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A new land cover map of central Africa derived from multi-resolution, multi-temporal AVHRR data

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Abstract. We describe a new map of the central Africa region that was derived from National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA AVHRR) observations using a fusion of Local Area Coverage (LAC, 1 km), Global Area Coverage (GAC, 8 km), and ancillary information. The land cover map, produced for the Central Africa Regional Program for the Environment (CARPE), offers a synoptic view of the extent of central African dense humid forests, at relatively fine spatial resolution. Land cover types include dense humid forest, disturbed or degraded forest and various savanna classes. Ancillary information includes political and park boundaries, settlements, rivers and roads. Map validation was performed using a combination of field visits and finer resolution imagery (Landsat Multi-Spectral Scanner (MSS)). Forest cover type mapping errors were at most 20 per cent. The resulting map is useful for addressing a number of resource management issues, a few of which are examined.

1. Introduction

The central Africa region supports the second-largest contiguous area of dense humid forest in the world (after Amazonia). The number of people living within the forested areas of the region is estimated to be 24 million (40 per cent of the total population), of which eighty per cent live by shifting cultivation (Bahuchet 1995). Most of the urban population of the region is highly dependent on forest resources for their daily livelihood (Trefon 1994). Despite this intensive resource use, very few studies have addressed the dynamics of land use and land cover change in the region. Most of the land use change has been associated with the conversion of forested areas to agriculture (Amelung and Diehl 1992). The most recent published estimates of land cover change for the 1981–90 period suggest an annual rate of deforestation ranging from 0.2 to 0.6 per cent (FAO 1993). However, logging activities are extensive and much of the exploitable dense humid forest is under concession or planned for exploitation in the near future (e.g. 36 per cent of the forest in Gabon (MTME 1996), 28 per cent of the forest in the former Zaire (Pagezy 1991)).

Earlier vegetation maps of the central Africa region have been developed by, for example, Keay (1959) and White (1983). Other country-specific vegetation maps have also been produced in the recent past (e.g. Congo (Devred 1958), Gabon (Caballé 1978), Cameroon (Letouzey 1985), Central African Republic (Boulvert

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1986)). These maps were, for the most part, produced through the use of extensive field visits in conjunction with aerial photographs. More recently, vegetation maps of the region have been developed using images from satellite remote sensing aided with computer classification routines, and these have been compared with maps produced previously (e.g. Laporte *et al.* 1995, Mayaux *et al.* 1997).

We report on the development of a new vegetation map for the region derived from a sensor fusion approach. The map was produced for the Central Africa Regional Program for the Environment (CARPE), an initiative funded by the U.S. Agency for International Development (USAID). The CARPE is supporting the design of an integrated spatial database for central Africa in order to advance tropical dense humid forest research activities in the region, to provide new information on forest extent for environmental policy decisions, and to serve local policy makers. The region of interest covers Democratic Republic of Congo (DRC, formerly Zaire), Congo, Cameroon, Central Africa Republic (CAR), Gabon and Equatorial Guinea. Collaborators include the forest service of DRC and Cameroon, World Conservation Society, World Wildlife Fund, and various university research groups.

2. Data and methods

The various data sets used to generate the map described here were prepared through a collaborative effort between the CARPE Project at the University of Maryland (UMD) and the Tropical Ecosystem Environment Observations by Satellites (TREES) Project at the Joint Research Centre (Italy). The data were collected by both groups and all data sets were geographically referenced to a common geographic grid, as described in §2.3. Initial maps were generated at a scale 1/4,000,000 (Laporte *et al.* 1995, Mayaux *et al.*, 1997).

The data used to develop the current map can be broadly classified into two groups: (i) land cover characteristics, derived mostly from spatially contiguous remotely sensed observations; (ii) ancillary information, consisting mostly of vector data describing hydrography, political boundaries and transportation networks.

2.1. *Land cover*

Regional land cover was mapped using two multi-temporal spectral classification techniques at different spatial resolution. All analyses were based on AVHRR (Advanced Very High Resolution Radiometer) observations from the NOAA (National Oceanic and Atmospheric Administration) series of Earth observing satellites.

Classification of the dense humid forests was based on analyses of the near- and mid-infrared channels of a set of single-date Local Area Coverage (LAC) images from the 1990s, which covered most of the humid forest belt roughly ± 3 degrees (± 330 km) north and south of the Equator. Different acquisitions were used for different areas depending on cloud cover and data quality (Laporte *et al.* 1995). The NASA/UMD CARPE component prepared maps of the area comprising Cameroon and DRC using the LAC data. The TREES project prepared the vegetation maps of Congo, Gabon, CAR and Equatorial Guinea (about 25 per cent of the region) using High Resolution Picture Transmission (HRPT) data. HRPT and LAC are different naming conventions and formats for the same data. Classification methods and discrimination of different land cover types are described in Justice *et al.* (1992) and Laporte *et al.* (1995).

Seven land cover types were derived from the AVHRR imagery (summarized in table 1). Savanna vegetation types were derived from the analysis of Global Area Coverage (GAC, 8 km) data alone. Classifications were performed using a temporal series of monthly Normalized Vegetation Difference Index (NDVI) data for the period 1982–87 to characterize seasonality and length of the growing season (Laporte *et al.* 1997). An unsupervised classification was performed using the first two components of a standardized principal component analysis (PCA), done with the seven years of data in order to minimize interannual variation. Classes generated were then grouped according to their spectral–temporal characteristics and their coincidence with the available ancillary information (existing vegetation maps, Landsat Multi-Spectral Scanner (MSS) imagery and field observations).

2.2. *Ancillary information*

Several socio-economic data sets (spatial coverages) were collected as part of the CARPE Geographical Information System (GIS). These coverages are continuously being updated at the World Resources Institute (WRI) and UMD for the CARPE program (available on the world wide web). Hydrographic data were obtained from the 1:1 000 000 ArcWorld vector coverage (ESRI 1992). Population from Deichman (1996).

Protected areas were obtained mostly from the World Conservation Monitoring Center at different spatial scales (WCMC 1993). The Nouabale–Ndoki National Park in Congo was mapped from boundaries provided by the National Geographic Society (Chadwick 1995).

Country boundaries, roads and cities were extracted from the 1:1 000 000 scale Digital Chart of the World (DCW), provided by ESRI (Environmental Systems Research Institute). Only roads classified as 'dual lane (divided) highways', and 'primary or secondary roads' were selected. All roads and boundaries were represented as vectors. Only 1 per cent of the populated point locations (cities and towns) were extracted based on their relative importance in terms of size.

2.3. *Map production and validation*

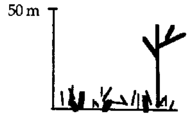
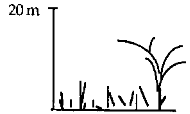
The final map was created using the ArcPlot module of ARC/INFO version 7 on UNIX workstations. An Arc Macro Language (AML) script was written to extract and draw each layer, and a master script was written to create the map environment and invoke the scripts for the layers.

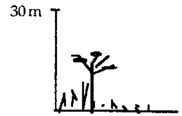
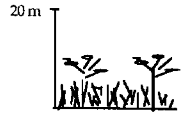
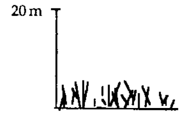
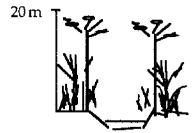
The classified images used for the vegetation layer were imported into a grid cell format and merged into one grid at 1 km spatial resolution. This meant that the coarse resolution grid cells of the GAC classification were represented in the output grid as aggregations of 1 km resolution grid cells ($\pm$ 39 LAC pixels). Each output grid cell was assigned the value of the high-resolution (LAC) classification where a class existed within the LAC grid. Where a class was unassigned or there were no data, the output grid was assigned the value of the low resolution (GAC) classification.

An assessment of forest types accuracy was performed using available Landsat MSS data from 1986 combined with field observations. Two MSS scenes acquired during the dry season were located in a forest/savanna interface and an additional one was located within the forest domain. Comparisons were made between forest/non-forest classes and, within the forest classes, between degraded forest, regrowth (secondary forest), and dense humid forest classes (Laporte *et al.* 1995).

An initial evaluation of the utility of the map for assessment of resource manage-

Table 1. Description of vegetation cover type classes mapped with the AVHRR LAC and GAC observations.

Cover types by domain	Description	Profile
Forest domain (derived from LAC)		
Dense humid forest	Closed forest canopy, logging can be present Multi-strata tree cover density (⩾100%)	
Cultivated forest = also called degraded forest	Degraded forest (forest converted by human activities) Mosaic of fallow, culture, open field, secondary forest or plantations Tree cover density variable generally low (0–60%)	
Savanna domain (derived from GAC)		
Dry savanna	Degraded woodland savanna Dominated by farmland landscape $600 < Pmm < 800$ Tree cover density variable generally low (<10%), occasionally 40%	

Transition zone between wet and dry savanna	Degraded woodland savanna Dominated by farmland landscape $800 < Pmm < 1200$ Tree cover density variable generally low ($<10\%$), occasionally 40%	
Wet savanna	Degraded woodland and grass savanna $1200 < Pmm < 1600$	
Edaphic savanna	Grass savanna dominant on Kalahari sand $1200 < Pmm < 1600$	
Savanna/forest mosaic (derived from GAC)	Riparian forest and fragmented forest in savannas $Pmm > 1500$ mm	

ment was done by examining forest population density in relation to the amount of dense humid forest versus disturbed forest. An index of forest 'vulnerability' (V) was computed as:

$$V = \frac{DF}{F} P_f \quad (1)$$

where DF is degraded forest area, F is dense humid forest area and P_f is the forest population density for the area.

3. Results and discussion

The derived land cover map of central Africa (Figure 1) comprises six layers:

- vegetation type class;
- hydrography (rivers);
- road network;
- protected areas and parks;
- prominent cities and settlements;
- political (country) boundaries.

At the scale shown roads, protected areas and cities are omitted for clarity.

It is clear from figure 1 that the region contains large areas of spatially contiguous forest cover, independently estimated to be ca 1 800 000 km^2 with the LAC data and ca 2 000 000 km^2 with the GAC data. The reason for differences in the two estimates is discussed in §3.1.

Land cover types and proportional land cover by country, as well as the entire central Africa region, are summarized in table 2. The largest extent of dense humid forest, relative to country size, was found in Gabon (80 per cent), followed by Congo (66 per cent), Equatorial Guinea (65 per cent), DRC (48 per cent), Cameroon (37 per cent) and CAR (10 per cent).

3.1. *Map validation*

Validation of the land cover classifications with Landsat MSS imagery and field observations showed that classification errors were mainly due to the coarse spatial resolution of the GAC data relative to spatial heterogeneity in the vegetation (figure 2). The largest errors (ca 20 per cent) were in the forest / savanna interface, where riparian forest and fragmented forest are intermingled with savannas. In this ecotone, forests are distributed following the river network. The largest riparian (gallery) forests are located in the south of DRC, and are evident even in the GAC imagery (figure 1).

In the forest domain, comparisons between the Landsat MSS and LAC land cover classifications resulted in errors that were less than 10 per cent in all cases. The difference between regional estimates of dense humid forest with LAC and GAC was primarily a result of the GAC data being less sensitive to forest disturbance than the LAC, owing to the finer resolution of the LAC data. Also, because the GAC classification is based on multi-temporal observations, non-forest evergreen areas (e.g. herbaceous evergreen swamp vegetation) were sometimes confused with evergreen forest.

Previous work has shown that AVHRR classifications may overestimate the extent of forested areas by up to $\sim$20 per cent compared to Landsat MSS (Laporte

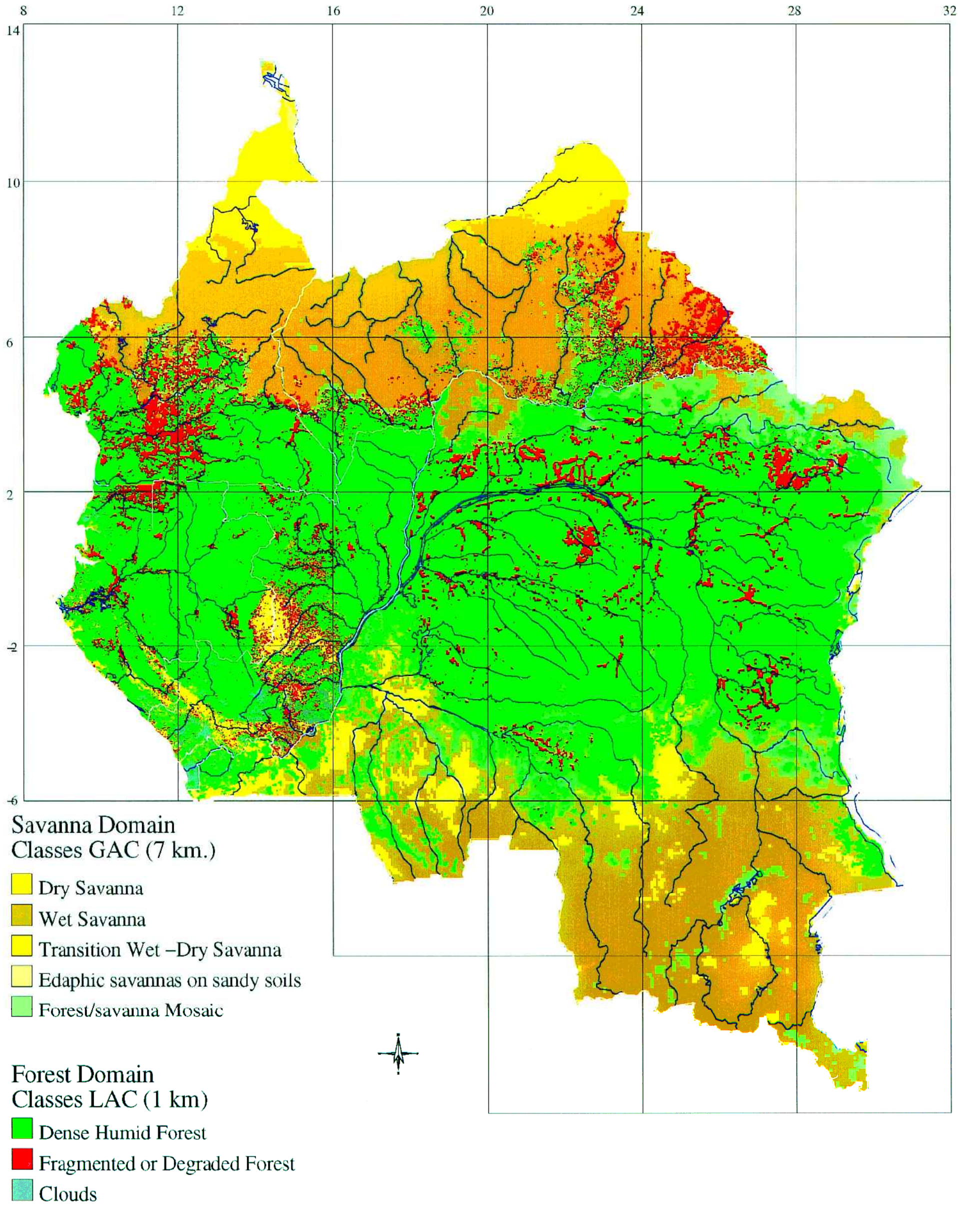


Figure 1. Vegetation map of central Africa derived from NOAA AVHRR data (GAC and LAC).

et al. 1995, Defries *et al.* 1997). The smallest classification errors were within the forest domain owing to the low spatial heterogeneity of the forest canopy relative to the forest/savanna interface. These results are in agreement with a more extensive analysis of AVHRR forest classification errors based on comparison with Landsat Thematic Mapper (TM) images across the tropical belt (Mayaux and Lambin 1995).

Whereas the new land cover map somewhat overestimates forest extent, largely as a result of misclassification errors at the savanna/forest interface, the patterns

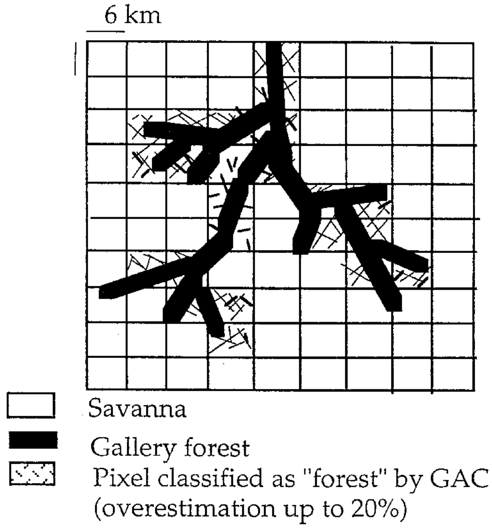


Figure 2. Illustration of the overestimation of forest extent using GAC AVHRR data in the forest/savanna interface.

and proportions of land cover classes are reliable for addressing issues of forest disturbance and degradation (discussed below).

3.2. *Savannas*

Savanna classes (the brown and yellow regions of figure 1) occupy approximately 46 per cent of the central Africa region, mainly as 'wet savannas' receiving average annual precipitation of 1200 to 1600 mm. Wet savannas are extensive in DRC, Cameroon and CAR. Edaphic savannas are located mainly in DRC and Congo on Kalahari sand formations at the forest/savanna interface. Savannas contain variable tree cover as a function of the type of land use, human population density and local biophysical factors. They are also unique in terms of biodiversity (e.g. endemic migratory ungulates and large predators) (Pomeroy 1993).

Savannas tend to be more densely populated by humans than the forested areas, although savanna inhabitants frequently rely on forest resources, including timber and fuelwood. Monitoring of the frequency and intensity of savanna burning using satellite imagery (e.g. Koffi *et al.* 1995, Justice *et al.* 1996, Scholes *et al.* 1996) suggests that fires can extend into forested lands and modify the forest/savanna boundary.

3.3. *Dense humid forests*

The GAC 'forest/savanna mosaic' land cover type (light green colour in figure 1) occurs mainly at the southern and northern boundaries of the forest domain. In the DRC, the largest areas of this mosaic are in the 'Occidental Kasai Region' and the 'Haut Zaire Region' (i.e. Bas and Haut Uélé). These areas contain a mosaic of riparian forest within savanna that may be locally extensive.

The largest extent of 'undisturbed' dense humid forest (dark green in figure 1) was located in the DRC around the Salonga Park, an area of northern Congo from 2° N to the CAR border, south-east Cameroon, and in the north-east of Gabon. Because fine scale logging activity was difficult to map at this spatial resolution, the true area of dense humid forest cover is likely to be less extensive. Field visits and

Table 2. Extent of land cover types by Central African countries and for the region estimated with GAC and LAC observations.

Country	Forest	Degraded forest	Non forest
Democratic Republic of Congo (ex-Zaire) ($2\,327\,642$ km^2)	GAC 1 390 032 km^2 (59.7%)	GAC not defined	GAC Wet savanna 860 220 km^2 (37%) Dry savanna 55 614 km^2 (2.4%) other 21 776 km^2 (0.6%)
	LAC 1 127 211 km^2 (48.4%)	LAC 87 457 km^2 (3.8%)	LAC 764 732 km^2 (32.9%) other 11 861 km^2 (0.5%)
Cameroon (466 266 km^2)	GAC 242 958 km^2 (52.1%)	GAC not defined	GAC Wet savanna 194 683 km^2 (41.8%) Dry savanna 25 068 km^2 (5.4%) other GAC 3556 km^2 (0.8%)
	LAC 173 850 km^2 (37.3%)	LAC 64 773 km^2 (13.9%)	LAC 118 507 km^2 (25.4%)
Gabon (264 694 km^2)	GAC 189 132 km^2 (71.4%)	GAC not defined	GAC Wet savanna 65 433 km^2 (24.7%) Dry savanna 9.875 km^2 (3.7%) other GAC 355 km^2 (0.1%)
	LAC 210 701 km^2 (79.6%)	LAC 23 437 km^2 (8.9%)	LAC 23 237 km^2 (8.8%) other LAC 3577 km^2 (1.4%)

Republic of Congo (341 691 km^2)	GAC 219 085 km^2 (64.1%)	GAC not defined	GAC Wet savanna 94 857 km^2 (27.8%) Dry savanna 27 672 km^2 (8.1%)
	LAC 224 615 km^2 (65.7%)	LAC 38 316 km^2 (11.2%)	LAC 47 480 km^2 (13.90%) other LAC 31 137 km^2 (9.1%)
Central Africa Republic (620 169 km^2)	GAC 114 520 km^2 (18.5%)	GAC not defined	GAC Wet savanna 504 579 km^2 (8.1%) Dry savanna 1070 km^2 (0.2%)
	LAC 60 897 km^2 (9.8%)	LAC 61 371 km^2 (9.9%)	LAC 464 374 km^2 (74.9%)
Equatorial Guinea (25 013 km^2)	GAC 21 615 km^2 (86.4%)	GAC not defined	GAC Wet savanna 3182 km^2 (12.7%) Dry savanna 114 km^2 (0.6%)
	LAC 16 207 km^2 (64.8%)	LAC 5860 km^2 (23.4%)	LAC 611 km^2 (2.4%) other LAC 1996 km^2 (8%)
Central Africa* (4 052 708 km^2)	GAC 2 177 244 km^2 (53.7%)	GAC not defined	GAC Wet savanna 1 728 765 km^2 (42.7%) Dry savanna 120 823 km^2 (3%)
	LAC 1 815 753 km^2 (44.8%)	LAC 218 242 km^2 (6.9%)	LAC 1 419 946 km^2 (35%) other LAC 179 045 km^2 (4.5%)

* including Cabinda (7124 km^2).

interpretation of Landsat images have shown, for example, that large areas of northern Congo have been selectively logged since the mid-1970s and the original forest composition has changed.

A Landsat TM image (figure 3) illustrates the ability of fine resolution remote sensing to delineate the extent of logging roads in densely forested areas, in this case the area around the Sangha river in northern Congo. Two TM scenes acquired 13 years apart (1978 and 1990) were used to map the extent of logging activity and associated road development in a 4400 km^2 area between the villages of Pokola and Kabo, Congo (figure 4). In the 1970s, few logging roads existed in this area. By 1990 most of the area between Pokola and Kabo was linked by a dense network of roads.

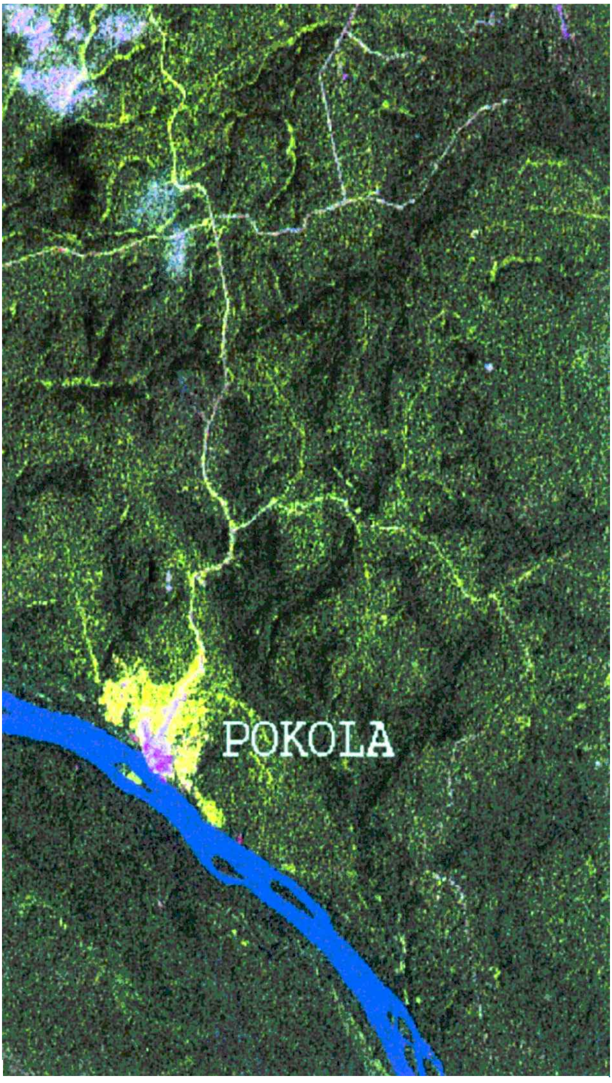


Figure 3. Landsat TM colour composite image (bands 5, 4, 3 shown in RGB) from 28 December 1990 (P/R 182–59) showing the area around Pokola in northern Congo (18 km by 27 km). Logging roads are visible as linear features extending into a forest mosaic (darker greens are mostly swamp forests).

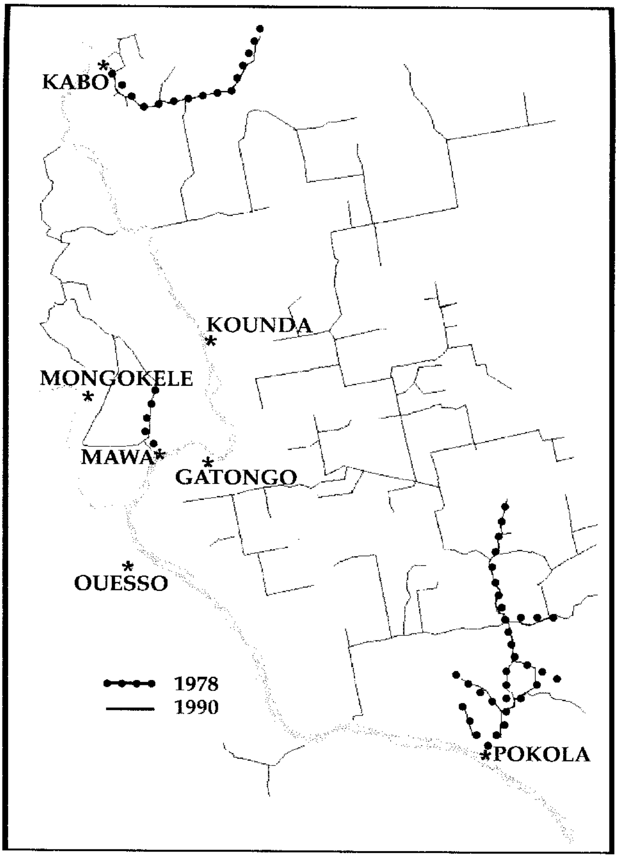


Figure 4. Map showing the increase in logging roads between 1978 and 1990 for a 54 km by 81 km area of the Sangha region of northern Congo. The extent of logging roads was derived from two Landsat TM scenes (20 April 1978 and 28 December 1990).

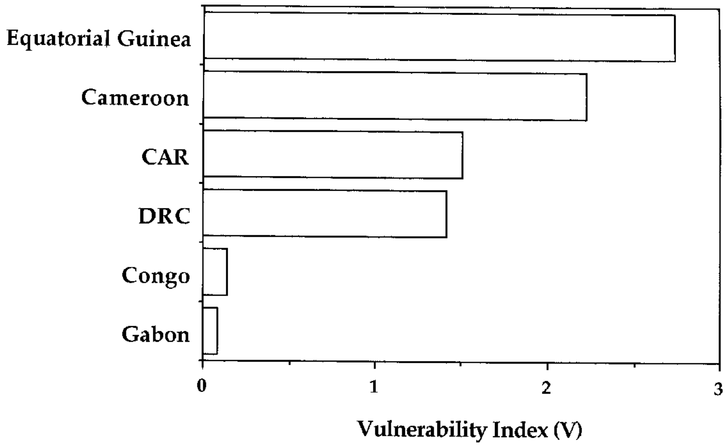
Between 1983 and 1990 more than 2 000 000 ha of forest were legally opened for logging in the Sangha region (DSAF 1991).

Logging roads can have an important impact on the biodiversity of the area (McRae 1997). Although abandoned logging roads provide suitable secondary forest habitat for lowland gorillas (supporting up to six nests per km^2 (Gauthier-Hion 1996)), these same roads allow poachers to deplete forest wildlife and facilitate the penetration of human settlements. Future maps of the region need to include fine scale information to allow improved differentiation between disturbed and mature forest.

Based on application of the 'vulnerability' index, countries that are most likely to suffer future forest degradation and loss of forest cover include Equatorial Guinea, Cameroon and CAR (figure 5). This simple index provides an indication of areas subject to potentially rapid change, but it should be extended to incorporate rates of population change, road density and condition, and other socio-economic variables to improve its utility for forest management (a focus of current research).

4. Conclusions

A new land cover map of the entire central Africa region was developed from multi-scale NOAA AVHRR time-series observations and a suite of ancillary data


Equatorial Guinea
Cameroon
CAR
DRC
Congo
Gabon
0
1
2
3
Vulnerability Index (V)