Multi-Attribute Vegetation Maps of Forest Service Lands in California Supporting Resource Management Decisions

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Abstract

Vegetation databases (digital maps) for USDA Forest Service lands in California (approximately 10 million ha) have been developed over the last decade using remote sensing and GIS methods. The databases are intended to support national and regional land-cover inventory and monitoring, interagency conservation and fire risk assessment, and wildlife habitat evaluation, as well as more traditional uses including land management planning and forest inventory within each National Forest. The digital maps are fine-scale relative to their extent, being derived from 30-m-resolution Landsat Thematic Mapper (TM) data and digital elevation models (DEMs). Map attributes included a vegetation life form class, a vegetation type, and canopy cover and size class estimates for forested polygons. Land-cover and vegetation type labels were more accurate than forest structure estimates. However, the mapping methodology is not static. New remote sensing data and analysis methods offer some promise to improve map attribute estimation. The database is being provided by the Forest Service to agency personnel, cooperators, and the public.

Introduction

Over the past two decades, land management and regulatory agencies, Earth system scientists, and non-governmental organizations have mounted a growing number of campaigns to develop large-area digital maps of vegetation and land cover (for example Tucker *et al.*, 1985; Goward *et al.*, 1985; Townshend *et al.*, 1987; Loveland *et al.*, 1991; Congalton *et al.*, 1993; Scott *et al.*, 1993; Davis, 1994; Stone *et al.*, 1994; Strahler *et al.*, 1994; Woodcock *et al.*, 1994; Zhu and Evans, 1994; Homer *at al.*, 1997; Gonzalez-Rebeles *et al.*, 1998; Scott and Jennings, 1998). These efforts vary in scale, methods, and the intended use of the products, from inventorying carbon and parameterizing land surface-climate interactions on a global scale, and continental-scale land-cover monitoring, to regional-scale land management, conservation planning, and biodiversity inventory. The databases are developed using increasingly complex procedures that rely on the seamless integration of remotely sensed data, advanced image processing methods, collateral spatial data, and georeferenced field data within a geographic information system (GIS). This paper reports on an integrated remote sensing-GIS project to develop digital vegetation databases for all of the approximately 10 million ha of United States Department of Agriculture (USDA) Forest Service lands in California (Table 1; Figure 1). The mapping methods were developed by university researchers in collaboration with the Forest Service. These procedures are currently being used operationally by the Forest Service and cooperating agencies within California.

The project was innovative in its development of a multi-attribute vegetation database, integrated with other spatially referenced data, to support the land management decisions that are being made based on the Forest Service's current ecosystem management paradigm. The database is being used to support land-cover and ecosystem inventory and monitoring, regional interagency land management planning, forest inventory and health, fire management, and single- and multiple-species habitat assessment, which are discussed below. This paper reviews the procedures used in the mapping project, and presents summaries of the resulting maps and their accuracy. We compare the cost of producing these maps using the current versus traditional methods (air photo interpretation), and discuss developments in remote sensing and geographical analysis that could improve the mapping methods and resulting data products.

Benefits of Multi-Attribute Vegetation Maps for Regional Land Management

The Forest Service is responsible for managing approximately 19 percent of the land area of California. The Forest Service is mandated to integrate its multiple land management objectives (silviculture, timber management, forest health, watershed protection, fire management, recreation, habitat conservation, old growth forest) under the ecosystem management paradigm (Franklin, 1993; Jensen *et al.*, 1996; Kohm and Franklin, 1997), to practice adaptive management (Smith, 1997), and to coordinate with other resource agencies on a regional basis. Therefore, methods were needed to produce a vegetation map with both spatial and categorical detail, and information about forest stand structure, that could be used in conjunction with georeferenced field inventory data and other mapped data to address a range of information needs. The digital maps described in this study include the following attributes: vegetation life form and land-cover type, vegetation type, forest cover (crown closure), and tree size class (discussed below). Three of the most

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Table 1. National Forests in California

National Forest	Ecoregion	Forest Area (ha)	Vegetation Mapping Completed	Accuracy Assessment Completed	Accuracy Sample Size	Lead Mapping Group
Angeles	Southwestern	284,169	1996	1998 FIA plots[1]	254	SDSU
Cleveland	Southwestern	233,323	1994	1998 FIA plots[1]	137	SDSU
Eldorado	Central Sierra Nevada	322,960	1999	(2001)	—	FS RSL
Inyo	Eastern Sierra Nevada	866,847	1994	1996 FIA plots[2]	187	FS RSL
Klamath	Klamath Province	983,377	1998	1999 FIA plots[1]	312	FS RSL
Lassen	Modoc Plateau	646,124	1995	1996 FIA plots[2]	291	FS RSL
Los Padres	Southwestern, Central Coast	796,903	1996	1998 FIA plots[1]	327	SDSU
Mendocino	North Coast	500,302	1997	1999 FIA plots[1]	190	FS RSL
Modoc	Modoc Plateau	846,870	1995	1996 FIA plots[2]	312	FS RSL
Plumas	Central Sierra Nevada	597,927	1993	1994 strat rand samp	165	BU
San Bernardino	Southwestern	326,721	1995	1998 FIA plots[1]	196	SDSU
Sequoia	Southern Sierra Nevada	470,017	1997	(2000)	—	FS RSL
Shasta-Trinity	Klamath, North Coast	1,278,540	1998	1999 FIA plots[1]	395	FS RSL
Sierra	Southern Sierra Nevada	574,163	1996	(2000)	—	SDSU
Six Rivers	Klamath, North Coast	524,853	1997	1999 FIA plots[1]	210	FS RSL
Stanislaus	Central Sierra Nevada	441,866	1991	1992 strat rand samp	121	BU
Tahoe	Central Sierra Nevada	474,807	1989 (update in progress)	(2001)	—	FS RSL
Tahoe Basin	Central Sierra Nevada	134,342	1999	1998 FIA plots[1]	253	BU

Notes:
[1]Fuzzy accuracy ratings for all potential map labels were derived from FIA data using decision rules.
[2]Inventory crew used expert judgement to assign fuzzy ratings to each FIA plot.
Strat rand samp = stratified random sample.

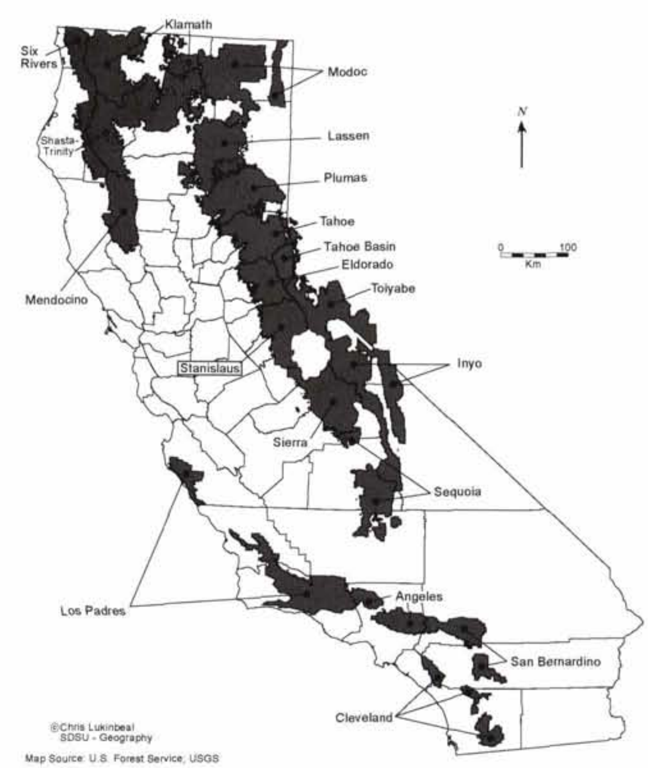

Figure 1. Map of the National Forests in California (county boundaries shown).

important uses of vegetation maps by the Forest Service and other agencies in California are resource inventory and monitoring, fire management, and habitat conservation planning. The following sections describe the current and potential uses of the vegetation maps reported on here in support of these applications, and comment on the aspects of map accuracy that are most critical to each application.

Resource Inventory and Monitoring

As mandated by the Resource Planning Act and National Forest Management Act (**http://www.fs.fed.us/forum/nepa/nfma-law.html**), the Forest Service is required to inventory vegetation resources, monitor forest health, and define allowable timber sale quantities. The Forest Service must report to Congress on the status of National Forest land resources, and use the information to develop national and forest level assessments. This baseline information is essential to any agency or entity that manages large areas of forested land. The vegetation maps described here play a major role in providing this information, particularly with respect to quantifying forest resources. The vegetation types defined in the maps serve to stratify the landscape. Field inventory data are collected according to the protocols of the National Forest Inventory and Analysis (FIA) program (systematic sample design — the plots are located at the nodes of a grid with a 3.4-mi (5.5-km) spacing). FIA plots are aggregated by vegetation types (or map strata) and used to estimate forest resources by species and tree size class. The area estimates from the vegetation maps for each stratum are then used in conjunction with the FIA data to estimate total timber volumes for entire Forests (Table 2), or estimate the area and condition of old growth forests (Beardsley and Warbington, 1996). Thus, the forest mapping effort has contributed significantly to a comprehensive inventory of forest resources on Forest Service lands in California which illustrate tremendous variability in total timber volume and quality of timber resources (i.e., volume per hectare). The vegetation maps also play a critical role in evaluating the resource base for smaller regions within National Forests, such as individual watersheds or Ranger Districts. Timber volume can be estimated for any geographical region of interest from the timber volume per unit area and the map areas for each forest type in the region. Other measures that derive from the FIA plots, such as species composition and forest damage and defects, can be estimated on a regional basis.

An advantage of digitally based forest maps is that they can be updated, using remote sensing and GIS-based methods, to monitor vegetation and land-cover change. The Forest Service Ecosystem Planning and State and Private Forestry divisions, together with the California Division of Forestry and Fire Protection (CDF), are engaged in a five-year, statewide effort to

Table 2. Conifer Area, Total Timber Volume, and Timber Volume per Unit Conifer Area

National Forest	Conifer Area (ha)	Total Timber Volume (m^3)	Timber volume (m^3) per ha
Shasta-Trinity	964,499	128,342,776	133
Klamath	753,625	97,086,874	129
Lassen	477,060	53,441,926	112
Plumas	477,057	75,613,787	159
Modoc	429,190	19,532,578	46
Sierra	383,606	70,146,364	183
Six Rivers	363,490	75,141,643	207
Stanislaus	306,598	43,630,784	142
Inyo	300,461	7,162,417	24
Tahoe	299,624	63,257,790	211
Sequoia	285,475	43,951,841	154
Eldorado	261,459	41,581,681	159
Mendocino	245,066	28,408,876	116
Los Padres	154,719	1,983,003	13
San Bernardino	136,368	4,957,507	36
Angeles	58,332	1,945,231	33
Tahoe Basin	56,260	8,904,627	158
Cleveland	15,583	316,336	20

identity and quantify land-cover changes (Levien *et al.*, 1998; **http://frap.cdf.ca.gov/projects/change_detection/change detectfr.html**). The project entails the integration of a large volume of ground and aerial data, while the vegetation maps provide the baseline information on land cover. Changes that are being mapped include increases and decreases in vegetation cover, which, when used in combination with the vegetation maps, can give information on changes in life form, tree size, and crown closure. The information is intended to support watershed disturbance analysis, timber inventories and sales planning, land-use and habitat management planning, pest-induced tree mortality monitoring, and fire fuel monitoring. Correct identification of patterns and causes of land-cover and canopy change relies heavily on the accuracy of the life form and forest-cover attributes (Stehman and Czaplewski, 1998; Stehman, 1999).

Fire Management

Fire management demands a major investment of resources by the Forest Service, CDF, and other agencies in the fire-prone ecosystems of California (Keeley and Scott, 1995; Keeley *et al.*, 1999). The vegetation maps developed for Forest Service lands comprise a major source of data for an ongoing GIS-based project aimed at mapping fire fuels, according to standard fuel models, for the entire state (**http://frap.cdf.ca.gov/projects/fire_mgmt/fm_main.html**). A map of fire fuel is an important input to fire spread models. Vegetation type and structure can also be used to map fire risk (Chuvieco and Salas, 1996) and the relationship between altered fire regimes, risk from catastrophic wildfire, and air pollution (Stephenson and Calcarone, 1999). The accuracy of the life form attribute is most critical for modeling fire fuels and hazards, followed by vegetation type. These types of analyses are essential for spatial decision support related to fire management, suppression, prevention, and land-use planning related to fire risk.

Species Conservation Planning

The Forest Service is mandated to protect and preserve populations of federally listed threatened and endangered plant and animal species, rare species and communities, game species, and other species of special concern on Forest Service lands. The Forest Service and other agencies are conducting assessments of biological diversity using data developed and analyzed using a GIS (Scott *et al.*, 1993; Scott and Jennings, 1998). Recently, several agencies (Forest Service, California Department of Fish and Game, and U.S. Department of Interior Fish and Wildlife Service) conducted a review of habitat and species conservation issues in the southern California mountains and foothills based on some of the vegetation maps discussed in this paper, as well as other digital mapped data sources (Stephenson and Calcarone, 1999; see also Hansen *et al.* (1993) and SAMAB (1996) for other examples of this type of assessment). In particular, the vegetation maps were used to (1) assess the status, trends, and distribution of terrestrial ecosystems; (2) predict habitat suitability for emphasized wildlife species based on habitat relations models; and (3) examine the relationship between habitat type, forest stand densification, and risk from altered fire regimes (Stephenson and Calcarone, 1999). Vegetation type and forest structure (cover and tree size) are the map attributes key to many habitat models for vertebrates (especially mammals and birds). It has been found that low map accuracies for canopy cover and especially tree size class (Woodcock *et al.*, 1994) can lead to erroneous predictions of habitat suitability (Franklin and Stephenson, 1996).

Database Access for Decision Support

The Forest Service's Pacific Southwest (PSW) Region (California) established the Remote Sensing Lab (RSL) in 1990 for the purpose of cooperative resource mapping and assessment with the CDF. The RSL's mission is to establish common mapping standards across all land ownerships in order to promote inter-jurisdictional resource inventory and planning, and to provide the most currently available data to the National Forests within the Region, their cooperators, and the public. The RSL's primary areas of responsibility include vegetation mapping, inventory, and monitoring on the National Forests (discussed above), and developing GIS data and services to support land management planning within an ecosystem framework. It is also the responsibility of the RSL to provide linkages between their databases and decision support systems used by the agency and its partners. The RSL has developed regional data standards for land management planning GIS layers, and has described these in the Regional Forest Resource Data Dictionary that it maintains. The RSL is also responsible for moving to the National Standards as they are identified under the GIS Core Layer effort. The RSL is assisting the PSW Region to convert to the National Resource Inventory System especially for databases associated with vegetation and soils. Spatial data in their archive are maintained in the UTM projection (zones 10 or 11) for forest-wide coverages, and the Albers equal-area projection for state-wide coverages. GIS data are provided in Arc-exportable format.

The vegetation database, as well as FIA inventory data and a plethora of GIS data and metadata (including map accuracy tables) are maintained by the RSL. The data are currently available online internally within the Forest Service, but will be available to the public via the Internet once the appropriate computer security measures are in place.

Database Design

The purposes for which the maps were intended drove the vegetation database design. The vegetation classification system, CALVEG (Matyas and Parker, 1980; Regional Ecology Group, 1981), is hierarchical with vegetation series nested within broad life-form/land-cover classes (Table 3). It is derived from a regional forest-type classification used in timber management, and Forest Service efforts to develop (1) a classification for use with remote sensing-based mapping and (2) an ecological type classification for vegetation (Gordon and White, 1994). The forest structure attributes — canopy cover and tree size class — were also derived from classifications originally developed to characterize timber resources, but adapted for use in habitat

TABLE 3. SAMPLE OF THE CALVEG CLASSIFICATION SYSTEM FOR AREA SHOWN IN PLATE 1

CALVEG Formation Class (Life Form or Land-Cover Type)	CALVEG Series
Conifer Forest/Woodland (CON)	JP — Jeffrey Pine
	MP — Mixed Conifer — Pine
	PC — Coutler Pine
	DM — Bigcone Douglas Fir
Hardwood Forest/Woodland (HWD)	QK — Black Oak
	QA — Coast Live Oak
	QC — Canyon Live Oak
	QR — Riparian Forest
Chaparral (CHP)	CA — Chamise Chaparral
	CQ — Northern Mixed Chaparral
	CD — Southern Mixed Chaparral
	CS — Scrub Oak Chaparral
	CX — Montane Chaparral
Soft Chaparral (SCH)	SS — Coastal Sage Scrub
	SB — Buckwheat/Sage
Sagebrush Scrub (SCH)	BS — Big Sagebrush
Herbaceous (HEB)	HG — Annual Grassland
	HM — Wet Meadow
Other Land Cover (NFO)	WA — Water
	BA — Bare Ground
	UB — Urban
	AG — Agriculture

Note: This is a small subset of the CALVEG types found in all the National Forests described in the paper.

evaluation and other purposes (Forest Service, 1994). The database structure of the resulting GIS map reflects a hierarchical conceptual model of the landscape. Polygons corresponding to vegetation stands (Woodcock and Harward, 1992; Franklin and Woodcock, 1997) are the fundamental mapping unit. Image processing and GIS modeling are initially pixel-based and the resulting map polygons are actually multiple-pixel "regions" derived from automated image segmentation (Plate 1a; Woodcock and Harward, 1992). The final map is vector-based, produced by generalizing each mapped attribute to segmentation-defined polygons. The result is a stand-based multiple attribute vegetation database of known accuracy. Accuracy assessment results are used for determining priorities for map improvement, and change detection is used to update vegetation maps on a coordinated 5-year schedule.

Remote Sensing Image Processing and GIS Modeling Methods

Historically, the Forest Service in the PSW Region produced maps of general land-cover and forest types as a basis for stratified sampling for timber volume inventory, originally by air photo interpretation and more recently using classification of satellite imagery (Strahler, 1981; Franklin *et al.*, 1986; Forest Service, 1994). New methods, described below, were developed over the course of a 10-year collaboration between the PSW Region, Boston University, and San Diego State University. Our goal was to develop procedures based on state-of-the-art remote sensing, image processing, and GIS modeling that could be operationally used by the Forest Service. The mapping procedures varied slightly among National Forests because regional characteristics of the vegetation varied, calling for greater emphasis on certain features in different areas. For example, discrimination of chaparral shrub types is important in southern and coastal California, while estimation of forest structure is critical in the Sierra Nevada. In this section we summarize this project using the results from the 18 National Forests distributed throughout the major ecoregions of California (Table 1, Figure 1).

The methods used to develop and evaluate the vegetation database have been described in detail elsewhere (Woodcock *et al.*, 1994; Franklin and Woodcock, 1997) and are only outlined here. The primary sources of input data were (1) Landsat Thematic Mapper multispectral imagery, acquired contemporaneously with the mapping (Table 1), i.e., a single summer image (high sun angle and lacking snow cover) for each National Forest or mapping area; (2) digital terrain data from USGS Digital Elevation Models (both TM and the DEMs have a 30-m nominal resolution); (3) FIA and other georeferenced field data; (4) true color resource aerial photography (usually 1:12,000 to 1:24,000 scale); and (5) other GIS data, including National Forest boundaries, roads, forest plantations, hydrography, and fire history. The processing steps are as follows:

(1) Image segmentation (Woodcock and Harward, 1992) is applied to TM data to define the multi-pixel objects used as the basic polygons or map units for all subsequent image processing or GIS modeling steps. The minimum map unit size was specified as ~1 to 2 ha (2.5 to 5 acres), and this value was used to constrain the image segmentation algorithm.
(2) General land-cover categories (vegetation life forms) are derived from unsupervised iterative classification of TM spectral data and texture (Ryherd and Woodcock, 1996).
(3) Vegetation gradient models, developed using field data, are used to predict CALVEG vegetation type labels from terrain variables (elevation, aspect and slope) derived from the DEMs (Franklin, 1995).
(4) A remote sensing canopy model (Li and Strahler, 1985) is used to estimate forest cover based on TM pixel brightness values and their variance within image segments (Woodcock *et al.*, 1997).
(5) Crown size class is estimated using either the canopy model, unsupervised clustering of the TM spectral data, or photointerpretation and on-screen labeling of polygon attributes, depending upon the vegetation type and National Forest.
(6) In several forests, hardwood cover within mixed conifer-hardwood stands was estimated from linear spectral mixture analysis (Smith *et al.*, 1990; Adams *et al.*, 1993; Shimabukuro *et al.*, 1994) based on the TM data and using image endmembers (Plate 1a). In other cases secondary vegetation labels were derived from the frequency distribution of the life form class membership (from Step 2) of pixels within polygons (Woodcock *et al.*, 1996).
(7) All remote-sensing-based methods for estimating stand structure were calibrated against a sample of field inventory plots or photointerpreted stands.
(8) Each attribute was interactively edited based on systematic interpretation of Forest Service resource photography.
(9) Each map was evaluated using a new accuracy assessment method based on "fuzzy sets" (Gopal and Woodcock, 1994; Woodcock and Gopal, 2000). Accuracy assessment was conducted using a stratified random sample of the mapped stands for two of the forests, and post-stratification of FIA plots for the others. FIA plots are now being used for all new map accuracy assessment work.

Resulting Maps

Plate 1b shows an example of life form, CALVEG, conifer cover, and hardwood cover attributes for a small area, centered on Laguna Meadows, Cleveland National Forest. Elevations in this area range from approximately 1500 to 2000 m and the montane meadow to the right of center is surrounded by Jeffrey Pine (*Pinus jeffreyi*) and Black Oak (*Quercus kellogii*) forest to the east and woodland with chaparral vegetation at the western lower elevations (Plate 1b, CALVEG). This area differs from the montane forest lands of the Sierra Nevada and Klamath Provinces because it lies at the southern extreme of the range of ecological conditions in California's National Forests (Figure 1). However, it illustrates the wide range of life forms (Plate 1b, Lifeform) and forest structure (Plate 1b, Cover) captured by our mapping methods. These figures also illustrate the spatial characteristics of the maps. For example, although the minimum mapping unit was specified to be 1 to 2 ha, the actual distribution of polygon sizes was determined by both the image segmentation algorithm, and the map labeling procedures. Image segments that received the same label for all attributes were merged. This resulted in smaller polygons for forest stands where structure was estimated (on the order of 5 to 25 ha), and larger polygons for shrub and herbaceous life forms that only received a vegetation type label (one chaparral polygon within the Cleveland National Forest was almost 7000 ha; Franklin and Woodcock, 1997).

Plate 2a summarizes the area of each land cover/life form class mapped for 18 National Forests (Table 1) in California (the Toiyabe is not included because it is not administered by the PSW Region; Figure 1). The patterns depicted, while not surprising to those familiar with California's biogeography, illustrate the great variety of conditions, and related land management issues, faced by the PSW Region. The Lassen and Modoc National Forests of the Modoc Plateau and the Inyo National Forest of the eastern Sierra are dominated by conifer forest (CON in Plates 1 and 2) and shrublands (SCH) with Great Basin affinities. The central and southern Sierran forests contain extensive mid-elevation conifer forest and non-vegetated surfaces (bare rock, NFO) in the alpine zone. Southwestern and Central Coast forests comprise chaparral shrublands (CHP) and some hardwood forest with limited areas of conifer forest.

Plate 2b shows the proportion of conifer area in each CALVEG vegetation type for selected National Forests. Note that the total extent of the conifer life form varies among the Forests from 156 to 9645 km^2 (Plate 2a, Table 2); therefore, Plate 2b emphasizes the relative extent of different conifer types across the region. Virtually all National Forests in California have significant areas of middle elevation Mixed Conifer dominated by Fir (MF) or Pine (MP). Some conifer types are restricted to the Southwestern region (DM, Bigcone Douglas Fir), and to the forests of the northern interior of the State (WF, White Fir; WJ, Western Juniper). Red fir (RF) is found in the higher elevations of northern forests, and more xeric types (EP, Eastside Pine; PJ, Pinon-Juniper; and JP, Jeffrey Pine) are found in forests on the leeward escarpments of mountain ranges (eastern Sierra) and in the drier Southwestern region. Coast Redwoods (RW) and Douglas Fir (DF) forests are found in the central and northern coastal region.

Reliability of Map Attributes

Table 4 shows life form accuracy based on the method of fuzzy sets (where reference plots are counted as "RIGHT" or correctly mapped if they have either the best possible, or an acceptable, map label - see Gopal and Woodcock (1994)). The most widespread life form in each National Forest (Plate 2a) is generally mapped with 85 percent or greater accuracy. For example, shrublands occupy 45 to 70 percent of each National Forest's land area in the southwestern forests and the assessments suggest 85 to 98 percent map accuracy for this life form (Table 4). The Sierra Nevada and Klamath Province forests are dominated by montane conifer forest (60 to 80 percent of their land area) and this life form is mapped with better than 90 percent accuracy. Lower accuracies for Conifer and Hardwood in the lower elevation Southwestern and Central Coast forests may occur because these life forms are found in an interdigitated spatial mosaic, with greater extent of life forms that are spectrally similar to each other (i.e., chaparral and evergreen hardwood). However, lower accuracy figures may also be a function of the accuracy assessment methods that were used. Accuracies are higher and more comparable to other National Forests when the same methods were used (Tables 1 and 4).

An example of the fuzzy accuracy assessment for the CALVEG vegetation types is shown for the conifer life form. It indicates 70 to 100 percent accuracy for those classes sampled with enough points to evaluate accuracy (Table 5). This is similar to other comparable vegetation mapping studies (Bauer *et al.* (1994), Basham May *et al.* (1997), and references therein; see also Wolter *et al.* (1995)) and an acceptable level of accuracy given the categorical detail achieved (comparable to Anderson Level III; Anderson *et al.*, 1976). Those categories with extremely low accuracy (20 to 50 percent) are classes for which refined gradient models should be developed, or classes should be aggregated, in order to improve the overall usefulness of the CALVEG map label. Frequently, half of the conifer categories in a given National Forest could not be assessed for lack of an adequate number of sample points. Additional accuracy sampling must, therefore, be directed towards those map classes because these uncommon types are often missed by the systematic sample design of the FIA sample plots.

In summary, accuracy estimates provided for each map attribute allow decision makers to make judicious use of the data for subsequent analyses and decision support, and allow the map producers to direct their efforts towards improving problematic maps attributes or classes. The importance of quantifying map accuracy can not be overemphasized. All maps contain errors, and it is sometimes difficult for map users to perceive errors in digital maps as variance in an estimated spatial distribution, rather than a cartographer's mistake (Goodchild, 1994). This database is intended to support various kinds of resource management decisions, outlined above. The vegetation data are one input into analyses ranging in complexity from simple estimates of land-cover area, to complex modeled predictions (habitat suitability, fire risk, fire fuels, water quality). Resource analysts must know if the data can support those models, and, if so, which attributes are accurate enough for their purposes, and at what level of categorical detail.

Cost of Mapping

We estimate that the cost of producing the vegetation maps described here is $0.30 to $0.40 per ha. Two decades ago it cost roughly $2.00 to $3.00 per ha (adjusted to today's dollars) to delineate, digitize, and label forest stands for timber inventory and mapping. The imagery is relatively inexpensive (a few thousand dollars per National Forest) when compared to resource photography ($75K to $100K per National Forest), although aerial photography continues to be acquired by the Forest Service for other purposes. Other land management agencies such as the National Park Service are developing large-area vegetation maps based on air photo interpretation and field survey at costs of approximately $2.50 or more per ha. Those costlier approaches, however, provide more detailed information about the floristic composition and structure of the vegetation, which may be required for some purposes. They also provide the greater spatial detail necessary for site-specific evaluations. The disadvantage of our approach is the limited categorical and spatial resolution and low accuracy for several map attributes or categories. This may be overcome to some extent with new types of remotely sensed data and new spatial data processing methods.

Summary

With relatively high efficiency (time and cost), multi-attribute vegetation maps were produced of known accuracy that varied among attributes and regions (National Forests). The currently implemented procedures demonstrate repeatable methods as well as some improvements in remote-sensing-based mapping approaches, but they fall short of providing accurate estimates of some vegetation attributes in some National Forests. In this context, there are two competing trends. One trend is toward increasing demands from resource managers for information about the landscape. From this perspective, vegetation map-

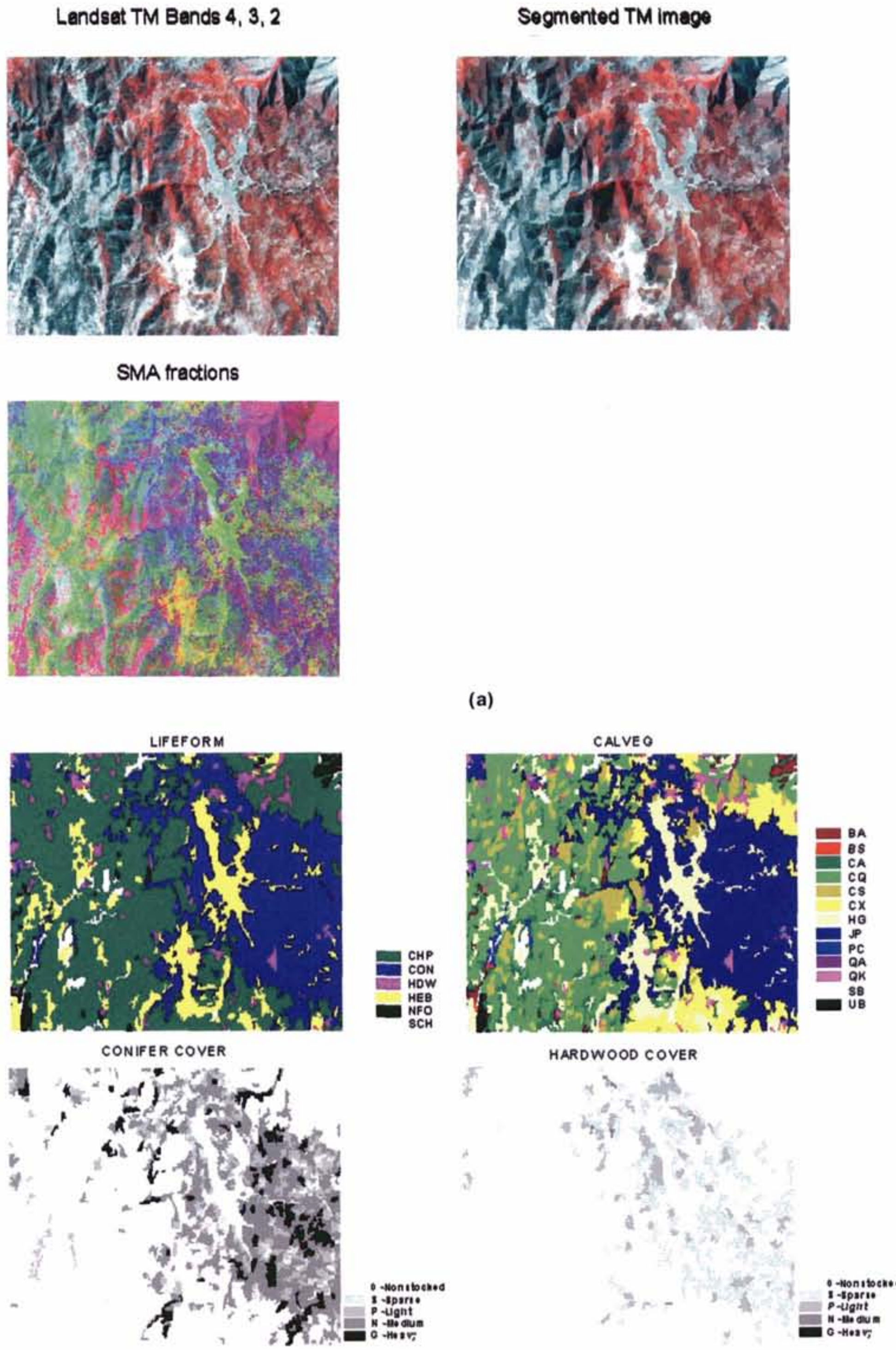

Plate 1. (a) A 9 km by 10 km area centered on Laguna Meadow, Mount Laguna, Cleveland National Forest, San Diego County: TM Band 4,3,2 image assigned to colors red, green, blue; same image segmented, with mean per-band brightness for each polygon placed in each pixel in the polygon; fraction images from spectral mixture analysis (SMA)—red is hardwood fraction, green is grass, blue is conifer. (b) Life form map; CALVEG map (class abbreviations in Table 3); conifer cover; hardwood cover, for same area.

Table 4. Life Form Map Accuracy Summary—Percent of Reference Plots Correctly Mapped

National Forest	Conifer	Hardwood	Shrub	HEB	NFO	Overall Weighted
Angeles	57% (70%)[1]	68% (68%)[1]	85%	—	33%	80%
Cleveland	63% (91%)[1]	67% (76%)[1]	98%	—	—	63%
Inyo	96%	—	90%	—	86%	90%
Klamath	97%	—	100%	—	—	88%
Lassen	96%	88%	67%	—	—	90%
Los Padres	68% (93%)[1]	75% (77%)[1]	88%	—	—	82%
Mendocino	99%	83%	76%	—	—	84%
Modoc	99%	—	90%	—	—	93%
Plumas	100%	60%	86%	94%[2]	—[2]	94%
San Bernardino	84% (91%)[1]	60% (80%)[1]	94%	—	—	80%
Shasta-Trinity	94%	89%	78%	—	—	90%
Six Rivers	97%	87%	—	—	—	87%
Stanislaus	94%	79%	—	—	—	88%
Tahoe Basin	98%	—	76%	87%	41%	80%

Notes: Results shown only for classes with at least 15 reference plots.
[1]Conifer and hardwood accuracy estimates higher based on field assignment of vegetation type (versus decision rules applied to raw field data—see Table 1).
[2]For Plumas accuracy assessment, barren (NFO) and Herbaceous (HEB) categories were grouped.

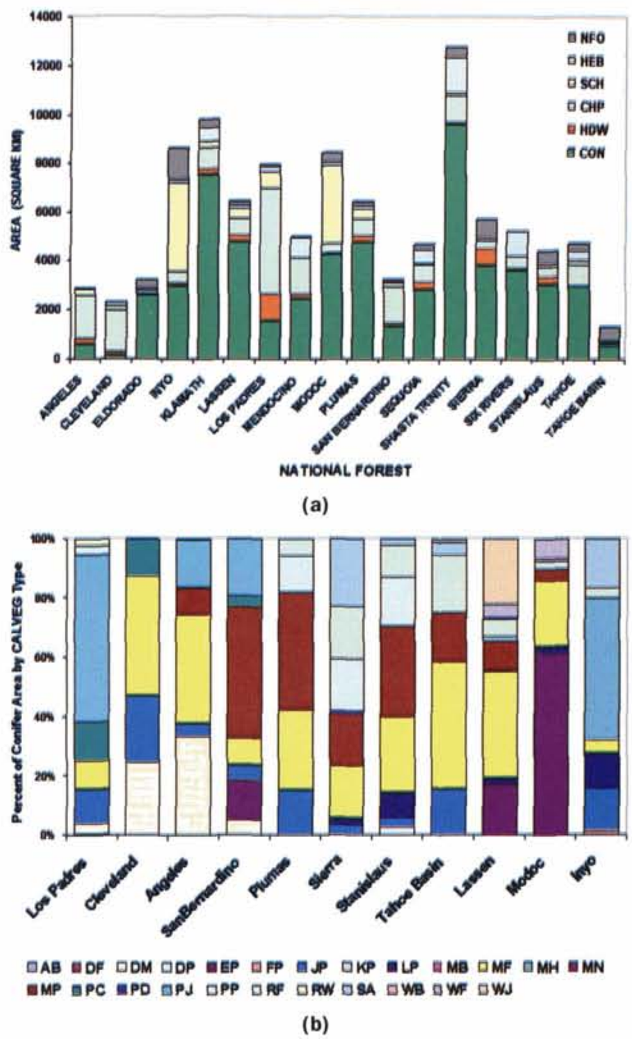

Plate 2. (a) Area of each major land cover or vegetation life form class mapped in the California National Forests (class abbreviations in Table 3). (b) Percent of conifer area by CALVEG type for selected National Forests (class abbreviations in Table 5).

ping problems are never truly solved, as the bar keeps getting raised. A simple example is our development of methods for producing timber type maps in the late 1970s (Woodcock *et al.*, 1980). While these maps produced useful stratification for timber inventory, the subsequent demand for more specific information on tree size and cover required new innovations such as the use of canopy reflectance models. More recently, information needs for land management decision support are pushing the demands even further. While spatially detailed, highly accurate, stand specific estimates of floristic composition and vegetation structure for large regions would be desirable for ecosystem management, this type of information may only be attainable from field based stand exams costing $20 to $30 per ha.

The opposing trend is towards improvements in remote sensing imagery and methods. In the mid-1980s, the move from Landsat MSS to TM and SPOT required new methods (such as image segmentation) but allowed for improved maps. More recently, new satellite sensor systems have come on line, with more planned for the near future, that promise to contribute to improved operational forest mapping for large areas (for example, RADARSAT, IRS, Enhanced Thematic Mapper, IKONOS, MODIS, and a number of others). Similarly, there are recent methodological innovations that would improve the mapping process, and possibly provide additional information about forest stands. For example, we recently developed and tested a new supervised classification method for mapping life forms and vegetation types based on an artificial neural network called fuzzy ARTMAP (described in Carpenter *et al.* (1992)) that directly integrates Landsat spectral data, terrain variables, and geographic location (Carpenter *et al.*, 1999). This approach requires many training sites, but once the data are collected, the processing stream is greatly simplified compared to the current operational methods. For the Sierra National Forest, unedited results of the neural network classifier were almost as accurate as the edited maps produced by the methods described in this paper. The use of fuzzy ARTMAP might provide significant streamlining of the mapping process.

As remote sensing scientists, we remain optimistic that new data and methods will improve the quality of information derived from satellite imagery and associated GIS data. However, this project also serves as a cautionary tale. The Forest Service needs detailed, fine scale, accurate, stand-specific information on vegetation composition and structure to support intra-agency and multi-agency natural resource and land management planning and decision making. This need has grown at a greater pace than affordable geospatial processing solutions for providing these data over large areas. The data-

Table 5. Summary of CALVEG Map Accuracy for Conifer Types, Selected National Forests

CALVEG	Angeles	Cleveland	Los Padres	San Bernad.	Plumas	Tahoe Basin	Inyo	Lassen	Modoc
Bigcone Douglas Fir (DM)	90% (10)	—	—	—					
Eastside Pine (EP)				37% (19)				83% (59)	95% (44)
Jeffrey Pine (JP)	—	89% (18)	64% (22)	—	—	96% (23)	79% (38)		
Lodgepole Pine (LP)							82% (17)	69% (13)	—
Mixed Conifer Fir (MF)	48% (25)	—	29% (14)	83% (12)	76% (21)	100% (32)	—	78% (67)	74% (48)
Mixed Conifer Pine (MP)	—	—		23% (35)	100% (16)	—		78% (55)	—
Coulter Pine (PC)	—	—	27% (11)	—					
Pinon Juniper (PJ)	—		94% (18)	—			83% (12)		
Red Fir (RF)					—	96% (25)	—	72% (32)	85% (13)
Subalpine Conifer (SA)				—		100% (19)	95% (19)	—	
White Fir (WF)					—	—		70% (10)	100% (24)
Western Juniper (WJ)								—	100% (50)

Notes: Results shown for map classes with at least ten reference plots (number of plots in parentheses). —indicates type is present on National Forest but less than ten plots for accuracy assessment. Additional types present in one of the National Forests listed but not enough points for accuracy assessment: Santa Lucia Fir (AB), Bristlecone Pine (BP), Foxtail Pine (FP), Knobcone Pine (KP), Cuyamaca Cypress (MC), Mountain Hemlock (MH), Tecate Cypress (MT), MacNab Cypress (MN), Gray Pine (PD), Limber Pine (PL), Ponderosa Pine (PP), and Redwood (RW); additional conifer types listed in Plate 2: Douglas Fir (DF), Douglas Fir-Pine (DP), Mixed Conifer w/Giant Sequoia (MB), Whitebark Pine (WB).

base described here, for example, includes a number of attributes whose accuracy is low for some areas, limiting their use in subsequent modeling and decision support. Improving the mapping methods remains a fruitful area of research. Further, the potential effect of map uncertainty or error should be emphasized in geographical decision support systems, because no database of this size and scope can be produced error-free. Decision support tools for visualization and sensitivity analysis related to map uncertainty are an essential future requirement.

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References

Adams, J.B., M.O. Smith, and A.R. Gillespie, 1993. Imaging spectroscopy: Interpretation based on spectral mixture analysis, *Remote Geochemical Analysis: Elemental and Mineralogical Composition* (C.M. Pieters and P. Englert, editors), Cambridge University Press, New York, pp. 145–166.

Anderson, J.R., E.E. Hardy, J.T. Roach, and R.E. Witmer, 1976. *A Land Use and Land Cover Classification System for Use with Remote Sensor Data*, U.S. Geological Survey Professional Paper 964, U.S. Geological Survey, Arlington, Virginia, 28 p.

Basham May, A.M., J.E. Pinder III, and G.C. Kroh, 1997. A comparison of Landsat Thematic Mapper and SPOT multi-spectral imagery for the classification of shrub and meadow vegetation in northern California, USA, *International Journal of Remote Sensing*, 18:3719–3728.

Bauer, M.E., T.E. Burk, A.R. Ek, P.R. Coppin, S.D. Lime, T.A. Walsh, D.K. Walters, W. Befort, and D.F. Heinzen, 1994. Satellite inventory of Minnesota forest resources, *Photogrammetric Engineering & Remote Sensing*, 60:287–298.

Beardsley, D., and R. Warbington, 1996. *Old Growth in Northwestern California National Forests*, Research Paper PNW-RP-491, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, Oregon, 47 p.

Carpenter, G.A., S. Gopal, S. Macomber, S. Martens, C.E. Woodcock, and J. Franklin, 1999. A neural network method for efficient vegetation mapping, *Remote Sensing of Environment*, 70:326–338.

Carpenter, G.A., S. Grossberg, N. Markuzon, J.H. Reynolds, and D.B. Rosen, 1992. Fuzzy ARTMAP: A neural network architecture for incremental supervised learning of analog multidimensional maps, *IEEE Transactions on Neural Networks*, 3:698–713.

Chuvieco, E., and J. Salas, 1996. Mapping the spatial distribution of forest fire danger using GIS, *International Journal of Geographic Information Systems*, 10:333–345.

Congalton, R.G., K. Green, and J. Teply, 1993. Mapping old growth forests on National Forest and Park lands in the Pacific Northwest from remotely sensed data, *Photogrammetric Engineering & Remote Sensing*, 59:529–535.

Davis, F.W., 1994. Mapping and monitoring terrestrial biodiversity using geographic information systems, *Biodiversity and Terrestrial Ecosystems* (C.-I. Peng and C.H. Chou, editors), Academia Sinica Monograph Series No. 14, Taipei, pp. 461–471.

Forest Service, 1994. *FIA User's Guide*, USDA Forest Service Pacific Southwest Region Remote Sensing Laboratory, Sacramento, California, 296 p.

Franklin, J.F., 1993. The fundamentals of ecosystem management with applications in the Pacific Northwest, *Defining Sustainable Forestry* (G.H. Aplet, N. Johnson, J.T. Olson, and V.A. Sample, editors), Island Press, Washington, D.C., pp. 127–143.

Franklin, J., 1995. Predictive vegetation mapping: Geographic modeling of biospatial patterns in relation to environmental gradients, *Progress in Physical Geography*, 19:474–499.

Franklin, J., T. Logan, C.E. Woodcock, and A.H. Strahler, 1986. Coniferous forest classification and inventory using Landsat and digital terrain data, *IEEE Transactions on Geoscience and Remote Sensing*, GE-24:139–149.

Franklin, J., and J. Stephenson, 1996. Integrating GIS and remote sensing to produce regional vegetation databases: Attributes related to environmental modeling, *Proceedings of the Third International Conference/Workshop on Integrating GIS and Environmental Modeling*, 21–25 January, Santa Fe, New Mexico, URL: http://bbq.ncgia.ucsb.edu/conf/santafe/papers/franklinjanet/mypaper.html.

Franklin, J., and C.E. Woodcock, 1997. Multiscale vegetation data for the mountains of Southern California: Spatial and categorical resolution, *Scale in Remote Sensing and GIS* (D.A. Quattrochi and M.F. Goodchild, editors), CRC/Lewis Publishers Inc., Boca Raton, Florida, pp. 141–168.

Gonzales-Rebeles, C., V.J. Burke, M.D. Jennings, G. Ceballos, and N. Parker, 1998. Transnational gap analysis of the Rio Bravo/Rio Grande Region, *Photogrammetric Engineering & Remote Sensing*, 64:1115–1118.

Goodchild, M.F., 1994. Integrating GIS and remote sensing for vegetation analysis and modeling: Methodological issues, *Journal of Vegetation Science*, 5:615–626.

Gopal, S., and C.E. Woodcock, 1994. Theory and methods for accuracy assessment of thematic maps using fuzzy sets, *Photogrammetric Engineering & Remote Sensing*, 60:181–188.

Gordon, H., and T.C. White, 1994. *Ecological Guide to Southern California Chaparral Plant Series*, USDA Forest Service, Pacific Southwest Region, San Diego, California, 162 p.

Goward, S.N., C.J. Tucker, and D.G. Dye, 1985. North American vegetation patterns observed with NOAA-7 advanced very high resolution radiometer, *Vegetatio*, 64:3–14.

Hansen, A.J., S.L. Garman, B. Marks, and D.L. Urban, 1993. An approach for managing vertebrate diversity across multiple-use landscapes, *Ecological Applications*, 3:481–496.

Homer, C.G., R.D. Ramsey, T.C. Edwards, Jr., and A. Falconer, 1997. Landscape cover-type modeling using a multi-scene Thematic Mapper mosaic, *Photogrammetric Engineering & Remote Sensing*, 63:59–76.

Jensen, M.E., P. Bourgeron, R. Everett, and I. Goodman, 1996. Ecosystem management: A landscape ecology perspective, *Journal of the American Water Resources Association*, 32:203–216.

Keeley, J.E., and T. Scott (editors), 1995. *Brushfires in California: Ecology and Resource Management*, International Association of Wildland Fire, Fairfield, Washington, 220 p.

Keeley, J.E., C.J. Fotheringham, and M. Morais, 1999. Reexamining fire suppression impacts on brushland fire regimes, *Science*, 284:1829–1832.

Kohm, K.A., and J.F. Franklin (editors), 1997. *Creating a Forestry for the 21st Century*, Island Press, Washington, D.C., 475 p.

Levien, L.M., C.S. Fischer, P.D. Roffers, and B.A. Maurizi, 1998. Statewide change detection using multitemporal remote sensing data, *Proceedings of the 7th Forest Science Remote Sensing Applications Conference*, 06–10 April, Nassau Bay, Texas, pp. 218–229.

Li, X., and A.H. Strahler, 1985. Geometric-optical modeling of a conifer forest canopy, *IEEE Transactions on Geoscience and Remote Sensing*, GE-23:705–721.

Loveland, T.R., J.W. Merchant, D.O. Ohlen, and J.F. Brown, 1991. Development of a land-cover characteristics database for the conterminous U.S, *Photogrammetric Engineering & Remote Sensing*, 57:1453–1463.

Matyas, W.J., and I. Parker, 1980. *CALVEG Mosaic of Existing Vegetation in California*, Regional Ecology Group, USDA Forest Service, Region 5, 630 Sansome Street, San Francisco, California, 27 p.

Regional Ecology Group, 1981. *CALVEG: A Classification of Californian Vegetation*, USDA Forest Service, Region 5, San Francisco, California, 188 p.

Ryherd, S., and C.E. Woodcock, 1996. Combining spectral and texture data in the segmentation of remotely sensed images, *Photogrammetric Engineering & Remote Sensing*, 62:181–194.

SAMAB (Southern Appalachian Man and the Biosphere), 1996. *The Southern Appalachian Assessment Terrestrial Technical Report*, Report 5 of 5, USDA Forest Service, Southern Region, Atlanta, Georgia, 246 p.

Scott, J.M., F. Davis, B. Csuti, R. Noss, B. Butterfield, C. Groves, H. Anderson, S. Caicco, F. D'Erchia, T.C. Edwards, Jr., J. Ulliman, and R.G. Wright, 1993. Gap analysis: A geographical approach to protection of biological diversity, *Wildlife Monographs*, 123:1–41.

Scott, J.M., and M.D. Jennings, 1998. Large-area mapping of biodiversity, *Annals of the Missouri Botanical Garden*, 85:34–47.

Shimabukuro, Y.E., B.N. Holben, and C.J. Tucker, 1994. Fraction images derived from NOAA AVHRR data for studying the deforestation in the Brazilian Amazon, *International Journal of Remote Sensing*, 15:517–520.

Smith, G.R., 1997. Making decisions in a complex and dynamic world, *Creating a Forestry for the 21st Century* (K.A. Kohm and J.F. Franklin, editors), Island Press, Washington, D.C., pp. 419–435.

Smith, M.O., S.L. Ustin, J.B. Adams, and A.R. Gillespie, 1990. Vegetation in deserts: I. A regional measure of abundance from multispectral images, *Remote Sensing of Environment*, 31:1–26.

Stehman, S.V., 1999. Basic probability sampling for thematic map accuracy assessment, *International Journal of Remote Sensing*, 20:2347–2366.

Stehman, S.V., and R.L. Czaplewski, 1998. Design and analysis for thematic map accuracy assessment: fundamental principles, *Remote Sensing of Environment*, 64:331–344.

Stephenson, J., and G.M. Calcarone, 1999. *Southern California Mountains and Foothills Assessment*, General Technical Report PSW-GTR-172, USDA Forest Service, Pacific Southwest Research Station, Albany, California, 402 p.

Stone, T.A., P. Schlesinger, R.A. Houghton, and G.M. Woodwell, 1994. A map of the vegetation of South America based on satellite imagery, *Photogrammetric Engineering & Remote Sensing*, 60:541–551.

Strahler, A.H., 1981. Stratification of natural vegetation for forest and rangeland inventory using Landsat digital imagery and collateral data, *International Journal of Remote Sensing*, 2:15–41.

Strahler, A.H., J. Townshend, D. Muchoney, J. Borak, M. Friedl, S. Gopal, A. Hyman, A. Moody, and E. Lambin, 1996. *MODIS Land Cover and Land-Cover Change Algorithm Theoretical Basis Document* (ATBD), Version 4.1, Boston University, Boston, Massachusetts, 102 p.

Townshend, J.R.G., C.J. Justice, and V. Kalb, 1987. Characterization and classification of South American land cover types using satellite data, *International Journal of Remote Sensing*, 8:1189–1207.

Tucker, C.J., J.R.G. Townshend, and T. Goff, 1985. Continental land cover classification using NOAA-7 AVHRR data, *Science*, 227:369–375.

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 & Remote Sensing*, 61:1129–1143.

Woodcock, C.E., A.H. Strahler, and T.L. Logan, 1980. Stratification of forest vegetation for timber inventory using Landsat and collateral data, *Proceedings of the 14th International Symposium on Remote Sensing of Environment*, 23–30 April, San Jose Costa Rica, pp. 1769–1787.

Woodcock, C.E., and V.J. Harward, 1992. Nested-hierarchical scene models an image segmentation, *International Journal of Remote Sensing*, 13:3167–3187.

Woodcock, C.D., J. Collins, S. Gopal, V.D. Jakabhazy, X. Li, S. Macomber, S. Ryherd, V.J. Harward, J. Levitan, Y. Wu, and R. Warbington, 1994. Mapping forest vegetation using Landsat TM imagery and a canopy reflectance model, *Remote Sensing of Environment*, 50:240–254.

Woodcock, C.E., S. Gopal, and W. Albert, 1996. Evaluation of the potential for providing secondary labels in vegetation maps, *Photogrammetric Engineering & Remote Sensing*, 62:393–399.

Woodcock, C.E., J. Collins, V.D. Jakabhazy, X. Li, S.A. Macomber, and Y. Wu, 1997. Inversion of the Li-Strahler canopy reflectance model for mapping forest structure, *IEEE Transactions on Geoscience and Remote Sensing*, 35(2):405–414.

Woocock, C.E., and S. Gopal, 2000. Fuzzy set theory and thematic maps: Accuracy assessment and area estimation, *International Journal of Geographical Information Science*, 14:153–172.

Zhu, Z., and D.L. Evans, 1994. U.S. forest types and predicted percent forest cover from AVHRR data, *Photogrammetric Engineering & Remote Sensing*, 60:525–531.