Optical Remote Sensing for Forest Area Estimation

The air photo dot-count method is now widely and successfully used for estimating operational forest area in the USDA Forest Inventory and Analysis (FIA) program. Possible alternatives that would provide for more frequent updates, spectral change detection, and maps of forest area include the AVHRR calibration-center technique and various Landsat Thematic Mapper classification algorithms. Should a switch from proven technology be advised, our general recommendation is to conduct several pilot studies that would focus on developing or refining tools and methodologies to allow objective, repeatable, and accurate forest area estimation using multispectral earth resource satellite data.

By Randolph H. Wynne, Richard G. Oderwald, Gregory A. Reams, and John A. Scrivani

As we start the 21st century, satellite remote sensing is not commonly an integrated component of forest inventories. As has been noted (Wynne and Carter 1997; Holmgren and Thuresson 1998), this situation stems in part from the often poor match between the information that can be objectively and accurately derived from satellite data and the information needed for forest management. At the same time, the remote sensing community has the tendency to oversell the promise of each new sensor that comes down the pike. Although engineering new and better spaceborne sensors is likely to solve many issues in both the short and the long term, many difficulties have arisen from our not having answered some fundamental questions about our goals.

Forest area estimation is an important part of most regional forest inventories. Aerial photography is often used-successfully-to estimate forest area. However, as reasons mount to replace this proven technology with satellite remote sensing, we have not reviewed our goals. Do we want accurate maps or reliable area estimates or both? For what level or type of planning-operational, tactical, or strategic-is the information required? We can answer these questions only if we understand both current and likely uses of remote sensing for forest area estimation.

Remotely sensed images can be divided, roughly, into fine, medium, and coarse resolution, represented by aerial photographs, earth resource satellite (e.g., Landsat) imagery, and weather satellite imagery, respectively. In this article we discuss the advantages and disadvantages of each of the choices for area estimation for regional forest inventories, with particular reference to the USDA Forest Service Forest Inventory and Analysis Program (FIA; for the history of FIA and details on the current program, see Frayer and Furnival 1999).

Aerial Photography

Historically, FIA has produced area estimates of forest type from a variation of double sampling (Chojnacky 1998; Reams and Van Deusen 1999). Aerial photo sampling is used to estimate forest area. Ground plots provide the basic estimates of volume, increment, and yield. A brief description of these two components follows.

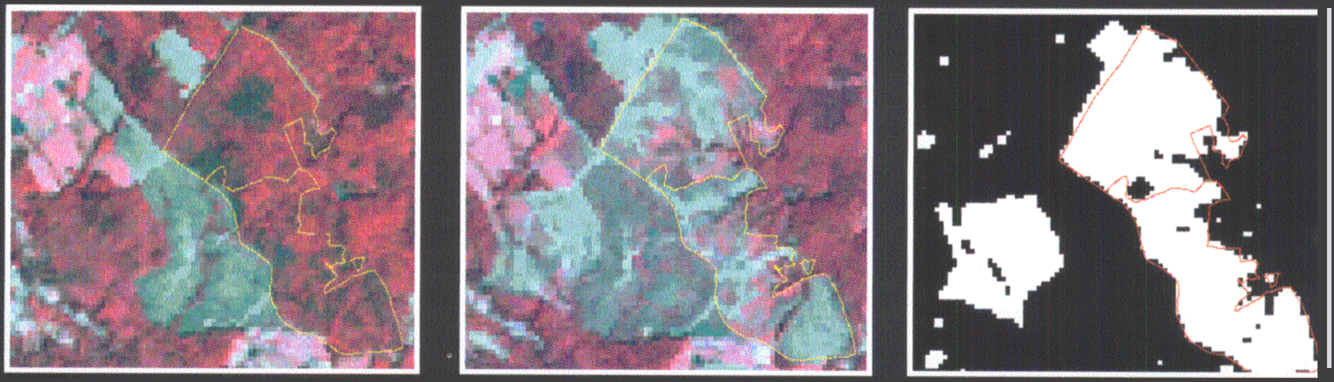


Figure I. Spectral change detection using **Landsat** TM. The image an the left shows a portion of Louisa County, Virginia, on October I, 1994. The image in the middle was acquired September 30.1996. Both are path 16, row 34,with band 4 shown in red, band 3 shown in green, and band 2 shown in blue. The sites of two harvests known to have occurred between the two dater are outlined in yellow. The image on the right is the result of subtracting the first principal component of the 1994 image from the first principal component of the 1996 image, then thresholding the resulting change image. The harvested areas are shown in white, the known harvests are outlined in red. Note that an additional harvest has been identified in the lower left.

Forest area estimation. FIA has traditionally estimated forest area with a two-phase sample. In the first phase, plots are centered on a systematic grid of points placed on aerial photos (primarily at 1:40,000 scale from the National Aerial Photography Program) with a density (in the Southeast) of approximately one point per 230 acres (Frayer and Furnival 1999). These plots are then classified into forest or nonforest by photo interpretation. The current definition of forest in FIA is land at least 10 percent stocked by forest trees of any size, or formerly having had such tree cover and not currently developed for nonforest use. The minimum area considered for classification is one acre. Forested strips must be at least 120 feet wide.

In the second phase, a subsample of the first-phase sample points is visited on the ground to confirm the classification. The sample of ground points enables the calculation of the standard error of the estimate.

Permanent plots for continuous forest inventory. Besides confirming forest and nonforest classification for forest area estimation, the second-phase ground samples are used to estimate tree and stand level attributes. In the Southeast, each plot consists of a cluster of four subplots totaling one-sixth acre. The current system in the Southeast (soon to be replaced by one based on a hexagonal grid) is a 3-by-3-mile grid of ground plots and a 3-by-6-mile grid of ground reference plots (also called intensification plots). This results in 173.6 ground plots and 86.8 intensification plots (used to correct area estimates) per 1 million acres. Combined, there are thus 260.4 (173.6 + 86.8) ground reference samples per million acres and 4347.8 photo interpretation points per million acres, resulting in an approximate 6 percent field check of the photo classification. For the annual inventory, only one-fifth of the present number of plots are remeasured in any one year. In some states, precise geographic coordinates are obtained for the permanent ground plots using global positioning system (GPS) technology, though these plot locations are not publicly available because of landowner agreements.

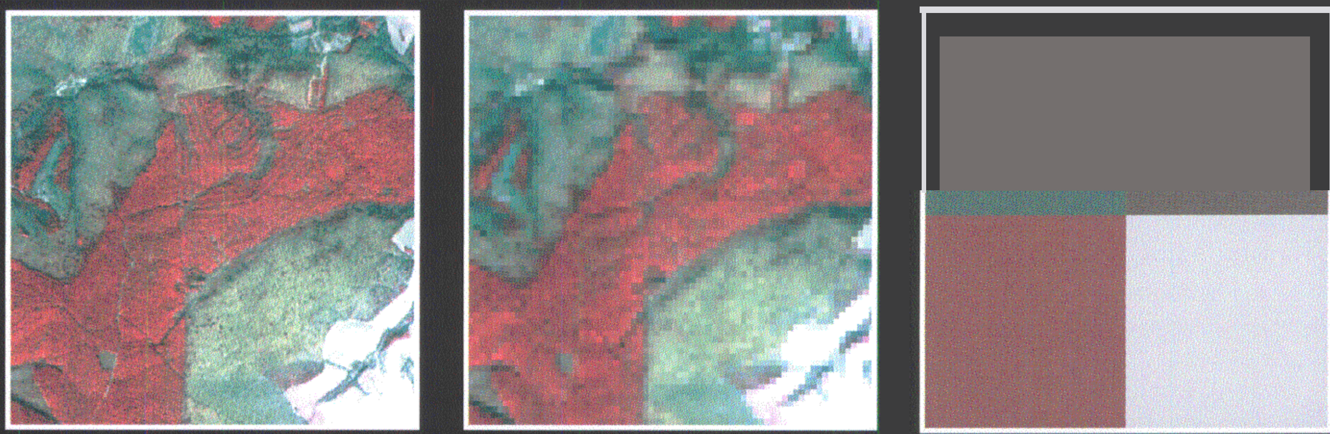
Table 1. Characteristics of NOAA-14 and NOAA-15 AVHRR and Landsat 7 ETM+.

	AVHRR	ETM+
Orbit type	sursynchronous	sursynchronous
Nadir ground resolution (m)	1,100 (all bands)	15 (panchromatic) 30 (multispectral) 60 (thermal)
Repeat coverage interval (days)	0.5	16
Swath width (km)	2,400	185
Quantization (bits)	10	Best 8 of 9
Band 1 (pm)	0 58–0.68	0.450–0.515
Band 2 (pm)	0.72–1.10	0.525–0.605
Band 3 (µm)	3.55–3.93	0 630–0.690
Band 4 (µm)	10.30–11.30	0.750–0.900
Band 5 (pm)	11.50–12.50	1.550–1.750
Band 6 (pm)	NA	10.400–12.500
Band 7 (µm)	NA	2.090–2.350
Panchromatic band (µm)	NA	0.520–0.900

Why Change?

The use of air photos to estimate forest area in phase 1 is proven and reliable. What, then, drives us toward satellite remote sensing? Among the reasons, unfortunately, is that it is available and trendy—an avant garde (and often highly subsidized) high

Figure 2. Spatial resolution of optical sensors. leaf-off Airborne Terrestrial Applications Sensor (ATLAS) is shown at original 4 m resolution (left) and degraded to resolutions of Landsat TM (middle; 30 m) and AVHRR (right; 1,110 m). The ATLAS images were acquired on March 17, 1999, over a forested portion of Appomattox-Buckingham State Forest in Virginia. ATLAS channel 6 is shown in red, channel 4 in green, and channel 2 in blue.



technology (e.g., Meyer and Werth 1990). However, there are other, more defensible reasons to use digital imagery, particularly satellite images. These include (but are not limited to) the following:

- The long-term viability of the National Aerial Photography Program (and comparable programs in other countries) is always in question.
- Satellite imagery provides an opportunity for more frequent updates.
- Certain analyses important for forest inventory (such as spectral change detection to improve removal estimates; see *figure 1*) can be more easily performed.
- A spatially explicit enumeration of the entire landscape—a map—can be produced in a more automated fashion. Provided the map produces good area estimates, it can be used to estimate stratum sizes and compute ground-plot expansion factors.

Moreover, it is the need for a spatially explicit enumeration of a constantly changing landscape that drives much of the use of satellite remote sensing. Unfortunately, however, a land cover classification that is assessed as 80 percent accurate is usually a hard-to-hit target. This is not to say that such maps are not useful for forest area estimation, but there are losses in statistical efficiency as thematic map accuracy decreases. The fact that we accept the degree of error present in most classifications is a testament to our real need for a map—any map. Far-reaching decisions are often made without due regard to the aggregate or spatially specific error present in this one data layer in a geographic information system, much less how that error propagates through analyses requiring multiple data layers. Calling this situation acceptable has, at times, prejudiced end-users against remote sensing (e.g., Ryerson 1989).

So what is required? We must recognize, at the outset, the application-specific limitations of particular sensors, particularly for operational use. This, in conjunction with knowledge of organizational planning needs and corresponding information requirements, should allow us to make the best choices for our organizations. The current optical spaceborne sensors most likely to supersede air photos for regional forest inventory are the advanced very high resolution radiometer (AVHRR) aboard the polar-orbiting weather satellites of the National Oceanographic and Atmospheric Administration (NOAA), and the Thematic Mapper (TM) or Enhanced Thematic Mapper Upgrade (ETM+) aboard the Landsat series of satellites.

The moderate-resolution imaging spectrometer (MODIS) aboard the NASA Terra platform (launched on December 18, 1999) has a spatial resolution similar to that of the AVHRR but much improved spectral resolution: The AVHRR has only two nonthermal bands but MODIS has 20. In addition, several new satellite sensors, including hyperspectral, high resolution, and active (radar and lidar), are scheduled for launch in the next two years and will be acquiring data suitable for regional analyses. Although these and other sensors bear mentioning as having some potential utility to forest managers, we focus on operational sensors with tested data and algorithms.

AVHRR

The principal US meteorological satellites are the polar orbiters and the geostationary operational environmental satellite series of satellites, both operated by NOAA. Of the two, the sensor most useful for forest area estimation is the AVHRR. The most germane characteristics of the AVHRR are shown in *table 1*. This weather satellite has some unique characteristics that make it a likely candidate for regional forest and nonforest stratification and regional forest area estimation. Among its advantages are the historic and planned continuity of the data stream, the high temporal resolution of the sensor, and the large swath of the sen-

Error Estimates Using Thematic Mapper Data

Forest type maps should be accompanied by an estimate of error.A map without an error estimate is lib: a point estimate with no variance:We have a bet but no odds. Contingency table analyses are often used to develop error estimates, but the type of estimate that should be used depends on the sampling scheme used to collect the data.We use double sampling to estimate type area totals, where the least accurate but most plentiful data, phase I, are the map itself, and the more accurate and more expensive data, phase 2, are derived from ground checking of the map types.

Data can be collected from the map in two ways: simple random sampling from the points on the map, or stratified random sampling where the strata are map types.The Southern Annual Forest Inventory System uses simple random sampling, and the example below is based on this sampling method.

For phase I estimates the marginal proportions for the two types of forest and nonforest are known from the classified image. If the type classifications were without error, the area by type would simply be the total number of census acres for the area multiplied by the marginal map proportions. However, the marginal proportions cannot be assumed to be 'correct. The corrections come from phase 2, a sample of ground truth locations selected on the map.

The classification results of a Thematic Mapper (TM) scene from central Georgia indicate that the marginal proportions for the two map categories are 68.52 percent for forest and 3 I .48 percent for nonforest (table 2). Using methods specifically developed for known map marginals (Card 1982), the true marginal proportions for forest and nonforest can be estimated as follows:

Proportion forest = 0.6852(30 I/337) + 0.3 148(40/ 153) = 0.6944

Proportion nonforest = 0.6852(36/337) + 0.3 148(I 13/I 53) = 0.3056

The variance of percent forest (pf) is as follows:

V(pf) = (.6852 – .6 I200356)(.6 I200356)/335.78 + (.3 I48 – .082300654) (.082300654)/I 54,252 = .0002574722

This is how several numbers in the above formula are derived:

(30 I/337)(.6852) = .6 I200356

.6852(490) = 335748

(40/I 53)(.3 I48) = .082300654

.3I48(490) = 154.252

The interval estimate of percent of forest is 0.6944 ± 2 √(.0002574722). If we carry out the mathematical operations, the 95 percent interval estimate for percent forest is .6944 ± .03209188.

Table 2. Contingency table for TM map categories and forest inventory and analysis ground plots (truths).

	TM map categories		
True	Forest	Nonforest	Total
Forest	301	40	341
Nonforest	36	113	149
Total	337	153	490
Map marginal proportions	0.6852	0.3148	

NOTE: The figures represent FIA ground plots and classified TM pixels in eight counties in central Georgia. This example is based on only 490 ground plots, but there would typically be several thousand in an operational setting.

sor. The principal disadvantages are the large pixel size (1,100 meters at nadir; *fig. 2, p. 33*), the low spectral resolution (only two nonthermal bands), and difficulties in classifying forest cover using the current USDA Forest Service definition. As an example of the last point, recent cuts would probably not be classified as forest, even though this will likely be a problem with analyses of single-date imagery from all medium- to coarse-resolution sensors in a landscape where agriculture and forestry are interwoven. Another example is the tendency for low-density residential developments with trees to be mistakenly classified as forest.

Zhu and Evans (1992, 1994) and Lannom et al. (I 995), refining methods developed by Iverson et al. (I 989), have demonstrated the utility of low spatial resolution (AVHRR) data for determining the forest cover of a region. In this hierarchical, subpixel calibration-center approach (Iverson et al. 1994), a TM scene for each physiographic region within the AVHRR image is classified into forest and nonforest categories. After registration to the AVHRR image, the classified TM scenes are used to compute percent of forest cover for the AVHRR pixels covered by the TM scenes. The relationship between percent of forest cover and AVHRR brightness values within each region is modeled using multiple linear regression. Finally, the resulting model is used to predict percent of forest cover for the remaining pixels. Lannom et al. (I 995) tested the percent of forest determined by this technique against the dot-count photo method in three Louisiana parishes and found no significant difference between the two.

The high temporal resolution of AVHRR data allows the analyst to choose both optimal spectral bands and dates-and to take advantage of seasonality to define forest and nonforest. If only one scene is analyzed (as is typical in the calibration-center approach), an early spring scene after leaf-out is usually best in areas with a mosaic of agriculture and forestry land uses, because the bare fields are spectrally distinct from forest cover. It is often not so easy to obtain a high-quality, cloud-free TM scene in this precise temporal window for a particular year and physiographic region.

Unfortunately, although this technique would likely improve both the timeliness and the statistical efficiency of forest area estimates-and could even assess the forested area of fragmented landscapes-the low spatial resolution of AVHRR (and similar) data makes the resulting maps unsuitable for landscape indicators (e.g., patch size, shape, and connectivity) of forest fragmentation and habitat suitability needed by resource managers (Holmgren and Thuresson 1998). In addition, because the calibration-center method predicts percent of forest cover for each pixel, single ground plots, which cover only a tiny portion of the pixel, cannot be used effectively to generate estimates of precision (standard errors). (Conceptually, however, a sample of plots within a precisely located AVHRR ground resolution cell could be used to generate estimates of precision.) Better maps and standard errors of the area estimate (see "Error Estimates Using Thematic Mapper Data," p. 34) can be obtained by determining forest area from sensors on the Landsat satellites.

Thematic Mapper

The principal earth resource satellites in the United States are the Landsat series. Although this discussion refers to data from these satellites, similar data from current systems (e.g., sensors aboard the French Satellites Pour L'observation de la Terre and Indian remote sensing satellites) and future systems should be considered implicit surrogates for Landsat data. Details of the ETM+ sensor (Landsat 7) are presented in *table 1*. The multispectral sensor has six nonthermal bands-three in the visible, one in the near infrared, and two in the midinfrared, all with 30-meter spatial resolution *(fig. 2)*. On the ETM+ a 15-meter panchromatic band has been added. Advantages of TM data for regional-scale forest area estimation include the historic and planned continuity of the data stream, moderate spatial resolution of the sensor, moderate spectral resolution of the sensor, and ability to compute standard errors of area estimates (Card 1982; see "Error Estimates Using Thematic Mapper Data"). The principal disadvantages include the low temporal resolution (particularly given the cloud cover in some regions), spectral resolution that may be too low for most uses to which the sensor is applied, relatively high data volume for regional scale assessments, and (like the AVHRR) difficulties in classifying forest cover using the current USDA Forest Service definition.

Despite some drawbacks, the TM and ETM+ sensors aboard the Landsat satellites have been (and will be) widely used for forest assessment and inventory. Thus there is a vast body of literature on classification algorithms, including unsupervised, supervised, and various hybrid approaches. These classification techniques are tangential to this article, whose focus is whether the sensor shows promise for operational integration into regional forest inventory systems. And the answer to that question is, simply, yes. In fact, TM data are already being used for forest area estimation and forest change detection in the annual forest inventory system of the USDA Forest Service North Central Region. The Gap Analysis Program (USGS Biological Resources Division) TM classification is being used to estimate forest area in the current inventory of Indiana (Dennis May, pers. commun.). And TM data are being used to operationally map vegetation in approximately 50 million acres in Washington and Oregon.

Bauer et al. (1994), in a study in northeastern Minnesota that preceded operational implementation of the annual forest inventory system, used TM data in a double sampling approach to estimate forest area in five counties. By using an inverse calibration approach to adjust for calibration bias (which assumes the image classification is without error because it is invariable), they underestimated forest area by 3 percent or less compared with the independent USDA Forest Service estimates for each county. Though no statistical comparison was done, one can compute a standard error from a classified TM scene (e.g., Card 1982; see "Error Estimates Using Thematic Mapper Data"). Additional categorical specificity reduced the reliability of the area estimates for certain categories.

That last point is one we feel obligated to address in detail. Although TM data can and have been used for reliable forest area determination, classification accuracy is significantly reduced and the analyst's effort greatly increased when classification is attempted beyond forest and nonforest to more specific forest types (e.g., deciduous, coniferous, and mixed, and especially for species associations within deciduous and coniferous forests). Practical experience has made this apparent to many of us over time, and now a decade of research using hyperspectral data for "well-behaved" geological applications has shown that the low inherent spectral dimensionality of TM data may be at fault in some instances, particularly at a spatial resolution resulting in many mixed pixels. However, many species are indistinguishable at any spectral resolution (e.g., Van Aardt and Wynne 2000), a problem exacerbated by complex spatial structures and diverse mixtures of species.

Even when a binary forest-nonforest classification is all that is required, it is often difficult to exceed 85 percent accuracy on a per-pixel basis. By comparison, experience at the USDA Forest Service Southern Research Station indicates that photo-based forest-nonforest interpretations often have accuracies of 95 percent or greater. Although the low spectral dimensionality may be a factor, there are other ways that classification accuracy can be improved. Just as we must move away from the paradigm of using only in situ sampling for forest inventory, remote sensing analysts must move away from routine classifications based entirely on differences between brightness value vectors in individual pixels. This means, for example, more routine use of multitemporal data: other spatial data, such as digital elevation models, tax maps, soils maps, and the like; and prior information about the landscape (e.g., whether the area was a forest the last time we checked).

Recommendations

All the techniques under consideration for operational use-the current air photo dot-count method, the AVHRR calibration-center technique, and various TM classification algorithms-are suitable for assessing forest area at a regional scale. Given that the dot-count method is proven and reliable, we must first evaluate the proposed alternatives, AVHRR or TM, for their ability to provide equally reliable information on forest area on an aggregate basis. Assuming this criterion is met, the proposed alternatives must then be evaluated for their costs and benefits.

Both TM and AVHRR data can form the basis for reliable forest area estimates, albeit with some difficulty at times. However, TM classifications (like the dot-count method) afford the possibility of calculating the standard error of the estimate, whereas no acceptable technique for that has yet been proposed for the AVHRR calibration-center approach. Both TM and AVHRR data can form the basis for maps useful for tactical and strategic planning, though maps derived from TM data are more useful in fragmented landscapes (e.g., most of the eastern United States or Europe) or when they are to be used as the basis for calculating expansion factors "on the fly." The tradeoffs between spatial and spectral resolution (higher for TM) and temporal resolution (higher for AVHRR) give TM data the edge for discriminating among material types and conditions. The spectral resolution of TM data also makes it preferred for spectral change detection (*fig.* I). Use of the current USDA Forest Service definition of forest cover will be difficult with data from both sensors in some cases, particularly with recent harvests and forested low-density residential developments.

Organizational needs differ, but our general recommendation is to conduct a series of pilot studies that would use multispectral earth resource satellite data to estimate forest area, recognizing their inherent limitations. This would mean, for example, that Landsat Thematic Mapper or comparable data be used only for separating forest from nonforest, leaving further separation for other sensors or field plots. (With enough data and work, species differentiation in temperate forests is possible, perhaps even with TM imagery (e.g., Wolter et al. 1995), but may more often fail than succeed; in any case, the quantity of data, level of effort, and untimely nature of the resulting information may obviate its utility for most organizations.) These pilot studies would focus on developing or refining tools and methodologies to enable objective, repeatable, and accurate forest area estimation using earth resource satellite data. They should be designed so that the maps of forest area produced as intermediate products (before area correction on an aggregate basis) are accurate enough to benefit forest managers. In addition, reliable information on cost and staffing impacts is needed before implementing any new protocol.

Spaceborne high-resolution, hyperspectral, and active (lidar and radar) sensors potentially suitable for regional area estimation will be launched in the next few years. These will likely make forest area estimation more objective and repeatable even without gains in categorical specificity. As such, we also recommend an active national research agenda that addresses the potential applications of new sensor technologies to forest area estimation. We cannot design current inventory systems around sensors that do not yet exist, but we can be ready to incorporate these data streams into our inventory systems.

Literature Cited

BAUER, M.E., T.E. BURK, A.R. EK, P.R. COFFIN, S.D. LIME, T.A. WALSH, D.K. WALTERS, W. BEFORT, and D.F. HEINZEN. 1994. Satellite inventory of Minnesota forest resources. *Photogrammetric Engineering and Remote Sensing* 60:287–98.

CARD, D.H. 1982. Using known map category marginal frequencies to improve estimates of thematic map accuracy. *Photogrammetric Engineering and Remote Sensing* 48(3):431–39.

CHOJNACKY, D.C. 1998. Double sampling for stratification: A forest inventory application in the Interior West. Research Paper RMRS-RP-7. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station.

FRAYER, W.E., and G.M. FURNIVAL. 1999. Forest survey sampling designs: A history. *Journal of Forestry* 97(12): 4–10.

HOLMGREN, P., and T. THURESSON. 1998. Satellite remote sensing for forestry planning: A review. *Scandinavian Journal of Forest Research* 13:90–110.

IVERSON, L.R., E.A. COOK, and R.L. GRAHAM. 1989. A technique for extrapolating and validating forest covet across large regions: Calibrating AVHRR data with TM data. *International Journal of Remote Sensing* 10(11):1805–12.

———. 1994. Regional forest cover estimation via remote sensing: The calibration center concept. *Landscape Ecology* 9(3):159–74.

LANNOM, K.B., D.L. EVANS, and Z. ZHU. 1995. *Comparison of AVHRR classification and aerial photography interpretation for estimation of forest area.* Research Paper SO-292. Asheville, NC: USDA Forest Service, Southern Forest Experiment Station.

MEYER, M., and L. WERTH. 1990. Satellite data: Management panacea or potential problem? *Journal of Forestry* 88(9):10–13.

REAMS, G.A., and P.C. VAN DEUSEN. 1999. The Southern Annual Forest Inventory System. *Journal of Agricultural, Biological, and Environmental Statistics* 4(3): 108–22.

RYERSON, R. 1989. Image interpretation concerns for the 1990s and lessons from the past. *Photogrammetric Engineering and Remote Sensing* 55(10):1427–30.

VAN AARDT, J.A.N., and R.H. WYNNE. 2000. *Spectral differentiability among six southern Appalachian tree species.* Proceedings, Second International Conference on Geospatial Information in Agriculture and Forestry, Orlando, Florida, January 10–12.

WOLTER, P.T., D.J. MLADENOFF, G.E. HOST, and T.R. CROW. 1995. Improved forest classification in the northern lake states using multi-temporal landsat imagery. *Photogrammetric Engineering and Remote Sensing* 61(9):1129–43.

WYNNE, R.H., and D.B. CARTER. 1997. Will remote sensing live up to its promise for forest management? *Journal of Forestry* 95(10):23–26.

ZHU, Z., and D.L. EVANS. 1992. Mapping midsouth forest distributions. *Journal of Forestry* 90(12):27–30.

———. 1994. US forest types and predicted percent forest cover from AVHRR data. *Photogrammetric Engineering and Remote Sensing* 60(5):525–31.

Randolph H. Wynne (e-mail: wynne@vt.edu) is assistant professor, and Richard G. Oderwald is associate professor, Department of Forestry, College of Natural Resources, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061; Gregory A. Reams is mathematical statistician, USDA Forest Service, Southern Research Station, Asheville, North Carolina; John A. Scrivani is research forester, Virginia Department of Forestry, Charlottesville.

This article was prepared with the support of NASA; the National Council of the Paper Industry for Air and Stream Improvement, Incorporated; the USDA Forest Service Southern Research Station; the Virginia Department of Forestry: and the Virginia Tech Department of Forestry.