turner W et al. 2003). The nesting of data from differing scales in an information hierarchy provides opportunities for gathering detailed, site-specific information over increasingly large areas. To use this information, researchers must understand the potential and limits of data at high spatial resolution and understand how these newly available data may be integrated with other spatial data sources (including lower-resolution satellite data). The number of options for sampling, scaling, and stratifying data, and the ease with which these options can be selected and applied, are poised to increase, allowing researchers to characterize ecological attributes with data from a range of scales.

In this article, we review data at high spatial resolution, and related applications, that offer unique options for generating information to characterize ecosystems (with a focus on forests). We introduce a range of systems—photographic and digital, airborne and satellite optical (approximately 400 to 2500-nanometer [nm] wavelength sensitivity)—for gathering high-resolution data (see also Lefsky and Cohen 2003). We also discuss potential and current limitations in the ability to estimate a suite of inventory and biophysical attributes. While much research and development has focused on stand-level attributes (e.g., height, age, density, species composition) gathered through forest inventory, techniques now exist to estimate values for attributes that are process-related (e.g., crown morphology, biomass, LAI) and are based on recognition of individual trees or objects rather than on stand-level or “average-tree” conditions. Further issues include the way in which accuracy is assessed and the level of accuracy with which attributes are estimated.

**High spatial resolution data**

Analog (hard-copy) aerial photographs have been used extensively and continue to be used in vegetation-mapping and forestry applications (Hall and Fent 1996), although digital aerial photographs are expected to become more prominent in the future (Caylor 2000). The components of aerial photography include the camera, lens, aerial film, processing, and printing, which together influence the quality of...
the resultant photograph. Recently introduced improvements in aerial photography acquisition include forward motion compensation, high-performance optical systems with lenses that achieve 100 line pairs per millimeter, GPS (global positioning system) interfaces, film data recording systems, and gyrostabilized mounts (Hall and Fent 1996, Read and Graham 2002). Characteristics such as camera type, aerial film type, speed, processing, and resolution influence the sharpness and quality of images (Eastman Kodak Company 2002, Hall 2003). The interpretation of analog aerial photographs relies heavily on the skills of a trained analyst, and the process can be both time-consuming and subjective (Holopainen and Wang 1998).

Scanning hard-copy photographs is increasingly common. It is seldom necessary or even desirable to scan at a level equivalent to the resolving power of the original aerial photograph (Nelson et al. 2001). Experience suggests that it is best to scan for a pixel size that is approximately 20% of the output size of the object of interest (Hall 2003). The pixel value of a scanned aerial photograph depends on the film type (e.g., spectral sensitivity, resolution), lens resolution, film processing, scale, elevation, and illumination at the time the photo was acquired, as well as, in the case of vegetation, the stage of phenology. Scanning is best undertaken using the original film or diapositive, since the resolving power of film is greater than that of paper. Atmospheric effects are also inherent in photographic images, and there may be bidirectional reflectance effects caused by differential shading of exposed and shaded sides of objects (e.g., tree crowns), especially at larger photographic scales (Fournier et al. 1995). Scanned aerial photo images can be converted to orthophotos through a differential rectification process that includes a digital elevation model, known exterior orientation parameters, and collinearity equations that relate object and image coordinates (Baltsavias 1999, Wolf and Dewitt 2000).

Digital aerial photographs can be obtained directly from small-format (e.g., Kodak DCS 420 and DCS 460) and large-format (e.g., Leica Helava ADS40, Zeiss/Intergraph DMC 2001) digital cameras (Graham and Koh 2002). Advances in video and digital camera technologies and in computer processing speed have enabled the development and testing of a number of airborne multispectral and hyperspectral imaging systems to complement existing aerial photographic programs (Wright et al. 2003). A single CCD (charge-coupled device) sensor with mosaic optical filtering and near-infrared airborne camera systems can produce imagery at very high spatial resolutions (pixel size < 25 centimeters [cm]). The use of definable and changeable spectral filters or spectrographs allows spectral resolution to be defined to within 10 nm. Driving the development of airborne remote sensing instruments, such as the Compact Airborne Spectrographic Imager (CASl; Anger et al. 1994), is the capacity to mobilize quickly at opportunist times and at user-specified locations. Speed and flexibility of response are important considerations in data acquisition. For example, in monitoring forest health, infestation and infection are often linked to variables such as disturbance, infecting agents, and the drought phenology of a particular forest type (Stone 1996). The seasonal date of image acquisition is an important factor in maximizing the discriminating potential of algorithms for image interpretation (Treitz and Howarth 1996; see Leckie and colleagues [1995] for a summary of image processing issues).

High spatial resolution data have recently become available from commercially operated satellite systems. Satellite-borne high-resolution sensors allow for the collection of data from a stable platform, at regular time intervals, with a relatively large footprint size. For example, the IKONOS system, launched in September 1999, collects panchromatic data (with a spectral range of 450 to 900 nm) with approximately 1-m spatial resolution and four channels of multispectral data (blue, green, red, and near-infrared) with approximately 4-m spatial resolution over a swath 11 km wide. The QuickBird satellite, launched in October 2001, collects panchromatic data (also 450 to 900 nm) with approximately 0.61-m spatial resolution and multispectral data (blue, green, red, and near-infrared) with approximately 2.44-m spatial resolution over a swath 16.5 km wide. Listings of current and proposed high-resolution satellite sensor systems may be found in Glackin and Peltzer (1999), Franklin SE (2001), Donoghue (2000), and Aplin (2003).

Applications
A wide range of applications for high spatial resolution data, including the remote measurement of structural attributes, may be applicable to ecological issues. In some instances, remotely collected data is combined with other commonly used data sources to better portray ecological attributes.

Forest structure. The extraction of information on forest structure from airborne or satellite data at high spatial resolution has been the subject of a large number of experimental and empirical studies. One approach has been based on per-pixel classification or regression analyses in which the spectral data are used to predict classes or continuous variables of structure. Some examples include the following:

- Conifer species composition and forest cover classification (Franklin SE et al. 2000, Key et al. 2001).
- Prediction of stem density and stand height (Franklin SE and McDermid 1993) and of stand volume and basal area (Walder et al. 2002).

The utility of these studies has been in developing an understanding of which forest attributes and which sensor systems might be integrated into an operational system for the collection of forest inventory data. Because of the high in-
vestment that the forest industry and government agencies make in producing vegetation inventories, it is unlikely that any single method of digital remote sensing could be used to replace operational inventories entirely. Instead, remotely sensed data must be considered at multiple scales together with, or as a complement to, the existing system for forest data collection. The estimation of crown closure on a continuous scale, rather than from the ordinal class data typically obtained by interpreting aerial photographs, is one advantage of a digital remote sensing approach (St-Onge and Cavayas 1997); the integration of remotely sensed data with multitemporal data or with data from other sources, such as lidar (light detecting and ranging), is another (Lefsky et al. 2001, Lim et al. 2003). A third possibility is the hierarchical nesting of image data to represent different scales of forest information, from individual trees to stand-level conditions, forest ecosystems, and larger areal units (Marceau et al. 1994).

A promising approach to image processing or information extraction has focused on the use of texture variables and vegetation indexes computed using spatial domain and different band combinations of image data at high levels of spatial detail. Applications have included assessment of forest productivity and crown gap (Blackburn and Milton 1997), monitoring of forest health (Lévesque and King 2003), and LAI estimation (Wulder et al. 1998). Combining the per-pixel approach with spatial- or texture-processing approaches has been shown to provide additional accuracy in the estimation of forest structure variables such as crown closure, LAI, and stand age (e.g., Franklin and McDermid 1993, Wulder et al. 1996a).

A relatively new approach—commonly considered part of the emerging model of “image understanding” (Guindon 1997)—has been developed on the basis of algorithms for the recognition of individual trees (Gougeon 1995a, Meyer et al. 1996, Culvenor 2003). The incentives for developing such an approach are obvious. The isolation of individual tree crowns on digital images creates the potential for more accurate classification of tree species, allowing researchers to construct area compilations of crown closure and stem density (as illustrated in figure 1). In turn, these estimates can be used in modeling of stand volume (Hall et al. 1998). Several methods have been developed for isolating individual tree crowns (Culvenor 2003), and their relative merits continue to be tested in a variety of forest environments. Such individual tree information is best considered as a sampling tool within the spatially explicit operational forest inventory. Images at high spatial resolution are data-storage and data-processing intensive when considered as a tool for managing forests at

Figure 1. Example of species classification and regrouping of individual tree crowns and tree clusters into structurally homogenous units, akin to forest inventory polygons. Individual tree isolation (Gougeon 1995a) and classification (Gougeon 1995b) were applied to IKONOS imagery at 1-meter spatial resolution. The study was located in the Lac à l’Ours region of Quebec, Canada.
the landscape level. Sampling of high-resolution images to
develop continuous estimates of stand attributes at the
single-tree level may be a viable approach for short-term
implementation of this technology.

**Forest biophysical data.** Biophysical data include measures of
forest ecosystem productivity, structure, and amount of veg-
etation. Typically, the measures of interest include LAI, above-
ground forest biomass, and NPP (Wulder 1998). The first of
these measures, LAI, has been defined as one-half of the to-
tal intercepting area per unit ground surface area (Chen and
Black 1992). An important measure of vegetation structure,
LAI is thought to govern many physical and biological
processes (e.g., photosynthesis, transpiration, evaporative-
transpiration) related to vegetation dynamics (Chen et al. 2002).
Forest biomass, or the dry mass of live plant material, is a measure
used in studies of forest ecosystem processes and in models
that calculate or forecast carbon budgets (Price et al. 1997, Kurz
and Apps 1999). Finally, NPP is the change or accumulation
of foliage, branch, stems, and root biomass over time. Estimates
of NPP are often based on ecological models that require
detailed inputs, many of which are feasible only when acquired
by remote sensing. Detailed maps of the magnitude and
spatial distribution of biomass are also required for these
estimates (Bernier et al. 1999, Fournier et al. 2000) but are
often impossible to acquire using coarse spatial resolution data,
because of mixed pixel effects and scaling relationships from
the field to large-area image mosaics (Chen et al. 2002).

Regional maps of LAI are routinely produced using satel-
lite data at medium or coarse spatial resolution (Spanner et
al. 1994, Fassnacht et al. 1997, Chen et al. 1999), but LAI
maps for a local area, individual stand, or tree are possible only
with high-resolution data (Gong et al. 1995, Hu et al. 2000,
Pellikka et al. 2000). Uncertainties and errors in LAI estima-
tion may occur because of the influence of understory vege-
tation, background reflectance, image registration, differences
in time between field measurements and image acquisition,
and insufficient spatial resolution to resolve land surface
variability. These uncertainties are resolved more readily with
high-resolution airborne or spaceborne data because of the
greater flexibility in timing of data acquisition and the
increased pixel size. The process of LAI mapping usually starts
with the measurement of LAI in the field. Destructive sam-
ing for direct LAI estimation is time-consuming and costly
(Cutini et al. 1998). Indirect, optical methods are often em-
ployed, as they can offer more rapid and consistent estimates
of leaf area at scales larger than the individual tree (Fournier
et al. 2003). From these field-based estimates, statistical mod-
els are developed to estimate LAI as a function of a spectral
measure (e.g., vegetation index) (Chen et al. 2002).

Image preprocessing is necessary when using any image
to estimate LAI. Geometric registration, conversion of image
radiance to reflectance, and correction for bidirectional
reflectance help improve the relationship between the image
and LAI (Chen et al. 1999). Stratification of images by land-
cover class has also been recommended as an approach to
improve LAI estimation over the landscape (Wulder et al. 1998,
Turner DP et al. 1999). High spatial resolution data have also
been used in scaling LAI to coarser-resolution data for map-
ing at regional and large-area levels (Fernandes et al. 2002,
Hall et al. 2003).

Interest in biomass estimation and mapping has grown for
a variety of reasons, including the national and international
commitments to reporting indicators of forest sustainability
(Chen et al. 1999). Previous mapping efforts based on
inventory data or on satellite data at coarse spatial reso-
lution (Penner et al. 1997, Brown et al. 1999) are useful for
meeting national reporting needs, but these methods are not
suited to detecting change and are too broad for many of the
forest management applications that are of increasing inter-
est (Franklin SE 2001). One approach has been to develop
models that estimate aboveground forest biomass as a func-
tion of inventory data; these models can be scaled to regional
and national levels (Bonner 1982). Because of the effect of im-
age calibration on model parameters, empirical models are
based on image-by-image calibration requirements. There are
limitations to the extent that this can be achieved at the lev-
els of accuracy required for satellite data. However, satellite data
at coarse spatial resolution can be used for the initial classi-
fication and stratification of the landscape, from which
higher-resolution airborne or satellite data might logically be
used to derive more detailed structural elements of a stand.
Recent studies with scanning lidar sensors show promise for
aboveground biomass estimation (Lefsky et al. 1999). A com-
bination of lidar data with optical data at fine spatial resolu-
tion may be used to derive the elements of stand composition
and structure at the level of detail required to permit ac-
curate biomass estimation and mapping.

Some airborne sensors can be configured to collect hyper-
spectral imagery at high spatial resolution. The CASI, for
example, can obtain imagery in 10 to 12 spectral channels at
60-cm spatial resolution, or in up to 196 channels at 20-m spa-
tial resolution from the same flying height. Hyperspectral
data can be collected at higher spatial resolution if the sen-
sor is configured to collect fewer channels (the trade-offs are
presented by Wulder and colleagues [1996b]). This combi-
nation of high spectral and spatial resolution allows for de-
tailed physiological information on the status of the forest
canopy or individual trees. Recent work has suggested that hy-
perspectral data at high spatial resolution can be correlated
empirically with the following:

- Chlorophyll pigments (Curran et al. 1997, Coops et al.
  2002).
- Band ratios, including wavelengths representing
carotenoids and chlorophyll (Peñuelas et al. 1995).
- Anthophyll cycle pigments and related photosynthetic
  performance (Gamon et al. 1992), and other measures
  of integrated leaf stress (Carter 1994).
Advances in the understanding of leaf physiology and spectral reflectance suggest that foliage health indicators may be developed on the basis of observations from hyperspectral data and from remotely sensed data at high spatial resolution (Zarco-Tejada et al. 2000). Reviews of imaging spectroscopy for ecological applications can be found in Curran (2001) and Ustin and colleagues (2004).

**Emerging methods and applications.** In addition to individual tree–based and inventory-based assessment of forest and vegetation attributes, a wide range of plot-based assessments of vegetation structure, including structural diversity, land cover, classification of habitat diversity, and within-stand variability, can be determined from imagery at high spatial resolution. Of the wide variety of methods and successful applications, five are cited here:

1. Standard image-based, per-pixel or texture classifications used to extract land-cover classes in mixed-wood and boreal forests (Franklin SE et al. 2000).

2. An image classification approach used to classify 1-m multispectral imagery into a number of land-cover types associated with conifer habitat in an alpine environment (McGregor 1998).

3. Habitat classification (coastal, marine, and wetland) using hyperspectral imagery at high spatial resolution (Marcus 2002), 4-m multispectral IKONOS imagery (Mumby and Edwards 2002), and multitemporal IKONOS imagery (Dechka et al. 2002).


5. Fitting of spatial statistical models such as semivariograms to represent forest structure (Lévesque and King 2003).

In this last approach, the semivariogram range, sill, and nugget are fitted to image objects and interpreted (Treitz and Howarth 2000). In seven mixed-wood stands in Alberta, Canada, Zhang and colleagues (2003) improved the accuracy

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**Figure 2.** Schematic representation of three forest plots, each with varying complexity in terms of vertical distribution of live and dead biomass: (a) a young (regrowth) forest, (b) a mature forest, and (c) an old-growth forest. To the left are typical remotely sensed images at high spatial resolution over similar forest types; to the right are photographs representing each general category. The ability to resolve individual features in an image, combined with the image’s texture, provides an indication of the forest’s structural characteristics and of the vertical distribution of biomass.
of forest species classification by more than 10% using texture obtained from kriging surfaces that they derived from imagery at high spatial resolution. Earlier, Bowers and colleagues (1994) used spatially detailed airborne sensor data to model balsam fir damage caused by insect infestation. Coops and Catling (1996) used a modified local variance method that assessed changes in the standard deviation of a moving 3 × 3 window on successively spatially degraded images. They developed a relationship that related the maximum level of variance observed to the vertical distribution of biomass within a forested canopy (see figure 2 for an example). The assessments were applied to estimate mammalian distribution and abundance over large areas (Coops and Catling 2002). These studies demonstrate that, by capturing the inherent image variance on a pixel-by-pixel basis, data from images at high spatial resolution can significantly improve the description, classification, and interpretation of patterns of vegetation.

Data integration. The integration of data from differing sources enables the generation of complex or derived ecological attributes. For instance, a third dimension can be incorporated into traditional two-dimensional remotely sensed data by using lidar (Lefsky et al. 2002) or radar data (Treuhaft et al. 2004). The integration of remotely sensed data into models can provide for model parameter initialization, incorporated as condition or state variables, or for validation of model outcomes (Coops and White 2003, Turner DP et al. 2004).

Remotely sensed data can convey information regarding the amount, distribution, structure, and condition of vegetation. The integration of remotely sensed data with other spatial data sources and models provides a powerful approach for generating ecological information. One example of such an approach is the US Geological Survey’s National Gap Analysis Program, or GAP (Jennings 2000), in which remotely sensed data with differing spatial resolution (i.e., Landsat, aerial videography, and photographs), spatial data (e.g., soils, elevation), and modeling are combined to produce detailed information on vegetation cover for maps of the United States.

Conclusions

Choosing which remotely sensed data to collect over forests for ecological studies and management is a function of what is needed and what is possible within the economic models that currently dominate forest assessment and planning. These needs are changing, and information resources are expanding. Remotely sensed data at high spatial resolution are available from a wide range of sensor and platform configurations, including analog aerial photography, digital aerial photography, video and digital cameras, and multispectral airborne and spaceborne sensor systems. The multitude of possible sources for high-resolution images is increasing the possibilities for extracting detailed information about forest structure, function, and ecosystem processes.

The extraction of structural and biophysical information about forests from imagery at high spatial resolution requires nontraditional approaches to digital analysis and, often, the careful use of complementary data such as lidar. Lidar provides unprecedented accuracy in estimates of forest biomass, height, and the vertical distribution of forest structure. To enable characterization at the landscape level, samples of remotely sensed data at high spatial resolution may be combined with more spatially extensive, yet less detailed, information sources such as Landsat or existing GIS (geographic information system) inventory databases.

One emerging role of data at high spatial resolution is the precise estimation of forest biophysical data within units of land cover. Combining estimates of remotely sensed attributes with the analytical utility of GIS and advanced forest process models is a powerful means of generating information that describes forests. This combination of methods contributes to better understanding of the influence of disturbances, management practices, and changing climate on the sustainability of forest ecosystems. The applications reviewed here suggest that timely spatial characterization of forest condition, extent, and structure is possible when using high-resolution data from airborne or spaceborne platforms as an information source. We expect continuing refinements to the need for information to characterize forest ecosystems, a need that may be addressed, in part, by the increasing availability of remotely sensed data at high spatial resolution. In attempts to understand ecological processes more fully, from the leaf to the globe, the sampling, scaling, and stratification of remotely sensed data at high spatial resolution are likely to play a key role.

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References cited


Heidelberg (Germany): Wichmann Verlag. (13 April 2004; www.ifp.uni-stuttgart.de/publications/phsw09/halsways99.pdf)


CCFM (Canadian Council of Forest Ministers. 1997. Criteria and Indicators of Sustainable Forest Management in Canada. Ottawa (Canada): CCFM.


