“Forest area and deforestation in Central Africa: Current knowledge and future directions”

by Wilkie D., Laporte N.

(pp. 119-138)

in

<u>African Rainforest Ecology and Conservation</u>

W. Weber, A. Vedder, S. Morland, L. White (Eds)

Yale University Press (2001)

Forest Area and Deforestation in Central Africa

Current Knowledge and Future Directions

David S. Wilkie and Nadine Laporte

Suitability of the central African climate for year-round plant growth and generally favorable geologic and topographic features have resulted in the formation of the second largest contiguous area of tropical moist forest (TMF) in the world (1.8 million km^2). This immense biome constitutes about 15% of the world's remaining TMF (UNESCO 1978) and encompasses the entire countries of Gabon and Equatorial Guinea, much of Congo, Cameroon, and Democratic Republic of Congo (DR Congo), and the southwestern corner of the Central African Republic (figure 8.1). Although climatic conditions over much of central and west Africa indicate that the landscape is capable of supporting TMF, only in central Africa has much of the forest escaped the logger's chainsaw and the farmer's axe (table 8.1).

From a regional perspective, we can pose three basic questions about the state of tropical forests in central Africa: What do we know about the present extent and state of the dense humid forest? What are the major factors that result in a change in state and extent? and What tools do we have available to us to detect and monitor changes in the forest? For most of the nations that constitute central Africa, statistics on forest extent, clearing, and reforestation are woefully inadequate. Deforestation statistics, therefore, are presented in this chapter to highlight their variability as much as to provide basic information. Of greater importance is a discussion of the factors that contribute to a change in forest status, and a critique of available methods for evaluating the impact of these factors on a regional scale. Information for this chapter draws heavily from the results of a Biodiversity Support Program (BSP) study, funded by the United States Agency for International Development (USAID), of central Africa's role in global climate change. We also draw on information from the first phase of the Tropical Ecosystem Environmental Observation by Satellite (TREES) project of the Joint Research Center of the European Community (Italy) and the USAID Central Africa Regional Program for the Environment (CARPE).

In this chapter we attempt to report on the most recent studies and the capabilities and limitations of the most recent technologies, particularly with respect to satellite remote sensing. The pace of change, however, often means that by the time such survey chapters as this are published, the tools available to researchers and practitioners have advanced from those described. Fortunately, the advent and explosion of the Internet

ISBN 0-300-08433-1.

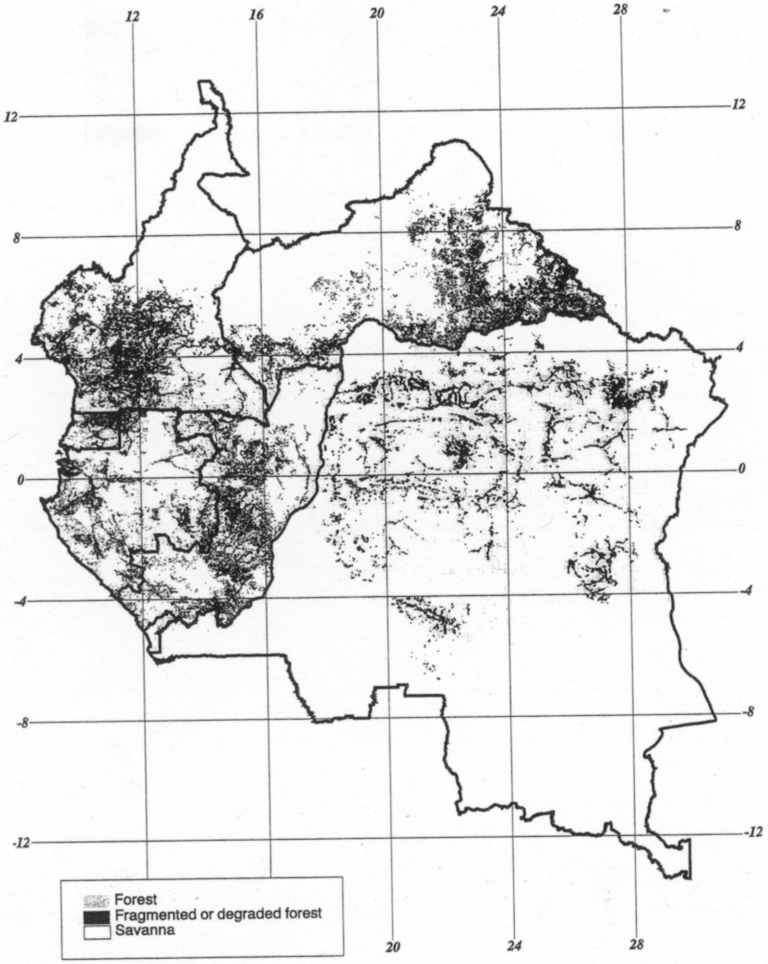

Figure 8.1. Vegetation map of central Africa derived from 1 km AVHRR imagery (1990s). From Laporte et al. 1998.

and the World Wide Web have dramatically increased our access to information on remote sensing and Geographical Information System (GIS) technologies, allowing us browse sources of remote sensing imagery, to locate and view the results of regional and global surveys of land cover, and to keep abreast of the latest advances in the field.

Estimates of Tropical Moist Forest Area

Unlike the Amazon, where over the past ten years a time series of high-resolution satellite imagery has been gathered to assess forest extent and the rate and distribution of deforestation (Skole and Tucker 1993), for central Africa there has been a concerted mapping effort only since the mid-1990s (Malingreau et al. 1995; Justice et al. 1995; Laporte et al. 1998; Mayaux et al. 1998). Quantitative data on the distribution and extent of vegetation types within each country of central Africa are often incomplete, and the data that do exist vary in quality.

Table 8.1

Forest Extent, Deforestation, and Reforestation Within Central Africa (1980s)

	ALL FOREST		DRY FOREST		MOIST FOREST		DEFORESTATION	REFORESTED
COUNTRY	AREA	%	AREA	%	AREA	%	PER YEAR (KM^2)	AREA (KM^2)
Cameroon	185	59	30	69	155	56	2,000–5,000	280
CAR	279	55	147	51	133	59	500–600	0
Congo	174	49	0	0	174	49	200–700	300–500
Equatorial Guinea	13	50	0	0	13	50	30	—
Gabon	173	35	0	0	173	35	150–600	300–500
DRC	832	57	91	54	741	57	2,000–4,000	400–600

Sources: Data from IIED 1988; Myers 1989; WRI 1991.

Note: % = % deforested; CAR = Central African Republic; DRC = DR Congo. Unless otherwise noted, areas are given in 10^3 km^2.

THE FOOD AND AGRICULTURAL ORGANIZATION

The most frequently cited source of forest information for central Africa dates back to 1981, when the Food and Agricultural Organization (FAO) published, in conjunction with the United Nations Environment Program (UNEP), the results of the Tropical Forest Resources Assessment Project: Forest Resources of Tropical Africa (table 8.2; see Lanly 1981). From this study, FAO/UNEP hoped to determine the extent and state of forest resources within Africa and to assess rates of deforestation and afforestation. Central Africa data sources and data veracity were, however, as varied as the geography, socioeconomic situation, and institutional capacity of the constituent nations. For example, measures of forest extent in Cameroon were based on aerial photogrammetry and visual interpretation of a sample of Landsat MSS (80 m resolution at 1:1,000,000 scale) satellite images obtained over a two-year period (1973–1975). In contrast, forest estimates for DR Congo were based on a questionnaire sent to the national forestry agency and relied heavily on Devred's 1958 map, which was itself a compilation of maps and vegetation surveys developed in the 1930s. Lanly (1983) attempted to rank the quality of data available on forest extent and deforestation of six nations within central Africa. Only data for Cameroon were ranked good.

Since the FAO report was published, it has become the major (or sole) source of forest area and deforestation data used by planners, conservation ecologists, and climate modelers. In fact, the FAO data are often the basis for unsourced tables and figures in secondary and tertiary articles that falsely give the impression of multiple data sources for central African forest statistics. More recently, the FAO has developed an inventory method that uses Landsat imagery to improve the estimates of forest area and rates of change (FAO 1996). This approach is discussed in more detail later.

OAK RIDGE NATIONAL LABORATORY

In 1990 the Oak Ridge National Laboratory (ORNL) completed a study for USAID to estimate carbon inventories and emissions for sub-Saharan Africa, as part of the primary project goal of estimating the extent to which sub-Saharan land-use change might be capable of mitigating global warming through additional carbon uptake (Graham et al. 1990). To achieve this goal, vegetation cover (forest, mixed forest-savanna, and savanna) was to be "deter-

Table 8.2

Forest Extent in Central Africa (1980s)

COUNTRY	CLOSED FOREST AREA	OPEN FOREST AREA	FALLOW AREA	ALL AREA
Cameroon	179,200	77,000	16,900	317,200
Central African Republic	35,900	323,000	41,000	399,900
Congo	213,400	—	11,000	224,400
Equatorial Guinea	12,950	—	11,650	24,600
Gabon	205,000	750	15,000	220,750
DR Congo	1,056,500	718,400	184,000	1,958,900
Total	1,702,950	1,119,150	323,650	3,145,750

COUNTRY	FOREST	WOODLAND	AGRIC-FALLOW	ALL
Cameroon	205,871	122,727	102,440	431,038
Central African Republic	102,018	321,440	198,609	622,067
Congo	181,798	69,294	56,543	307,635
Equatorial Guinea	19,287	633	1,581	21,501
Gabon	144,908	21,763	77,094	243,765
DR Congo	897,002	1,084,415	208,831	2,190,248
Total	1,550,884	1,620,272	645,098	3,816,254

Sources: Data from Lanly 1981 (upper table) and Millington et al. 1991 (lower table).

Note: All figures are given in km².

mined" for each country using contemporary sources of information. After evaluating what recent timber inventory, forest resources, and exploitation maps were available, Graham and colleagues realized that methodological and land-cover classification differences precluded meaningful comparisons, and they decided to rely on data from the FAO/UNEP 1981 forest resources report as the basis for their deforestation projections. Graham and colleagues also decided to use the draft digitized FAO vegetation map (Lavenu 1987) and the White (1983) vegetation map for forest area coverage.

ADVANCED VERY HIGH RESOLUTION RADIOMETER NORMALIZED DIFFERENCE VEGETATION INDEX

Concerns about biomass fuel availability in sub-Saharan Africa resulted in a joint UNDP/World Bank Bilateral Energy Sector Management Program assessment of woody biomass standing stock and sustainable yield in sub-Saharan Africa (Millington et al. 1991). This study was one of the first attempts to map land-cover types in sub-Saharan Africa by interpretation of digital AVHRR (Advanced Very High Resolution Radiometer) Normalized Difference Vegetation Index (NDVI) data (Millington et al. 1991) at a ground resolution of 8 km. Although the forty-three biomass/land-cover classes generated in this study are not synonymous with FAO (Lanly 1981) and White (1983)

Table 8.3

Percentage of Closed Forest Cover by Country

	FAO = UNEP 1981		MILLINGTON ET AL. 1981	
	COUNTRY	REGION	COUNTRY	REGION
Cameroon	39	11	44	13
Central African Republic	6	2	16	7
Congo	62	13	53	12
Equatorial Guinea	46	1	69	1
Gabon	80	12	56	9
DR Congo	47	62	40	58

Note: All figures are percentages. Country figures indicate the percentage of the area of each country that is covered by closed forest, whereas regional figures indicate the percentage of the region's total closed forest cover found in each country.

vegetation cover types (a perennial problem when compiling country-based information), they allow a very rough comparison when clumped into Forest and Woodland categories (see table 8.2).

Although the FAO and AVHRR-NDVI country-level estimates of forest cover differ from 12% to 54% (table 8.3), both show that DR Congo contains the largest area of closed forest in the region (table 8.4) and that closed forest covers from about 40% to 80% of each country (with the exception of the Central African Republic). The total area of all closed forests within the region was estimated at approximately 3,000,000 km² (approximately 30% of the conterminous United States). To further demonstrate the range of uncertainty associated with estimates of forest extent and deforestation within central Africa, data for each country are presented (see table 8.4).

AVHRR-LAC /HRPT

Most recent studies of forest cover in central Africa have relied on AVHRR images for regional (national and multinational) forest surveys, owing to the frequent data acquisition (which increases the probability of acquiring cloud-free coverage), large area view, and relatively low cost. It is difficult, however, to acquire AVHRR data over areas with perennial cloud cover, and spatial resolution is often too coarse to detect finer-scale changes, particularly those characteristic of land-cover transformation by slash-and-burn settlers throughout much of central Africa. Nonetheless, degraded forest mosaics, including fields, fallow, and secondary forest, can be mapped at the regional scale. For example, estimates of the extent of degraded forest have been reported by country for the entire Congo Basin (Laporte et al. 1998).

As an important contribution to the International Geosphere Biosphere Program (IGBP 1992), a 1 km resolution vegetation map for the entire tropical belt was recently generated from AVHRR imagery (Malingreau et al. 1995; Mayaux et al. 1998). These vegetation maps provide a 1990s baseline for long-term monitoring at a regional scale. Reduced-resolution copies of the TREES project vegetation maps are available from the European Commission Joint Research web site. A similar effort has been undertaken for the central Africa regional maps by the USAID-funded

Table 8.4

Difference in Estimates of Forest Cover for Central Africa

	FAO CLOSED/OPEN AREA (KM^2)	MILLINGTON FOREST/WOODLAND AREA (KM^2)	DIFFERENCE	%
Cameroon	256,200	328,598	-72,398	28
Central African Republic	358,900	423,458	-64,558	18
Congo	213,400	251,092	-37,692	18
Equatorial Guinea	12,950	19,920	-6,970	54
Gabon	205,750	166,671	39,079	19
DR Congo	1,774,900	1,981,417	-206,517	12

Sources: FAO data are from FAO 1981; Millington data are from Millington et al. 1981.

Central African Regional Program for the Environment (CARPE).

The TREES project and other studies (Justice et al. 1993; Laporte et al. 1995, 1998; Mayaux et al. 1998) used high-resolution imagery (Landsat TM and MSS) to verify AVHRR land-cover classifications as part of the BSP Central Africa Global Climate Change and Development project (BSP 1993). This effort has resulted in vegetation maps with four land-cover classes (forest, degraded forest, mixed forest-savanna, and savanna) for Cameroon and DR Congo. A comparison of cover-type areal estimates between the different approaches (table 8.5) has increased our knowledge of the extent and state of the forest within central Africa. The level of error in forest-cover estimates, based on comparison of the AVHRR data with a sample of higher-resolution Landsat MSS imagery and limited field surveys, ranges from 8% (overestimation in dense forest areas) to 21% (underestimation in forest-savanna transition areas). To improve forest-cover estimates using AVHRR, the TREES project developed a methodology to calibrate and correct the resulting classified images. After correction, the residual errors computed on an independent sample of high-resolution scenes varied from 1% to 1.5% for central Africa (Mayaux and Lambin 1995).

AVHRR image analysis allows for a useful first approximation of the extent and state of forest resources in central Africa (table 8.6), but it is not ideal for detecting and characterizing forest change over time (Justice et al. 1993). Moreover, like all optical sensors, it is unable to image areas with perennial cloud cover. These difficulties have prompted the use of alternative data sources, which are described next.

ERS-1 AND JERS-1 SAR

As the TREES project progressed toward completion of a "wall-to-wall" AVHRR image mosaic of central Africa, gaps in coverage of areas with perennial cloud cover became a critical concern. In late 1993 the TREES/ERS-1 1994 project was initiated to assess the usefulness of high-resolution (30 m) Synthetic Aperture Radar (SAR) imagery for regional forest monitoring, with an emphasis on discriminating forest from non-forest land cover (Malingreau and Duchossois 1996). With a mobile receiving station located in Libreville, Gabon, 477 scenes were acquired during the period from July 15 to August 28, 1994. The images were resampled to 100 m nominal spatial resolution to improve the signal-to-noise ratio,

Table 8.5

Estimates of Areal Vegetation Extent from Cameroon and DR Congo

	CAMEROON		DEMOCRATIC REPUBLIC OF CONGO	
	FAO ('80s)	LAPORTE ('90s)	FAO ('80s)	LAPORTE ('90s)
Forest	191,600	168,087	1,056,500	1,117,963
Degraded forest	45,350	64,218	78,000	102,821
Mixed forest-savanna	68,550	63,691	824,400	437,565
Savanna	22,550	24,709	30,700	34,299
Total	328,130	320,795	1,989,680	1,692,738

Sources: FAO data are from Lanly 1981; Laporte data are from Laporte et al. 1995.

Table 8.6

Forest Extent Derived from AVHRR 1 km Resolution Imagery

	LAPORTE ET AL. 1998 (1989–1990)	MAYAUX ET AL. 1998 (1990–1992)
Cameroon	173,850	173,780
Central African Republic	60,897	60,370
Congo	224,615	239,160
Equatorial Guinea	16,207	18,110
Gabon	210,701	206,770
DR Congo	1,127,211	1,141,470

Note: All figures are in km^2.

while retaining sufficient detail for regional-scale analysis. The resulting mosaic covers the entire tropical forest domain of central Africa ($>$2500 km^2) as well as the northern and southern forest-savanna transition zones. Acquisition of wall-to-wall imagery for the whole region within a two-month period demonstrates the utility of non-optical active imaging systems for tropical rain forest monitoring. Preliminary visual examination of the regional mosaic showed that the satellite-based SAR data were able to distinguish the boundaries between evergreen or semi-deciduous forest and the mixed seasonal forest-savanna in southern Congo Basin, and were able to detect savanna islands within the forest zone. The radar data were also able to discriminate some old-growth from postagricultural secondary-growth vegetation. However, rainfall immediately prior to data acquisition can affect the SAR signal, making it difficult to interpret the data.

Interpretation of SAR imagery within tropical forested regions of Africa is in its infancy, and an operational use for forest mapping and monitoring is still under development. Work by Dobson et al. (1995) and others suggests that land-cover classification using the experimental SAR satellites ERS-1 and JERS-1 is more accurate and at a higher spatial resolution than that generated by classification of NDVI data from multitemporal AVHRR imagery. ERS-1 data allowed differentiation of forest from non-forest distribution in central Africa but failed to distinguish different woody vegetation or degraded forest classes (de Gauwer and de Wulf 1997).

A new vegetation map of Africa, based on the JERS-1 SAR data, is under development through a collaboration between the Jet Propulsion Laboratory (JPL) and the TREES project. Validation of this map will attempt to merge optical and radar data and will be undertaken in collaboration with the University of Maryland and in-country partners identified through CARPE.

Estimates of Forest Change and Deforestation

Slash-and-burn agriculture, logging, infrastructure development, mining, and fuelwood extraction all contribute, in different ways, to changes in forest extent and composition. The scale of the impact of these factors is a function of population density and growth rate, and regional and national economic conditions and policies. For example, forests close to major ports, such as Pointe-Noire in Congo, are often cut, whereas more isolated forests are high graded, with less than one or two trees extracted per hectare. Similarly, fuelwood gathering in rural areas with low population densities has no visible effect on the forest, whereas densely populated urban areas cause the development of "halos" of deforestation. In the case of Kinshasa, DR Congo, the halo extends over 100 km from the city center. In northeastern DR Congo, fluctuations in the world price of coffee, national tax policies, and a degrading infrastructure have resulted in the periodic expansion, abandonment, and rehabilitation of large commercial coffee plantations, and accompanying changes in the subsistence agricultural areas cleared by plantation laborers.

Land transformation in central Africa clearly varies in spatial and temporal scale. Choice of remote sensing imagery and the methodology for detecting and characterizing landscape change must, therefore, be appropriate to the scale of land transformation and the level of analysis (i.e., local, regional, or national). Given present extent and rate of deforestation in central Africa, the resolution of AVHRR imagery is unlikely to be sufficient for monitoring land transformation over much of the area. Attempts to measure landscape change in the region have thus employed high-resolution imagery when the temporal resolution of these data are sufficient (Stancioff and Pessutti 1981; Wilmet and Vennetier 1986; Castiaux et al. 1991).

FOOD AND AGRICULTURAL ORGANIZATION

Two primary goals of the UN/FAO project were assessment of: (1) the state of the forest cover for the reference year 1990; and (2) the rate of change in forest cover between 1981 and 1990 (Singh 1990; FAO 1996). The assessment was conducted in two phases. The first phase was based on collecting and organizing forest-cover data made available by countries. Statistical (tabular) data were compiled within a database (FLORIS). Spatial data were compiled within a GIS. Forest-cover data contained within FLORIS were based on country assessments prepared on different dates. The FAO developed a deforestation model that combines forest-cover estimates with such ancillary data as human population growth, ecological zones, precipitation, and socioeconomic variables to correct data gathered on differing dates to the standard reference years of 1980 and 1990.

Country forest-cover estimates based on the model were made under the following scenarios: (1) when reliable multi-date inventories were available to calibrate the model and subsequently compute the standardized results; (2) when a reliable single-date inventory was available; and (3) when no reliable inventory data were available. In the third case the standardized results were computed using a general (uncalibrated) model. Estimates of baseline forest-cover area were extracted from existing vegetation maps, which were entered into scenario 2 above. Clearly, scenario 1 was the optimal approach, when possible.

The second phase of the project, performed to improve "traditional" FAO forest-cover estimates, was designed around a sampling approach using remote sensing imagery and a common system of classification and interpretation to estimate global deforestation rates over the previous decade (Singh 1990). For this phase, the project used a random sampling of forty Landsat MSS 1:250,000 color print pairs (one from 1980 and the other from 1990) covering central and southern Africa. The approach uses a geographical stratification and a second-stage forest-cover vegetation map. The Landsat images are visually interpreted, and change is determined using transparent overlays and dot-grid counts. Although this approach is simple, its cost effectiveness varies depending on the availability of imagery, the representativeness of the sampling scheme, and, most important, the ability of photo-interpreters (foresters from the region) to characterize land-cover types within the imagery and to detect land transformations between the image pairs. The skill and experience of photo-interpreters is vital to assessing land transformation accurately. This method is more fully described elsewhere (FAO 1996).

The first phase of the study was completed in late 1994, and data in the form of national language "Country Briefs" are available on the FAO web site. Forest-cover estimates for 1980 and 1990 in central Africa (table 8.7) show the total change in cover over that time period, and an estimate of annual forest-cover change. All information for central African nations was generated using either scenario 2 or scenario 3 (i.e., the accuracy of the information is in doubt). Although the FAO has generated new estimates of forest cover for Africa, we are still left without confidence limits on the estimates for central Africa and are thus unsure whether they are an improvement over the 1981 FAO assessment. Comparison of table 8.4 and table 8.7 shows that FAO has not only generated new estimates of forest cover for 1990 but has revised (downward for all countries other than Equatorial Guinea) its original estimates for the extent of forest in 1980. A recent comparison (Mayaux et al. 1998) of FAO forest estimates with the 1990s estimates from TREES and the International Union for the Conservation of Nature (IUCN) supported this result.

Table 8.7

Forest-Cover Change Estimates for Central Africa Between 1980 and 1990

	1980 AREA (KM²)	1990 AREA (KM²)	DIFFERENCE AREA (KM²)	% CHANGE
Cameroon	215,690	203,500	-1,220	-0.6
Central African Republic	318,540	305,620	-1,290	-0.4
Congo	201,880	198,650	-320	-0.2
Equatorial Guinea	18,960	18,260	-70	-0.4
Gabon	193,980	182,350	-1,160	-0.6
DR Congo	1,205,970	1,132,750	-7,320	-0.6

Sources: FAO 1996 (FAO 1990 assessment). Reprinted by permission of the Food and Agriculture Organization of the United Nations.

BIODIVERSITY SUPPORT PROGRAM

To illustrate some of the methodological problems that can be expected in quantifying deforestation within central Africa, Justice et al. (1993) conducted a change detection study on four locations within the region chosen to provide a range of land-cover types (figure 8.2: Kanaga, Landsat Path/Row 177/64; Nyunzu 173/64; Ituri 174/58; Kutu 180/62). For each study site a search of the Landsat MSS archive was undertaken and near-anniversary images were selected at least nine years apart and with minimal cloud cover. Using unsupervised classification, visual labeling of classes, and pixel-by-pixel change detection, all four areas showed low rates of deforestation (< 0.1% per year). More important, the study showed how the low dynamic range and few spectral bands of Landsat MSS imagery resulted in considerable spectral overlap of land-cover types, and therefore an inability to discriminate among them. In addition, the relatively coarse pixel size (~80 m) produced an abundance of mixed pixels that were particularly prevalent in highly heterogeneous areas or areas where there were such linear features as gallery forests. The greatest limitation of this study was acknowledged to be lack of adequate ground information. Neither of the analysts conducting the classifications had firsthand knowledge of the areas, nor were such high-resolution products as aerial photography or videography available.

NASA LANDSAT PATHFINDER PROJECT

In 1990 the National Air and Space Administration (NASA), in conjunction with the United States Environmental Protection Agency and the United States Geological Survey EROS Data Center, began developing a process for using large amounts of high-resolution satellite imagery to map the rate of tropical deforestation (Asrar and Dokken 1993). The project focused initially on the Amazon but has been expanded as part of NASA's Earth Observing System activities to cover the tropical rain forests of central Africa and Southeast Asia. The Landsat Pathfinder Project is acquiring several thousand Landsat scenes at three points in time: mid-1970s, mid-1980s, and mid-1990s. Once the three-epoch data set is available, much more accurate estimates of forest extent and condition can be prepared and deforestation rates determined. Standardized land-cover classes and methods of analyses developed by the Pathfinder project will enhance the utility of the resulting vegetation-cover maps and will greatly facilitate the ability to conduct cross-country comparisons. Forest-extent coverages are now available for DR Congo and the Central African Republic for the 1980s and 1990s. Because of the persistence of clouds for most of Gabon, southern Cameroon, and Congo, and because of the absence of a Landsat receiving station in the region, a complete wall-to-wall map is still not available for these three countries. Products from the Pathfinder project can be downloaded from the NASA Pathfinder web site.

REGIONAL ENVIRONMENTAL INFORMATION PROJECT

The World Bank Regional Environment Information Management Project (REIMP) was implemented in 1997. The overall goal of the REIMP is to enhance the capacity of the six nations of central Africa to collaboratively monitor natural resource use and land-cover change, and with this information plan appropriate actions for natural resource management. Specific objectives are to establish a "demand-driven and action-oriented information system and to build capacity at local, national and regional levels to improve monitoring, land use planning, priority setting, and decision making for natural resource management, particularly for forest biodiversity conservation and management in the Basin" (Rantrua 1996). The project was financed

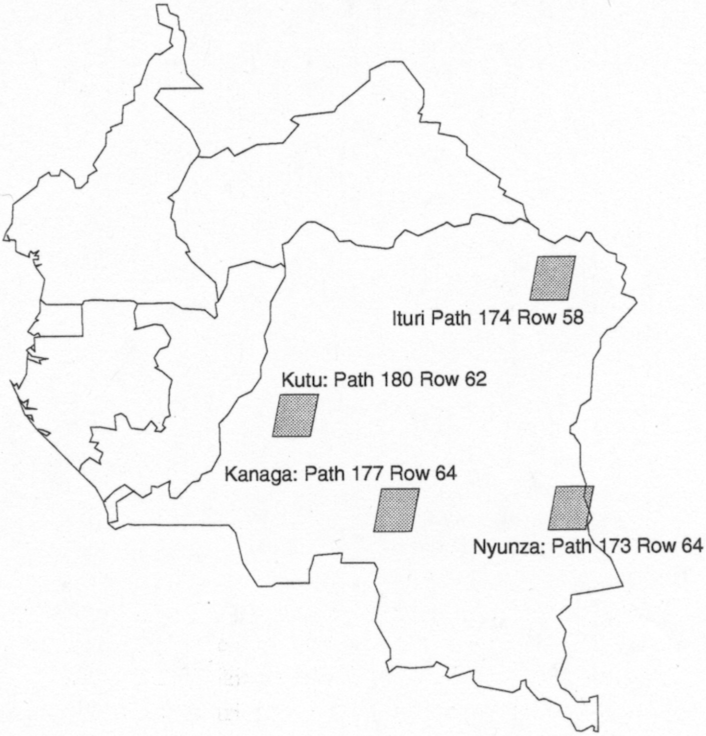

Figure 8.2. Map showing the locations of Landsat MSS scenes in the BSP study (Justice et al. 1993).

largely by the Global Environment Facility, although other multilateral and bilateral agencies (EU, UNDP, USAID, GTZ, FAC, ACDI, and AGCD) have expressed interest in participating, and others are already collaborating (FAO-Africover, NASA-Pathfinder, USAID-CARPE, and EU-ECOFAC). Links are also in place with non-governmental organizations (NGOs) active in the region (IUCN, WWF, and WCS).

The REIMP will acquire high-resolution satellite coverage for the basin, high-resolution aerial photography for urban areas, and regional 1:200,000 scale and local (urban) 1:50,000 scale topographic information. Data will be compiled or generated to create thematic maps of biodiversity, climate, soils, land use, and demography at 1:200,000 scale. Systems for managing, sharing, and using geographic data will be put in place, and personnel will be trained in the use of geographic databases for monitoring and decision making. The project will also work on increasing Internet connectivity to ease the exchange of data within and among nations. Each nation is expected to create a National Environmental Information Network (Réseaux Nationaux d'Information Environnementale—RNIE) to compile and exchange monitoring and planning information among governmental and non-governmental agencies within the country. Representatives from the national-level RNIEs would participate in a regional environmental information council (Conseil Régional de l'Information Environnementale—CRIE) that would attempt to develop collaborative solutions to transboundary environmental challenges. More information on the REIMP project can be found at its web site.

Assessing the Reliability of Deforestation Estimates

Grainger (1993) offers a checklist of questions for assessing the reliability of deforestation-rate estimates. These include:

- Who made the estimate, and is it a primary or a secondary source?
- What type of forest and what kind of changes are included?
- Is the estimate based on measurements or subjective judgment?
- If measurement, what kind of remote sensing was used and what resolution?
- What were the dates of measurements?
- Was the whole country or region surveyed, and if not, was a statistical sampling methodology used?
- If a remotely sensed survey was compared with a map, on what measurements was the map based?
- Is the figure an estimate of an actual "historical" change or a projection of a possible future change?

Any study related to land-use and land-cover change should deal explicitly with these eight points in order to avoid confusion between estimates and to better understand the limitations of the data sets used.

Availability of and access to high-resolution satellite imagery for the Congo Basin are likely to improve in the future. However, the accuracy of estimates concerning forest cover and conditions will improve only if systems are put into place to integrate field survey information effectively into the process of classifying remote sensing imagery (Wilkie and Finn 1996). Although software from remote sensing image analysis can quickly categorize the landscape within an image into classes of similar spectral reflectance, only a knowledgeable individual using detailed ground survey information can label each category in complex landscapes. Thus although automatic digital classification analysis of remote sensing information is possible, without field-based information the human interpreter would often be unable to assign classes to a particular land-cover type. GPS-assisted low altitude aerial videography (Sidle and Ziewitz 1990; Marsh et al. 1994) will help greatly with image classification and validation, by providing rapid and accurate field survey information over relatively large areas. Because land transformation in central Africa is primarily the result of small-scale agricultural activities, however, accurate image interpretation will still require field demographic and land-use surveys conducted by trained individuals (Wilkie 1994). In-country personnel in natural resources and forestry departments and ministries have considerable field experience, and with fluency in local languages are usually best equipped to gather interview information. Yet in-country personnel may lack appropriate technical skills and usually lack the resources to conduct systematic surveys.

The key to enhancing the accuracy of, and confidence in, remote sensing image analysis estimates of forest cover in the Congo Basin is to develop strategies to team up the work of field-based conservation biologists with remote sensing experts and vegetation modelers. This will require that donors provide suitable training and logistical support to national departments and ministries to enable them to obtain the much-needed field data, and that NGOs, government agencies, and universities provide opportunities and incentives for scientists working at local and global levels to communicate and share information with one another.

Development of the International Geosphere Biosphere Program (IGBP) Data and Information System (IGBP-DIS) and the System for Analysis Research and Training

(START) is a major undertaking to establish networks of research scientists and to create global data sets essential to modeling climate change and monitoring land transformation at regional and global scales (Justice et al. 1995). The IGBP-DIS development and implementation process may provide the forum for improving collaboration among field scientists and researchers of global change. The United States Geological Survey, NASA, and IGBP-DIS should increase efforts to include field personnel of national and international conservation NGOs active within central Africa in the creation and validation of regional and global satellite-based land-cover data sets.

By more effectively combining the knowledge and experience of field-based researchers with those of remote sensing specialists, our ability to generate accurate maps of natural resource bases and land-cover change for the region will be enhanced greatly.

It is clear from the above program and data summaries that substantial variation exists in our estimates of forest extent, condition, and rate of deforestation. This should not be surprising given the size of the area involved, the differing categories used to classify forests, the range of factors that adversely impact central Africa's forests, and the limited infrastructure at a national level available to monitor forest resources. Despite the lack of accurate statistics, past studies agree that the forests of central Africa are subject to relatively low rates of deforestation compared to the rest of tropical forested Africa or the Amazon. Approximately

Table 8.8

Programs and Their Associated Web Sites

ABBREVIATION	NAME	WEB SITE
CARPE	Central Africa Regional Program for the Environment	http://carpe.umd.edu/
EDC	EROS Data Center Landsat Data Distribution	http://edcdaac.usgs.gov/
ERS-1	European Remote Sensing Satellite	http://earth.esa.int/ERS/
JERS-1	Japanese Earth Resources Satellite	http://yyy.tksc.nasda.go.jp/Home/Earth_Obs/e/jers_e.html
	Mapping activities, central Africa	http:// www-radar.jpl.nasa.gov
NASA/UMD Landsat Pathfinder	National Aeronautics and SpaceAdministration/ University of Maryland	http://www.geog.umd.edu/tropical/
REIMP	Regional Environment Information Management Program	http://www.esd.worldbank.org/reimp/
Space Imaging	Satellite imagery distributor (formerly EOSAT)	http://www.spaceimaging.com/index.htm
SPOT	Système Pour l'Observation de la Terre	http://www.spotimage.fr/spot=us.htm
START	System for Analysis Research and Training	http://start.org
TREES	Tropical Ecosystem Environment oberservation by Satellite	http://ewse2.jrc.it/anonymous/construct/build.pl/98692

0.2–0.6% of forest in central Africa is cleared annually, in contrast to 1% for the Ivory Coast and more than 0.9% on average for the rest of west Africa. However, with present rates of population growth, the rate and extent of deforestation in central Africa are likely to rise rapidly (Barnes 1990). Given the uncertainty of present estimates of forest cover for the region, the likelihood of increasing human impact on forests, and the unknown consequences of global warming on regional weather patterns, what strategies should be adopted to improve our assessment and monitoring of forest extent, composition, and rate of change? The first steps in establishing such a strategy include:

- coordination of national and international efforts to build and maintain spatial databases (satellite imagery, GIS forest maps, and so on);
- exchange of information and expertise between countries (through workshops, networks, the Internet, and so on);
- investigation of the operational use of such new tools as radar imagery or such new optical sensors as MODIS (moderate-resolution imaging spectroradiometer) for land-cover and change-detection studies;
- multi-sensor data fusion;
- multi-scale assessment of deforestation; and
- development of a spatially explicit model of deforestation combining sociocultural and economic factors.

Given the size of the forested regions in central Africa and the need for relatively quick but reliable estimates of areal extent and conversion rates, what is the most cost-effective source of forest information? Field surveys are extremely expensive and, though detailed, provide information at only the local level. Remote sensing, with its synoptic view and repeated coverage, is the most obvious choice for basin-wide forest surveys and has, most recently, been the key to improving estimates of forest cover and condition. Remotely sensed information can be drawn from a variety of sources: multi-spectral and radar imagery, aerial photography, and aerial videography. For a regional survey, how does one choose the best source of imagery? Appendixes 8.1 and 8.2 provide a brief outline of the features, advantages, and disadvantages of each source of remote sensing information. A more comprehensive treatment of the types and uses of remote sensing imagery for natural resources assessment and monitoring can be found at the web sites listed in table 8.8 and Wilkie and Finn 1996.

ACKNOWLEDGMENTS

Information for this paper was compiled during completion of a report titled *Central Africa Global Climate Change and Development* published by the Biodiversity Support Program, a USAID-funded consortium of World Wildlife Fund, the Nature Conservancy, and World Resources Institute. Thanks to Chris Justice and Ned Horning of the NASA Goddard Space Flight Center for collating the past and present uses of remote sensing in central Africa and for generating the Landsat TM image of northern Congo. Lee White and Scott Goetz provided many useful comments on earlier drafts of the manuscript.

REFERENCES

Asrar, G., and D. J. Dokken. 1993. *Earth Observation System reference handbook*. NASA, Washington, D.C.

Barnes, R. F. W. 1990. Deforestation trends in tropical Africa. *African Journal of Ecology* 28:161–173.

BSP (Biodiversity Support Program). 1993. *Central Africa: Global climate change and development—technical report*. Biodiversity Support Program, Washington, D.C.

Castiaux, N., M. Massart, and J. Wilmet. 1991. Environmental study of tropical African urban areas by multispectral satellite imageries (Lubumbashi in Zaire, central Africa). Twenty-fourth International Symposium on Remote Sensing, Rio de Janeiro, Brazil.

de Gauwer, V., and R. de Wulf. 1997. *Potential use of ERS-SAR data to discriminate natural and degraded woody vegetation types in central Africa*. European Space Agency, Florence.

de Grandi, G., M. Leysen, E. Nerzy, A. Bresati, F. Amar, and A. Fung. 1995. Wave scattering modeling of natural target under time evolution: A test case towards the physical interpretation of multi-temporal ERS-1 images over tropical forest. Pages 688–690 in *Proceedings: IGARSS conference.* International Geoscience and Remote Sensing Symposium, Florence.

Devred, R. 1958. La végétation du Congo Belge et du Ruanda-Urundi. *Bulletin de la Société Royale Botanique de Belgique* 65:409–468.

Dobson, M. C., F. T. Ulaby, and L. E. Pierce. 1995. Landcover classification and estimation of terrain attributes using synthetic aperture radar. *Remote Sensing of Environment* 51:199–214.

FAO (Food and Agricultural Organization). 1994. *Tropical forest assessment 1990: Country briefs.*

———. 1996. *Forest resources assessment 1990.* FAO Forestry Paper 112.

FAO-UNEP. 1981. *Tropical forest resources assessment project: Forest resources of tropical Africa. Part 1: Regional synthesis.* FAO, Rome.

Graham, R. L., R. D. Perlack, A. M. G. Prasad, J. W. Ranney, and D. B. Waddle. 1990. *Greenhouse gas emissions in sub-Saharan Africa.* Oak Ridge National Laboratory, Oak Ridge, Tenn.

Grainger, A. 1993. Rates of deforestation in the humid tropics: Estimates and measurements. *Geographical Journal* 159:33–44.

IGBP. 1992. *Improved global data for land applications—a proposal for a new high resolution data set.* IGBP Report No. 20. International Geosphere Biosphere Program, Paris.

IIED. 1988. *Natural forest management for sustainable timber production.* IIED/ITTO, London.

Justice, C. O., G. B. Bailey, M. E. Maiden, S. I. Rasool, D. E. Strebel, and J. D. Tarpley. 1995. Recent data and information system initiatives for remotely sensed measurements of the land surface. *Remote Sensing of Environment* 51:235–244.

Justice, C. O., N. Horning, and N. Laporte. 1993. Remote sensing and GIS contributions to a climate change program in central Africa. In *Central Africa: Global climate change and development—technical Report.* Biodiversity Support Program, Washington, D.C.

Lanly, J. P. 1981. *Tropical forest resources assessment project (GEMS): Tropical Africa, Tropical Asia, Tropical America.* 4 vols. FAO/UNEP, Rome.

———. 1983. Assessment of forest resources of the tropics: A review article. *Forestry Abstracts* 44:6.

Laporte, N. T., S. J. Goetz, C. O. Justice, and M. Heinicke. 1998. A new land cover map of central Africa derived from multi-resolution, multi-temporal AVHRR data. *International Journal of Remote Sensing* 19:3537–3550.

Laporte, N., C. Justice, and J. Kendall. 1995. Mapping the dense humid forest of Cameroon and Zaire using AVHRR satellite data. *International Journal of Remote Sensing* 16:1127–1145.

Lavenu, F. 1987. Digitized vegetation map of Africa—descriptive memoir and map prepared for the department of forestry resources. FAO, Rome.

Malingreau, J. P., F. Achard, G. D'Souza, H. J. Stibig, J. D'Souza, C. Estreguil, and H. Eva. 1995. AVHRR for global tropical forest monitoring: The lessons of the TREES project. *Remote Sensing Reviews* 12:29–40.

Malingreau, J. P., and G. Duchossois. 1996. *The TREES/ERS-1 SAR '94 project.* European Commission Joint Research Centre, Ispra, Italy.

Marsh, S. E., J. L. Walsh, and C. Sobrevila. 1994. Evaluation of airborne video data for land-cover classification accuracy assessment in an isolated Brazilian forest. *Remote Sensing of Environment* 48:61–69.

Mayaux, P., F. Achard, and J. P. Malingreau. 1998. Global tropical forest area measurements derived from coarse resolution satellite imagery: A comparison with other approaches. *Environmental Conservation* 25:37–52.

Mayaux, P., and E. Lambin. 1995. Estimation of tropical forest area from coarse spatial resolution data: A two-step correction function for proportional errors due to spatial aggregation. *Remote Sensing of Environment* 53:1–16.

Millington, A. C., R. W. Critchley, T. D. Douglas, and P. Ryan. 1991. *Estimating woody biomass in sub-Saharan Africa.* World Bank, Washington, D.C.

Myers, N. 1989. *Deforestation rates in tropical forests and their climatic implications.* Friends of the Earth, London.

Rantrua, F. 1996. *Central African region: Regional Environmental Information Management Project (REIMP-CA)—project information document.* GEF/World Bank, Washington, D.C.

Sidle, J. G., and J. W. Ziewitz. 1990. Use of aerial videography in wildlife habitat studies. *Wildlife Society Bulletin* 18:56–62.

Singh, K. D. 1990. Design of a global tropical forest resources assessment. *Photogrammetric Engineering and Remote Sensing* 56(10):1353–1354.

Skole, D., and C. J. Tucker. 1993. Tropical deforestation and habitat fragmentation in the Amazon: Satellite data from 1978 to 1988. *Science* 260:1905–1910.

Stancioff, A., and J. Pessutti. 1981. Evaluation of the deforestation of the Nyunzu area by means of Landsat MSS imagery. Report on the accomplishments of ERTS Zaire in north Shaba, 1980–1981: Volume 2. Contract #AID-AFR-C-1483. USAID, Washington, D.C.

UNESCO. 1978. *Tropical forest ecosystems: A state-of-knowledge report*. UNESCO, Paris.

White, F. 1983. *The vegetation of Africa: A descriptive memoir to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa*. UNESCO, Paris.

Wilkie, D. S. 1994. Importance of detailed field data to assess land use and land cover transformation in central Africa using Landsat MSS imagery. *Human Ecology* 22(3):379–403.

Wilkie, D. S., and J. T. Finn. 1996. *Remote sensing imagery for natural resources monitoring: A guide for first-time users*. Columbia University Press, New York.

Wilmet, J., and P. Vennetier. 1986. Croissance urbaine et évolution d l'environement à Brazzaville (Congo) et Kinshasa (Zaïre). *Photo-Interpretation* 86(5):37–43.

WRI. 1991. Forests and rangelands. Pages 101–120 in *World Resources 1990–91*. World Resources Institute, Washington, D.C.

Yamaguchi, Y., A. B. Kahle, H. Tsu, T. Kawakami, and M. Pniel. 1998. Overview and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). *IEEE Transactions on Geoscience and Remote Sensing* 36:1062–1071.

APPENDIX 8.1

Trade-Offs Associated with Various Forms of Image Data for Land-Cover Mapping

Commercial Aerial Photography

Large-format aerial photography (i.e., at least 70 mm film stock) is used in most countries throughout the world to generate topographic and land-use maps. Thus, archival panchromatic, color, and IR aerial photography often can be purchased from national or state cartographic agencies. If photographs are not available for your area, commercial companies can be contracted to obtain photographs at the most appropriate time and scale. Aerial photography is most appropriate for applications that: have a small area or local perspective, < 1,000 km²; constitute once-off or baseline mapping; and are interested in detecting and identifying small features, <10 m in diameter. The advantages of aerial photography include high spatial resolution, simple operation, and low cost of analysis equipment. The disadvantages of aerial photography include the limited spectral range of photographic film; limited digital analysis (which can be conducted only by scanning photographic prints or transparencies); difficulty in interpreting large volumes of data (large areas); high data acquisition and analysis costs per km² for areas greater than 1,000 km². Soon, new sensors launched by such private companies as Space Imaging will sell very high resolution satellite imagery (5 m).

Non-Commercial Aerial Photography

Aerial 35 mm photography is most often obtained on an ad hoc basis by the researcher. Using your own 35 mm camera, oblique photographs are shot through the open windows of a rented small plane flying over the target area. Aerial 35 mm photography is most appropriate for applications that: involve one or a few small areas, <5 km²; require frequent, repeated coverage; and are interested in detecting and identifying very small features, <5 m in diameter. Advantages of 35 mm aerial photography include: inexpensive microscale surveys (sampling) and monitoring; superior spatial resolution (<1:500 scale possible); simple operation; and low cost of analysis equipment. Disadvantages are: geographic rectification is required for area estimation of features; digital analysis is possible only by scanning photographic prints or transparencies; color infrared film may require users to process and print their own negatives; photographic film has a limited spectral range; and it is difficult (in time and labor) to interpret large volumes of data (large areas).

Advent of digital cameras that merge traditional 35 mm photography with CCD digital data collection adds ease of digital processing to the advantages of aerial 35 mm photography. The Kodak DC 260 digital camera features a 1,536 × 1,024 pixel CCD sensor with 24-bit color. File size is 1.5 MB for a single black-and-white image and 4.5 MB for a 24-bit color image. The Minolta RD-175 offers a 1,528 × 1,146 three-CCD digital camera attached to a standard 35 mm camera lens system.

Though more expensive than photographic imaging and with somewhat lower pixel resolution, digital cameras provide for almost immediate access to images that can be transmitted electronically across telephone lines and computer networks, can be digitally processed and enhanced, and can be integrated easily into documents using desktop publishing software. The resolution of digital cameras is likely to match that of 35 mm photography in the near future. It should be noted, however, that as digital camera resolution increases, so do image storage requirements. For example, DC 260 requires 1.5 MB to store a single black-and-white image, whereas a 1,732 × 1,732 resolution camera, matching the resolution of 35 mm film, would require 3.0 MB to store a single black-and-white image and more than 12 MB for a true color image. Relatively inexpensive digital cameras with lower pixel resolution are now also available.

Aerial Videography

Aerial videography can be obtained much like 35 mm photography, by pointing a videocamera or camcorder through the window of a rented airplane. More often, however, the videocamera is mounted outside the window, pointing directly down, and is controlled remotely by the researcher within the plane (Sidle and Ziewitz 1990). Aerial videography is most appropriate for applications that: involve a few relatively small areas or samples along a transect or linear feature, <50 km^2; require frequent, repeated coverage; and are interested in detecting and identifying relatively large features, >5 m in diameter. As with aerial photography, the spatial resolution of aerial videography can be increased by increasing the focal length of the camera lens or by reducing the altitude of the aircraft. Thus, although it is possible to use aerial videography to count poached elephant carcasses, this high spatial resolution comes at a cost of a very narrow field or view (i.e., narrow survey strip width). Advantages of aerial videography are: low cost—it is the least expensive system for small- to mid-scale surveys (sampling) and monitoring; ability to view imagery during image acquisition; the possibility of visual and digital analysis; simple operation; visible to near-IR spectral range of video cameras; and low cost of acquisition and analysis equipment. Disadvantages of aerial videography are: low pixel resolution; the requirement of relatively high light levels for image acquisition; and the requirement of geographic rectification for area estimation of features.

Optical Satellite Imagery

Satellite imagery can be purchased from commercial companies (e.g., EOSAT and SPOT Image) or from government agencies (e.g., United States Geological Survey, Eurimage). Images can be obtained in digital form (i.e., the image is stored on tape or disk and must be transferred to, and viewed on, a computer) or as black-and-white or color prints and transparencies. Although at present, satellite imagery provides the most comprehensive regional-scale land-cover and land-use information globally, these data are not available for the years before 1972, when the first Landsat satellite was launched. Satellite imagery is most appropriate for applications that: have a large area, regional, or global perspective, >20,000 km^2; require several spatially separate areas to be surveyed, monitored, or compared; require frequent, repetitive coverage; require or can take advantage of multispectral data; and are interested in features larger than the spatial resolution of the imagery. Advantages of satellite imagery are: wide spectral range (UV–thermal); quantitative biophysical measurements from radiometric information obtained from calibrated sensors; wall-to-wall coverage; historical data; digital and visual analysis; digital and photographic (analog) output; ease of comparing different scales and wavelengths; semi-automated processing that makes use of full dynamic range of the data; and low cost. Disadvantages of satellite imagery are: low spatial resolution relative to airborne and ground-based sensors; high startup equipment costs.

Side Looking Airborne Radar (SLAR) and Synthetic Aperture Radar (SAR) Imagery

Radar imagery can be obtained either by plane or by satellite. The preceding remote sensing systems all depend on the sun to illuminate landscape features. In contrast, radar systems provide their own source of illumination by transmitting an EMR signal in the microwave region. These microwaves are reflected back from landscape features and are detected by the sensor. The timing and intensity of the return signal are used to generate the final radar image. To overcome the cloud-cover problems associated with passive optical systems (e.g., Landsat MSS, TM, SPOT, and AVHRR), microwave remote sensing systems should improve spatially extensive data coverage. Advantages of radar are: the ability to obtain data regardless of weather conditions. Disadvantages of radar are: airborne equipment is expensive; satellite systems are primarily experimental; spatial resolution is moderate; image analysis and interpretation methods for natural resource management are not well developed; and radar provides information on terrain and vegetation texture and water content only.

SAR data are available through the European Space Agency in Frascati (Italy). As part of the JRC-ESA TREES project, wall-to-wall ERS-1 SAR mosaic for the entire central African region was built on the data acquired in 1994 using a mobile receiving station located in Libreville, Gabon (de Grandi et al. 1995). Furthermore, the Canadian satellite RadarSat, launched in late 1995, is providing C band (5.3G Hz) SAR satellite data with a ground resolution of 10–100 m ($1,600 per scene). And the Global Rainforest Mapping Project (GRFM) now distributes freely resampled data (100 m) from the Japanese Earth Resources Satellite (JERS-1).

SAR data are available for much of central and west Africa. JERS-1 data were acquired in January–March 1996 for an area between 9° N and 9° S. The Congo River Basin was also covered during October–November 1996, when seasonally wet forests were inundated. Madagascar was acquired in January 1997. The JERS-1 SAR mission terminated on October 11, 1998.

The Earth Observing System (EOS)

Earth Observing System (EOS) satellites are providing new imagery of the earth. Among the new sensors, the MODIS instrument supplies high spectral (thirty-six channels between 0.4 mm and 15 mm) and temporal (two-day cycle) resolution imagery at moderate spatial resolutions (250–1,000 m). These data provide a unique opportunity for regional and global land-cover change studies. On the same platform, the ASTER instrument will collect high spatial resolution (15–90 m) multi-spectral (visible through thermal IR) observations, providing substantial information for subpixel scaling analyses with other instruments (Yamaguchi et al. 1998).

Other Sensors

The Russian Almaz satellite provides 15 m resolution radar imagery on a by-request basis (distributed by Hughes STX in Lanham, Maryland, and SPOT Image Corporation in Reston, Virginia), but the high cost of data ($0.9 per km²) is likely to preclude its use for regional surveys.

APPENDIX 8.2

Choosing the Most Appropriate Imagery

Choice of an appropriate source of remote sensing information depends on the size of the area to be surveyed and the level of detail required. All imagery available for central Africa exhibits a trade-off between spatial detail (the smallest object that can be identified in the imagery) and spatial and temporal coverage. Figures 8.3 and 8.4 show this trade-off graphically. Notice how a single NOAA-AVHRR image has almost basin-wide coverage but its spatial resolution does not capture fine detail within the landscape. In contrast, aerial videography covers only an extremely narrow swath of the landscape but does so with great detail. Table 8.9 describes in very general terms the type of landscape features that can be identified at difference map scales, and table 8.10 summarizes the trade-offs among map scale, spatial resolution, and spatial coverage for the most commonly available sources of land-cover and land-use data for central Africa.

Availability and Relative Costs of Different Remote Sensing Imagery for Regional Mapping

Wall-to-wall mapping of forest cover in the Congo Basin would require more than 40,000 aerial photographs (assuming 50% overlap) at a scale of 1:60,000; more than 700 SPOT images; 120 Landsat TM images; or only 2 AVHRR scenes. These figures do not include the duplicate images that need to be acquired to ensure cloud-free coverage or series of images necessary for vegetation seasonality or land-cover change analysis. For example, the TREES project had to acquire 150 AVHRR scenes to generate a relatively cloud-free forest map of the region.

Central African nations vary greatly in their archives of aerial photography. For example, Cameroon has a relatively complete (nationwide) archive of historical aerial photography, whereas Congo has only very limited photography. Contemporary aerial photographic coverage (within the past ten years) does not exist on a national or regional basis, and would be prohibitively expensive to obtain and analyze. Satellite remote sensing is thus the only feasible approach to monitoring forest cover over the whole basin. Several remote sensing systems are suitable for assessing central Africa's forest resources at different temporal and spatial resolutions (see table 8.10). The AVHRR sensor provides daily coverage at 4 km resolution, and 1 km resolution at only $90 per scene. The high temporal resolution offers the greatest opportunity for obtaining cloud-free imagery quickly and allows for very generalized vegetation mapping at a regional scale. The coarse spatial and spectral resolution limits its usefulness for change detection studies, however.

Although a series of high spatial resolution Landsat and SPOT satellites have been in orbit since 1973 and 1986, respectively, complete coverage for central Africa still does not exist because of dense cloud cover, the absence of a concerted effort to obtain data, and the high cost of obtaining imagery since Landsat was privatized in 1984 (prices rose from $200 per scene to $3,500). The future may not be so bleak. U.S. legislation (the Land Remote Sensing Policy Act of October 28, 1992, Public Law 10255) recognizes the failure of commercialization of the Landsat program by amending the Remote Sensing Commercialization Act of 1984. The amendment moved the Landsat program (acquisition, archiving, pricing, and distribution of imagery, and development of new satellite systems) to the National Aeronautics and Space Administration (NASA) and the Department of Defense (DOD) for joint management. The law provides access to Landsat imagery at marginal cost for U.S. agencies and researchers in the U.S. Global Climate Change Research Program and its international counterpart programs, researchers financially supported by U.S. government agencies, and international noncommercial organizations cooperating with the U.S. government on projects. By June 1999, Landsat 7 imagery was available to the public at the cost of duplication and handling (approximately $200). But the major constraint to Landsat data acquisitions for central Africa is still the absence of a permanent ground receiving station.

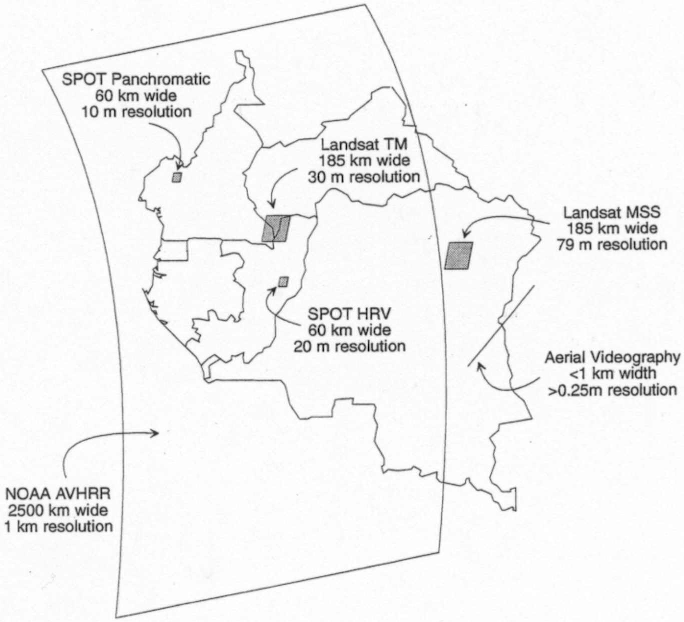

Figure 8.3. Spatial coverage of various remote sensing systems relative to the area of the Congo Basin.

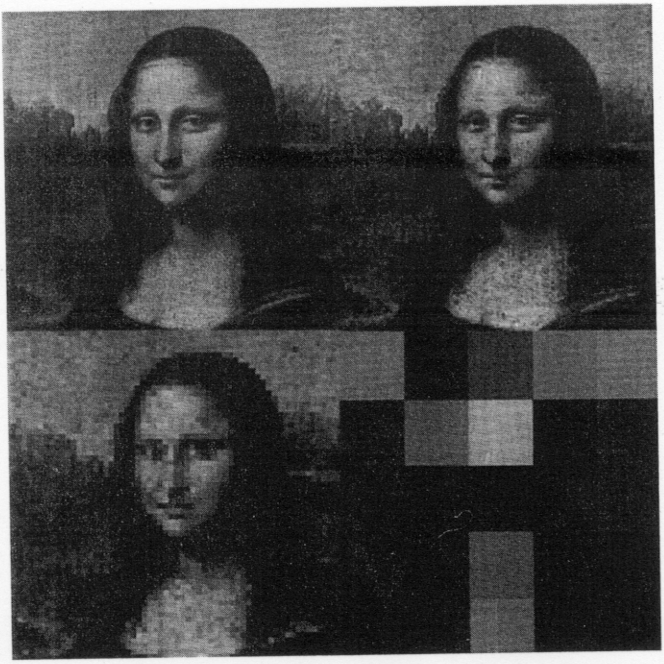

Figure 8.4 Four images of the Mona Lisa, representing the detail visible within SPOT panchromatic 10 m resolution imagery (*top left*), Landsat TM 30 m resolution imagery (*top right*), Landsat MSS 79 m resolution imagery (*bottom left*), and NOAA AVHRR 1 km resolution imagery (*bottom right*).

Table 8.9

A General Guide to What Features Can Be Identified at Various Scales

SCALE	FEATURES
1:500	Plant species, size of individual trees, uses of buildings, function of industries
1:5,000	Volume of timber, wetland boundaries, outline of minor tributaries, transportation networks, property boundaries
1:50,000	Outline of areas of evergreen and deciduous trees, outline of areas of forest associations, direction of flow of water, outline of shorelines, major transportation routes, measurement of agricultural land
1:500,000	Regional vegetation and land-use classification
1:5,000,000	Major river systems, continental vegetation zones, continental cloud cover

The SPOT system is fully operational, with four satellites in orbit. However, the price of SPOT imagery (from \$1,400 to \$3,000) and the relatively small area covered by each scene (60 × 60 km) would make a SPOT acquisition for the region almost five times the cost of Landsat TM. High-resolution coverage of the region may not therefore be feasible until Landsat 7 is fully operational.

Table 8.10

Trade-Offs Between Spatial Resolution and Spatial Coverage for Various Remote Sensing Systems

SENSOR SYSTEM	PLATFORM	MAP SCALE	SPATIAL RESOLUTION	TEMPORAL RESOLUTION	FIELD OF VIEW	IMAGE FORMAT
NOAA AVHRR	Satellite	>1:1,000,000	1.1 to 4 km	12 hours	2,700 km	Digital
Landsat MSS	Satellite	>1:500,000	79 m	16 to 18 days	185 km	Digital
Landsat TM	Satellite	>1:150,000	30 m	16 days	185 km	Digital
SPOT HRV	Satellite	>1:100,000	20 m	5 to 26 days	60 km	Digital
SPOT	Satellite	>1:50,000	10 m	5 to 26 days	60 km	Digital
Panchromatic radarsat	Satellite	>1:50,000	10 to 100 m	3 to 24 days	45–500 km	Digital
Photography	Aircraft	>1:500	>0.10 m	Archive or on demand	<20 km	Hard copy
Videography	Aircraft	>1:500	>0.25 m	Archive or on demand	<10 km	Digital
Digital photography	Aircraft	>1:500	>0.25 m	Archive or on demand	<20 km	Digital