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Mapping the dense humid forest of Cameroon and Zaire using AVHRR satellite data

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Abstract. Central Africa contains the second largest contiguous rain forest in the world. The current state of this forest is poorly known. The most recent comprehensive national forest distribution maps of the central African region are from the period between 1950–1980 and are not representative of more recent forest degradation or conversion. In this study NOAA-AVHRR data at 1 km resolution have been used to develop current maps of the dense humid forest extent for Zaire and Cameroon. Preliminary estimates of the areal extent of the rain forest are made. Validation of the AVHRR maps is performed through comparison with high resolution satellite imagery (Landsat-MSS) and existing maps. Forest cover maps generated by this study are a fundamental step leading to multi-scale mapping and monitoring of global tropical forests.

1. Introduction

An accurate assessment of rain forest extent and rate of change is important from several different perspectives. At the national level this information provides the basis for developing improved forest management policies. At the regional level, the scientific community involved in the modelling of biogeochemical cycles requires accurate tropical vegetation distribution maps to improve their model inputs. Current national-scale forest inventories in Africa are often incomplete and do not allow a comprehensive view of rain forest distribution (Justice 1992, Malingreau 1992).

There are substantial disagreements on estimates of forest extent and deforestation rates mainly due to differences between vegetation classification typologies and diversity in methodologies, such as comprehensive mapping versus statistical sampling or modelling assessment (Townshend 1992). However, it is known that as much as 50 to 80 per cent of the rain forest of west Africa has been depleted (FAO 1993, Laporte 1990, Myers 1989). The central African rain forest still occupy a large portion (75 per cent) of their bioclimatic domain (FAO 1993), but they are under increasing pressure for timber resources and agricultural land (Justice *et al.* 1992, FAO 1993). Most of the central African rain forest is located in Zaire and Cameroon.

'Forest degradation' or 'conversion' is used in this study to describe land cover changes due to shifting cultivation or permanent plantation (palm, coffee, etc.) in the rain forest domain. Traditional shifting cultivation is sustainable as long as deforested areas are small and fallow long enough to restore a forested formation. At least 15 years are necessary to form a young *Musanga cecroïdes* secondary forest (Trochain 1980), after which pioneer species are slowly replaced by shade tolerant species (Swaine and Halle 1983). But with the increase in human population densities and their more sedentary lifestyle, as well as the establishment of new villages along the road networks, people abandoned subsistence strategies in favour of destructive concentrated exploitation, with the result that reforestation no longer occurs (Malaisse and Binzangi 1985).

The availability of high temporal frequency coverage of satellite observations provides a homogeneous and consistent database allowing the development of standardized multi-scale methodologies for timely assessment of rapid changes occurring in tropical forests (Skole and Tucker 1993, Justice *et al.* 1992). The study described here uses coarse resolution satellite data from the National Oceanic Atmospheric Administration (NOAA) series of meteorological satellites to provide recent rain forest distribution maps for the Republic of Zaire and Cameroon. These maps are compared to and validated with available high resolution remote sensing images and existing maps.

2. Background

The Advanced Very High Resolution Radiometer (AVHRR) is a scanning radiometer and provides data in five spectral channels (Kidwell 1984). For any one location, data are available for three days out of nine within 35° from nadir, compared to the eighteen day repeat cycle of Landsat and twenty-six for the 'Système pour l'Observation de la Terre' (SPOT). AVHRR data have been used for a variety of vegetation monitoring studies in sahelian Africa to assess savanna biomass production (Tucker *et al.* 1985 a), primary productivity (Prince 1991, Diallo *et al.* 1991) and vegetation phenology (Justice *et al.* 1985). They have also been used for continental land cover classification (Tucker *et al.* 1985 b) and estimates of rain forest extent in South America (Cross 1991) and Africa (Nelson and Horning 1993, Paivinen *et al.* 1992, Laporte 1990).

The AVHRR channel 3 ($3{\cdot}55$–$3{\cdot}95\,\mu$m) is particularly well suited for separating classes of different brightness temperature (Kerber and Shutt 1986) and is often used to separate forest from savanna during the dry season (Laporte 1990, Malingreau *et al.* 1989). A simple thresholding method using channel 1 ($0{\cdot}58$–$0{\cdot}68\,\mu$m) was adequate to separate forest from non-forest in the north of Madagascar (Nelson and Horning 1993). The near-infrared channel 2 ($0{\cdot}725$–$1{\cdot}1\,\mu$m) provides the best discrimination between degraded forest and rain forest (Laporte 1990, Malingreau *et al.* 1989). Within the rain forest, the infrared reflectance from vegetated areas is associated with shifting cultivation and plantations. Road networks and associated agricultural land are clearly distinguishable from the surrounding darker rain forest areas. The lower near-infrared reflectance of the surrounding primary forest is due to shading from the irregular forest canopy (Malingreau *et al.* 1989). The spectral responses of these broad vegetation types are sufficiently distinct and contrasting to enable consistent spectral discrimination (Laporte 1990, Malingreau *et al.* 1989, Justice *et al.* 1992). Other more subtle variations are apparent within rain forest canopies, however, consistent interpretation is confounded by variations across the image caused by Sun-sensor geometry and atmospheric effects (Middelton 1991, Holben 1985).

Mapping and monitoring global tropical forests with NOAA-AVHRR data is a fundamental step towards a comprehensive forest monitoring programme and will assist with the prioritization of mapping at a finer scale (Malingreau *et al.* 1992). The most important constraint for using satellite data to monitor the equatorial forests is the persistence of cloud cover. Although there is considerable promise in the use of microwave imagery to overcome cloud cover there is currently no permanent receiving station for acquiring such data over central Africa.

High resolution images are generally used for validation of the 1 km NOAA-AVHRR derived maps (Justice *et al.* 1992). For a complete validation of global 1 km rain forest maps, ground information concerning the vegetation cover, land use practice age and structure of the vegetation cover associated with sampling sites is extremely important. Well documented locational information should be identified based on Landsat sampling across the tropical belt. This information ideally should be standardized, stored and regularly updated in a tropical information system (D'Souza *et al.* 1993, FAO 1993).

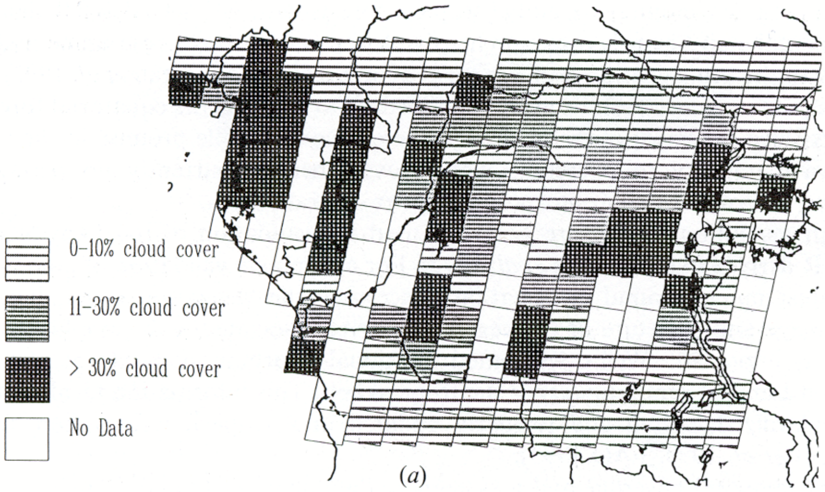
High temporal coverage and a systematic data acquisition and archiving policy are essential for a comprehensive monitoring of forest evolution in tropical areas. In this respect the high resolution satellite coverage of central Africa is currently poor and does not allow a comprehensive mapping. Several on-going projects provide information on tropical forest, such as the FAO Tropical Forest Assessment project (FAO 1981) for estimation of deforestation rate; the Landsat Pathfinder (Lawrence 1992) currently working on a wall-to-wall mapping of the rain forest using Landsat MSS images for three time periods 1970s mid 1980s and 1990s), and the Tropical Ecosystem Environment Observations by Satellites project (TREES 1991) mapping tropical forests with both coarse and higher spatial resolution satellite imagery.

3. Dataset

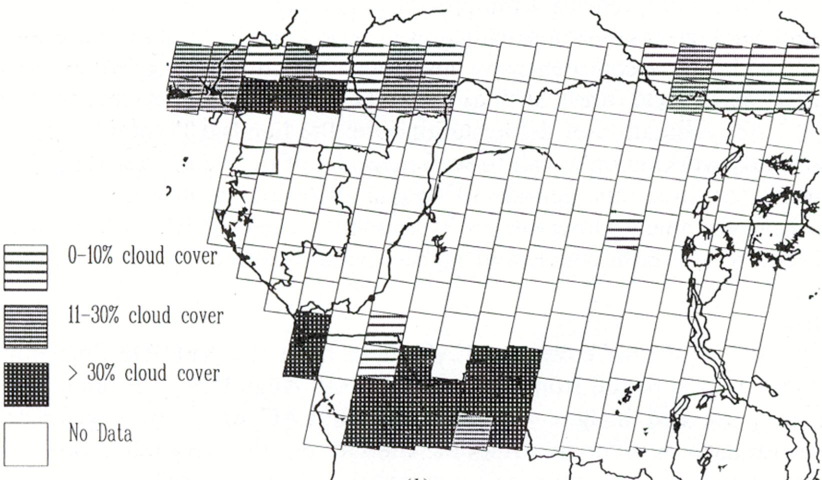
The 1·1 km local area coverage (LAC) data from the AVHRR were obtained from NOAA for the period from December 1989 to August 1990. From a screening of over two hundred images, thirty dry-season LAC orbits were geometrically corrected for two geographic windows centred on the dense humid forest of Cameroon and Zaire. Maximum value composite channel 3 images (Holben 1985) were produced using 8 dry season images for Cameroon (1989–1990) and 10 images for the (1988–1989) dry season for Zaire.

Recent high resolution data for central Africa is sporadic (see figure 1 (*a*), (*b*), (*c*)). The NOAA AVHRR currently provides the only spatially and temporally consistent dataset for the entire region. Three Landsat-MSS images from 1986 were used for quantitative validation of the vegetation classification maps produced from the LAC AVHRR analysis. Landsat-MSS scenes were selected along a south–north transect corresponding to different forest/non-forest interfaces. The choice of images was also determined by data availability, quality and access to local knowledge to assist in the interpretation. Each scene covered an area of approximately 34 000 km^2.

In addition to the MSS validation, published vegetation maps of the region were used for comparison with the AVHRR LAC derived maps: the UNESCO Vegetation Map of Africa (White 1983) at a scale of 1:5 million; the FAO-Cameroon Forest Service vegetation map of Cameroon at a scale of 1:1 million (FAO/UN 1980) and Cameroon Forest Service national forest inventory maps covering a portion of the south of the country (ONADEF 1989). The most detailed national scale vegetation map of Cameroon is a map at 500 000 scale (Letouzey 1985). A vegetation map at


0–10% cloud cover
11–30% cloud cover
> 30% cloud cover
No Data

(*a*)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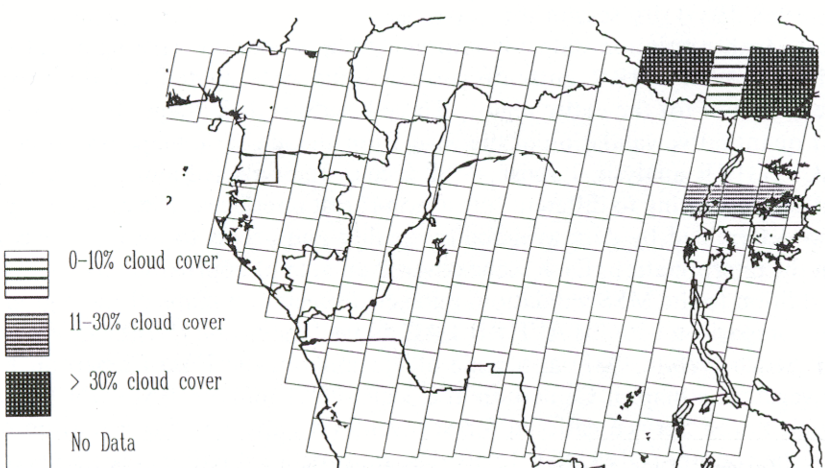
(*b*)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No Data

(*c*)

1:5 million is currently the most comprehensive vegetation map published for Zaire (Devred 1985). Finally, published FAO forest extent estimates for the 1980s and 1990s were compared with our results.

4. Methods

Four main vegetation types are visually identifiable on LAC colour composite images: (1) dense humid forest or rain forest including swamp forest, (2) degraded rain forest which includes shifting agriculture, regrowth plantations and raffia palm, (3) mixed forest and savanna, and (4) savanna (Justice *et al.* 1992, Laporte 1990, Malingreau *et al.* 1989). The correspondence between these remote sensing vegetation classes and traditional vegetation nomenclature is given in table 1.

Table 1. Correspondence between LAC-AVHRR derived vegetation classes with the Yangambi vegetation classification (Trochain 1957) and FAO classes (FAO/UN 1992).

Vegetation types derived from AVHRR analysis	Vegetation classes from the Yangambi classification	FAO typology (FAO 1991)
(1) Dense humid forest: undisturbed forest old secondary forest Tree cover >80%	Closed climatic forest formation: dense moist forest (evergreen and semi-deciduous) mangrove swamp forest, periodic swamp	Closed forest: tree cover >70% tree cover from 40 to 70%
(2) Degraded forest from (1) shifting cultivation young fallow plantations Tree cover variable <80%	Secondary forest derived from the degradation of the dense humid forest forest fallow	Agricultural impact on natural forest (*) short fallow cropping >=33% long fallow cropping <33%
(3) Mixed forest/savanna: mosaic of (1), (2) and (4) with (4) dominant woodland savanna Tree cover from 10 to 40%	Mixed forest/grassland and grassland formation intermingled with dense forest patches or gallery forest Woodland savanna	Fragmented forest forest fraction from 10 to 40% forest fraction from 40 to 70%
(4) Savanna: tree savanna shrub and grass savanna Tree cover <10%	Grass savanna, tree savanna and shrub savanna intermingled in different proportions	Shrubs

(*) Fallow cropping is defined by $\frac{\text{cultivated area}}{\text{cultivated area}+\text{fallow area}} \times 100$.

Figure 1. (*a*) Eros Data Center Landsat-MSS coverage available for the central African region for 1986; (*b*) 1987; (*c*) 1988.

A simple thresholding method using channel 2 and 3 was performed to separate the vegetation types. LAC data were classified interactively on an image processing system using channel 3 composited images and channel 2 images. Figure 2 illustrates the steps leading to the discrimination of the different vegetation types. The first threshold allows differentiation of the savanna class from forested and mixed forest savanna vegetation types using the maximum value composite channel 3 images. Other thresholds are applied on channel 3 composite images to map the mixed forest/savanna and degraded forest classes located in the savanna domain. Finally the less cloudy channel 2 single-date images were used independently to map the dense humid forest from the degraded forest.

For the classification of Landsat imagery, visual analysis of a distributed sample of images (6) and limited field checking in south-west Zaire and south Cameroon provided the preliminary training and validation needed to determine the radiance characteristics of the different classes. Three of the MSS scenes were classified using an automated supervised classification procedure. Training sites for forest, swamp forest, degraded forest, agriculture, savanna and water classes were selected based on availability of field information. The Landsat classifications were limited by the low radiometric quality of the MSS channel 1 and 2 data. However, they provide a general representation of the actual vegetation distribution based on available ground information.

Corresponding LAC AVHRR and Landsat MSS images were geometrically registered using distributed ground control points identifiable in both images. A

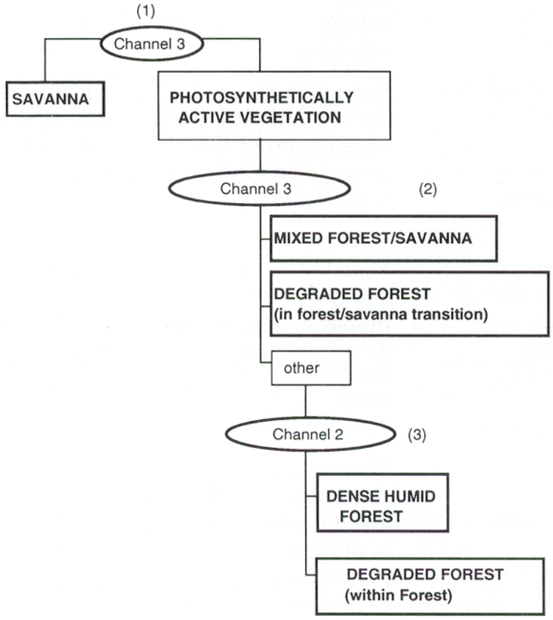


Figure 2. Thresholding method used for the classification of LAC-AVHRR imagery. ▭ LAC vegetation types, ▭ LAC temporary classes, ⬭ LAC channels used to map vegetation types. (1) and (2) Maximum value composite channel 3 images, dry season 1989–1990 (8 dates for Cameroon and 10 dates for Zaire); (3) single date channel 2 images.

third degree polynomial fit was performed to fit LAC control points to their corresponding MSS control points using a least squares regression model. The LAC AVHRR classified image was then geometrically transformed to fit the MSS image using a nearest neighbour resampling.

Preliminary validation of the LAC derived vegetation map was undertaken using two approaches. First, the LAC maps were compared to existing national forest maps from the Office National de Développement des Forêts (ONADEF) 1989, the Cameroon vegetation map (Letouzey 1985) and the Zaire vegetation map (Devred 1958) and the vegetation map of Africa (White 1983). The vectorized vegetation maps were gridded to the LAC pixel resolution using Arcinfo Geographical Information System (GIS) for comparison with the LAC vegetation map. Second, the LAC-AVHRR derived maps were compared visually with Landsat and SPOT images of the region.

A quantitative evaluation of the AVHRR forest mapping was undertaken using three MSS images from 1986. MSS data, at more than ten times the spatial resolution of the LAC data, were considered to be an adequate representation of the actual vegetation distribution. Percentage of error associated with the mapping of the dense humid forest was computed from LAC-AVHRR and Landsat-MSS classification confusion matrix for the three sites.

The percentage of error (e) associated with the mapping of the dense humid forest was computed from the confusion matrix as:

$$e(\%) = \frac{\text{Forest class LAC area} - \text{Forest class MSS area}}{\text{Forest class MSS area}} \times 100 \qquad (1)$$

One MSS image (S1) was located in the Cuvette Centrale of Zaire representative of the forest/degraded forest interface. Two sites were chosen in the transition zone between forest and savanna: site 2 (S2) in the northern hemisphere where three different interfaces are present (forest/savanna, forest/degraded forest and degraded forest/savanna) and site 3 (S3) in the southern hemisphere (Lake Mai Ndombé/Bandudu region), where a forest/savanna interface is dominant.

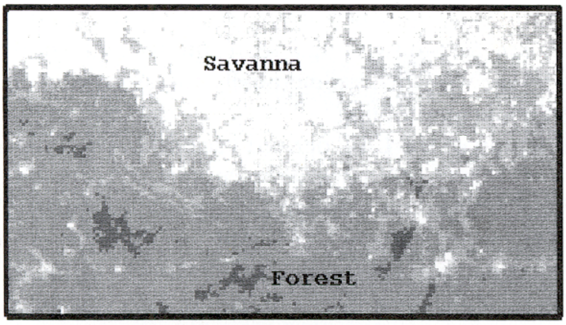
5. Results

5.1. *Resulting maps*

During the dry season simple thresholds on channel 3 allow differentiation of the savanna with the forest domain. Figure 3 illustrates the high contrast found at the forest and savanna interface using channel 3. The grey tones correspond to the mixed forest and savanna class, which has an intermediate spectral signature between forest and savanna.

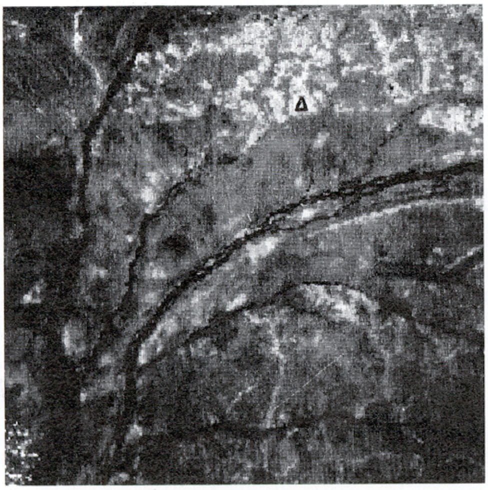
Figure 4 shows a channel 2 image for the Equator region of northern Zaire. Areas of high infrared reflectance (white) are associated with shifting cultivation and plantations, like around Budjala. The Oubangui river (in black) oriented north–south delineates the border with the Congo Republique and the Central African Republique.

The forest maps derived from the AVHRR dataset are presented for Cameroon and Zaire in figure 5. Three broad regions can be identified; the contiguous rain forest in green, a region of mixed forest and savanna occurring at the periphery of the central forest (orange) and the region of predominantly savanna (yellow) to the north and south of the mixed forest/savanna class. Within the mixed forest/savanna



I--------------------I 100 km

Figure 3. Channel 3 image of northern Congo (25 January 1989). Elevated brightness temperatures are shown in white and light grey (savanna environment). The dense humid forest in dark grey and black (low brightness temperature).



Δ BUDJALA (ZAIRE) I------I 33 km

Figure 4. LAC-AVHRR channel 2 image (26 January 1989), Budjala region (3°30′ N, 19°30′ E) in Zaire. Degraded forest is depicted as white, water as black and forest as grey.

zone, the forest is predominantly secondary forest with small stands of primary forest. Within the contiguous forest, areas of degraded forest (red) have been identified. These areas generally follow the communication network and are associated with shifting cultivation and villages along the roads or rivers. From these data 45 350 km^2 of Cameroon rain forest is mapped as degraded forest (mainly shifting cultivation) and 102 821 km^2 for Zaire. The three boxes show the location of the MSS sites used for the quantitative validation of the 1 km LAC vegetation map. The Landsat MSS colour composite image used for validation (site 3, Mai Ndombé

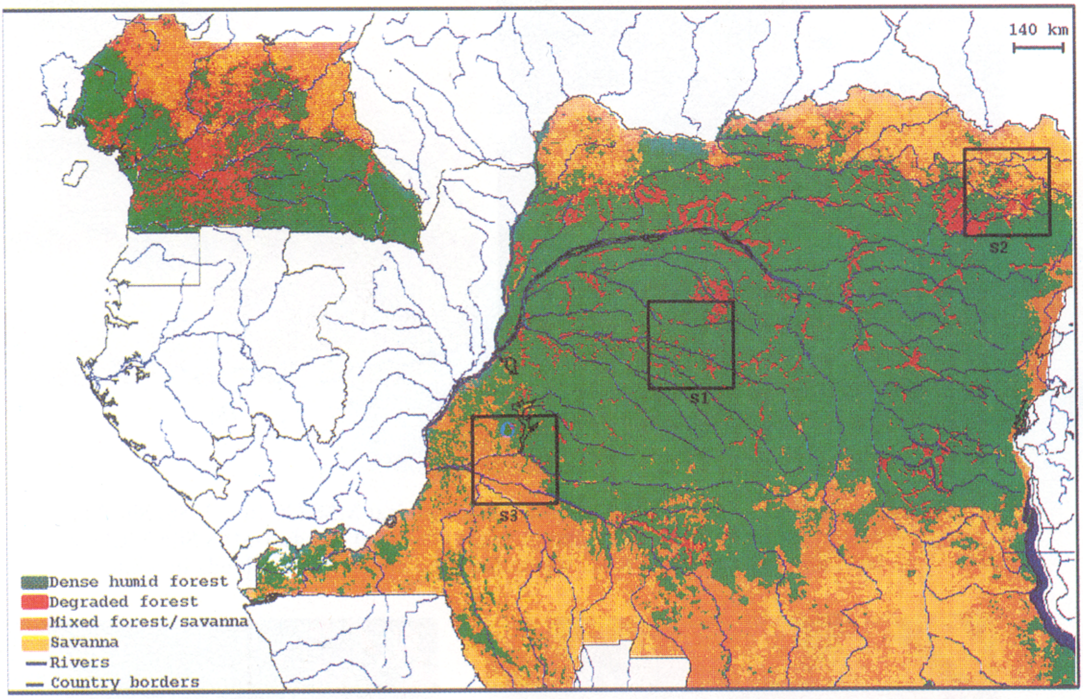


Figure 5. Illustration of the LAC-AVHRR vegetation map of the dense humid forest of Zaire and Cameroon (1989–1900). Boxes (S1, S2, S3) show the location of the Landsat-MSS sites selected for quantitative validation.

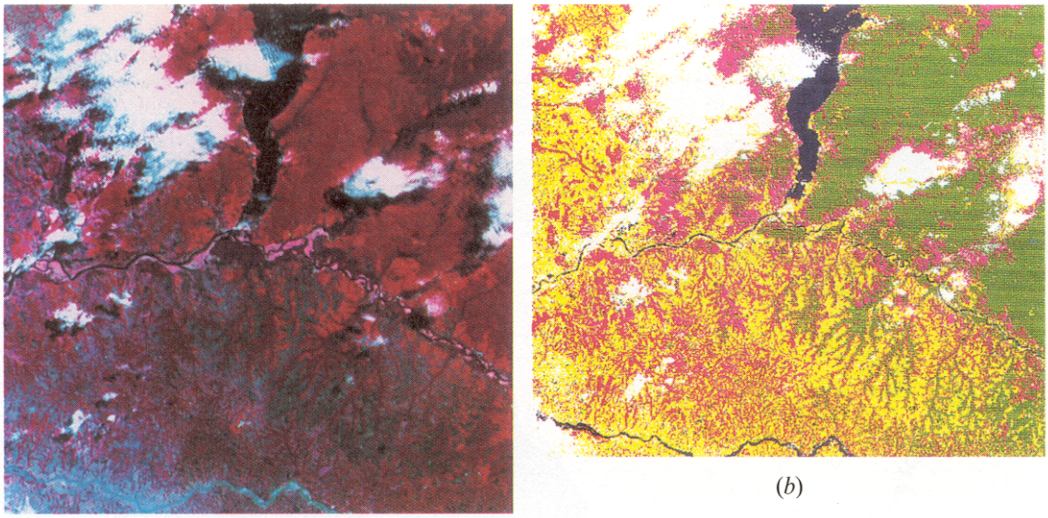
region in south Zaire) is illustrated in figure 6 (*a*). The forest areas (red) occupy most of the northeastern part of the image. The light blue tones are associated with dry savanna. A mixed forest and savanna area is delimited north and south by two rivers. Lake Mai Ndombé (black) is located in the northern centre of the image. White tones are associated with clouds and dense haze. The MSS classification (figure 6 (*b*)) depicts forest in green, degraded forest as red and savanna as yellow. LAC-AVHRR imagery covering the same region is shown in figure 7. The forest areas (in green) are well represented north and east of the Lake Mai Ndombé; savanna and mixed forest savanna formation (red) dominate the south and west of the lake. Figure 8 illustrates the LAC classified image corresponding to site 3. The black lines correspond to the boundaries of the Devred vegetation classes (Devred 1958).

5.2. *Comparison of the resulting maps with published maps and Landsat imagery*

5.2.1. *Qualitative validation*

Area estimates for the classes derived from the LAC vegetation map were compared with FAO statistics for Zaire (FAO/UN 1981) and Cameroon (FAO/UN 1980), as well as to the estimates for 1990 (FAO 1993). The FAO statistics for Cameroon were estimated from Landsat images acquired in the mid-1970s (UN/FAO 1980). The data source for Zaire is unknown.

Using the 1980 (FAO/UN 1980) forest area. We can roughly estimate that 20 000 km^2 of the rain forest of Cameroon has been lost since the mid 1970s (table



(*a*)

(*b*)

Figure 6. (*a*) Full scene colour composite image Landsat MSS (20 June 1986) Site 3 (180-62), Channel 4, 2, 1 in red, green and blue. (*b*) Classified Landsat-MSS Site 3. Classes have been grouped using the LAC vegetation map colour code. Clouds in white.

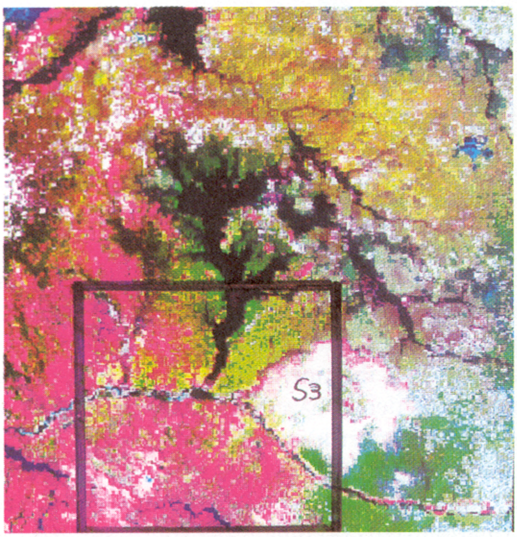


Figure 7. Zaire (Mai Ndombé region) LAC colour composite image 10 February 1989 combining channel 3, 2, 1 in red, green and blue.

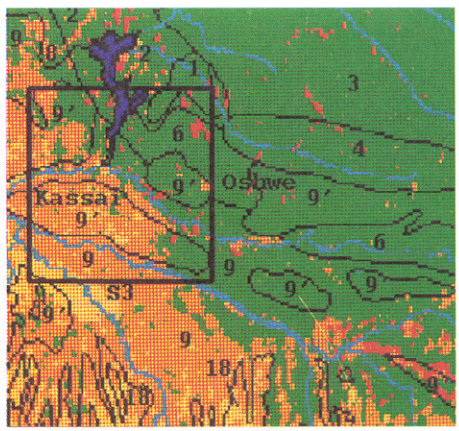


Figure 8. Vegetation map of the Bandudu region (Zaire) derived from the NOAA-AVHRR dataset. The limits of the Devred vegetation map are depicted in black: (1) Edaphic forest. Mixed swamp forest and periodically flooded forest. (3) Dense evergreen humid forest and dense humid semi-deciduous forest of degradation mixed with swamp forest for more than 60 per cent. (4) Mixed forest with degraded forest from evergreen and semi-deciduous forest types. (9) Dense humid semi-deciduous subequatorial forest. (9′) Guinean forest mixed with secondary dense forest with islands of guinean savannas. (18) Guinean and Soudano-Zambezian savannas (tree savanna in valley—grass savanna on plateau).

Table 2 (*a*). Results of forest extent errors for the 3 MSS sites from computed LAC/MSS confusion matrix.

Vegetation classes	Cameroon FAO 1980 (km^2)	Cameroon LAC 1989 (km^2)	Zaire FAO 1981 (km^2)	Zaire LAC 1989 (km^2)
Dense humid forest	191 600	168 087	1 056 500	1 117 963 (1)
Degraded forest	45 350	64 218	78 000	102 821
Mixed forest/savanna	68 550	63 691	824 400	437 565 (2)
Savanna	22 550	24 709	30 700	34 299

(1) The large discrepancy in the areal extent of mixed forest savanna class, which occurs in the transition zone between forest and savanna, is a result of different classification schemes adopted by the two methods.

Table 2 (*b*). Areal extent (km^2) for LAC-AVHRR rain forest map (1989) for Zaire and Cameroon compared to the most recent FAO statistics (FAO 1993).

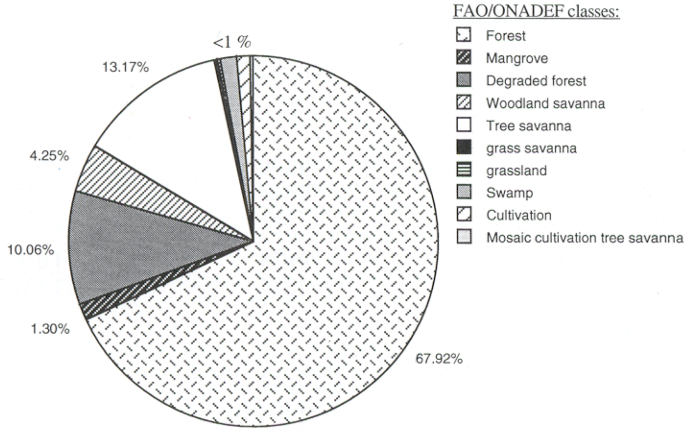
	Cameroon	Zaire
LAC 1989–90		
Rain forest (km^2)	168 087	1 117 963
FAO 1990		
Forest (km^2)		
– Wet (1)	80 170	606 183
– Moist (2)	99 464	450 320
Hill and Montane (3)	17 581	74 781
Total 1 (1, 2)	179 634	1 056 503
Total 2 (1, 2, 3)	197 215	1 131 284
Difference FAO/LAC (in km^2)		
Total 1	+11 547 (6%)	–61 460 (6%)
Total 2	+29 128 (15%)	–13 321 (1%)

2 (*a*)). In Zaire, the original date of the data source and differences in vegetation typology make any comparison difficult.

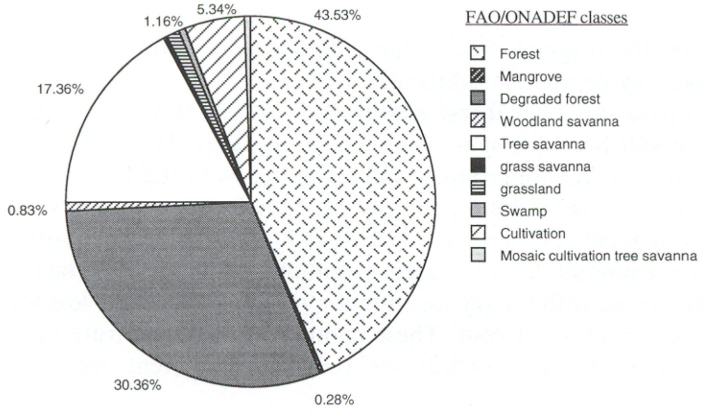
If we compare the 1990 forest assessment (FAO/UN 1993) to the 1989 LAC forest map we still have the same problem of typology. When the wet and moist forest classes from FAO are grouped and compared with the LAC forest extent for 1990, LAC underestimates by 6 per cent the rain forest extent in Cameroon and overestimates by 6 per cent the forest extent in Zaire. If hill and montane forest are included in the computation of the areal extent of the FAO forest, the discrepancy is larger for Cameroon, with an underestimation of 15 per cent, and less for Zaire with an underestimation of 1 per cent. These comparisons demonstrate the difficulty in estimating changes from classifications based on different methodologies and typologies.

A comparison of the LAC classification with FAO-ONADEF 1980 map (FAO/UN 1980) shows that 69 per cent of the area classified as forest on the LAC map corresponded to forested area, 10 per cent to the degraded forest and 13 per cent to tree savanna (figure 9 (*a*)). The LAC degraded class corresponds to 44 per cent of forest area, 30 per cent of degraded forest and 17 per cent of tree savanna on the FAO-ONADEF 1980 map (figure 9 (*b*)). The accuracy of the cover resolution maps is however insufficient to allow the interpretation of differences in vegetation extent in terms of land cover changes between the existing maps and the LAC vegetation map.

A comparison of the satellite-derived boundaries with the Devred map (Devred 1958) shows the core area of moist forest in the Cuvette centrale to be mapped the same, but with considerably more detail in the satellite-derived boundaries at the northern and southern margins. One notable difference is that large areas of the Devred class (9) dense humid subequatorial semi-deciduous forests occur within the region classified as mixed forest and savanna with the satellite data (orange). This is most marked in the Bandundu Province, for an area limited in the north by the Kassai River and Kikwit to the south (5° S, 18·9° E), as illustrated in figure 8. Field observations from aerial survey collected in 1990 lead us to believe that the Devred classification is inaccurate for the current vegetation cover in this area, which was observed to be predominantly savanna. The area has probably been degraded since



(*a*)



(*b*)

Figure 9. (*a*) Comparison of the LAC-AVHRR forest class with the FAO/ONADEF vegetation map classes (FAO/UN 1980). (*b*) Comparison of the LAC degraded forest class with the FAO/ONADEF vegetation map classes (FAO/UN 1980).

originally mapped in 1958. Remnant forest and degraded forests can also be observed along the river networks on the MSS image of 1986 (figure 6 (*a*) and (*b*)).

The Devred class (9′) mixed secondary forest with islands of guinean savanna occurs within the forest class, mapped with the LAC data. This is most evident for an area northeast of Oshwe (3·4° S, 19·3° E) and north and south of the Lukenié River in Bandundu Province. However, we have no corroborating data for these locations.

The UNESCO Vegetation Map of Africa (White 1985) shows similar vegetation limits to those depicted by Devred. There is a good correspondence between the boundaries of the Guinea-Congolian lowland rain forest (wetter and drier types) and the satellite-derived forest boundary for the northern margin of the forest. Areas of discrepancy are more evident in the southwest where the dense humid forest distribution is more complex. Figure 10 (*a*) shows the correspondence between LAC forest class and UNESCO Vegetation Map (White 1983). More than 80 per cent of the LAC forest class corresponds to White's forest class. Most of the degraded forest mapped with LAC (88 per cent) corresponds to forested area on the White map,

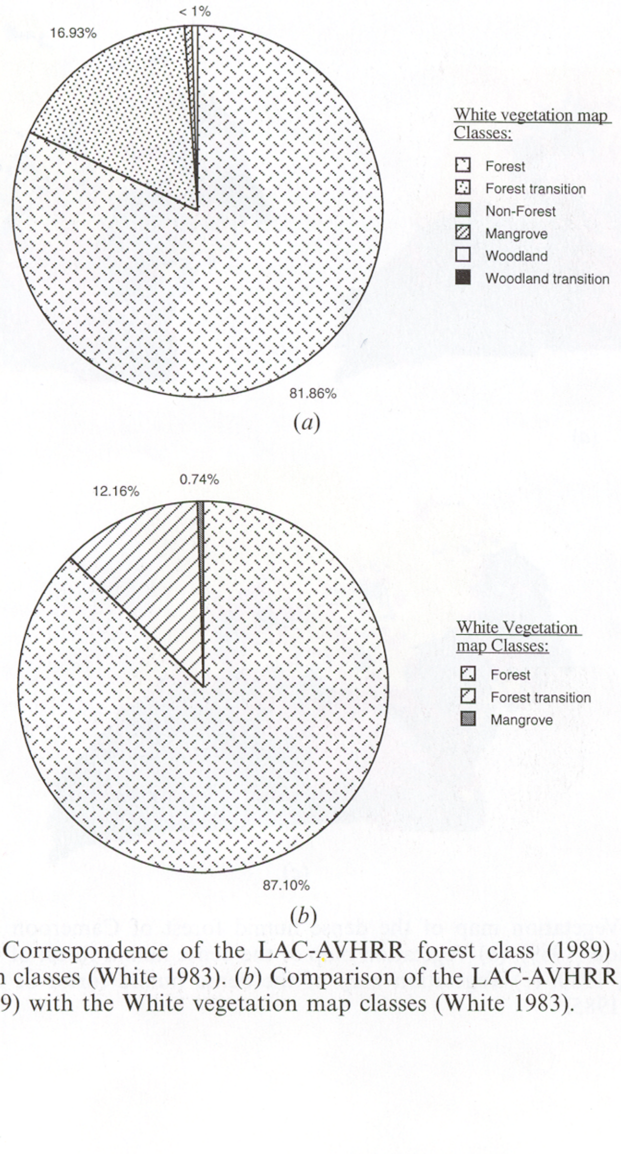
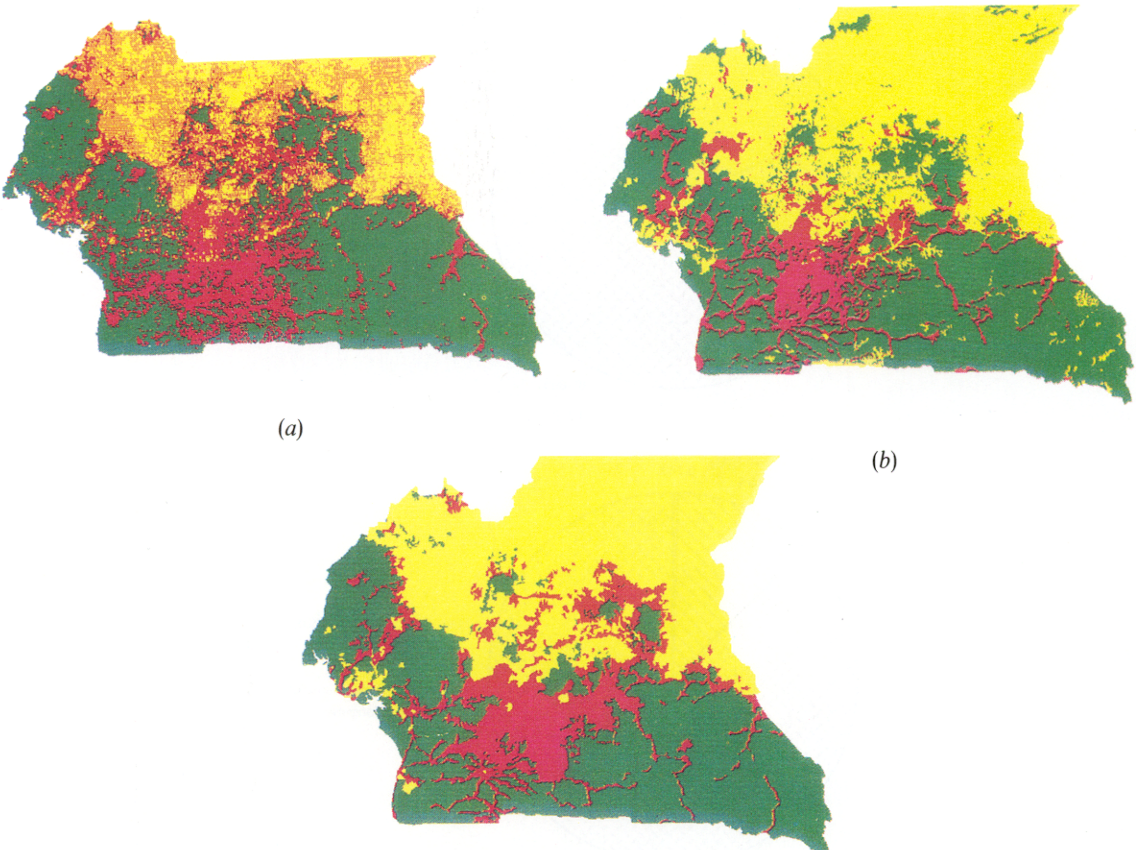


Figure 10. (*a*) Correspondence of the LAC-AVHRR forest class (1989) with the White vegetation classes (White 1983). (*b*) Comparison of the LAC-AVHRR degraded forest class (1989) with the White vegetation map classes (White 1983).

indicating that this map is more a potential vegetation map than an actual vegetation map; 12 per cent of the degraded forest area corresponds to White's forest transition area (figure 10 (*b*)). The Zaire National Forest Services (SPIAF) is currently evaluating the LAC map of potential zones of degraded forest.

In Cameroon the forest extent is better known. The map derived from LAC data shows a good correspondence with the Letouzey map, especially in its delineation of degraded forest (red class). Discrepancies are observed in the south-east portion of the image along the road between Mamfe and Kumba (5° N, 9·2° E). The AVHRR data available for this region are poor due to atmospheric attenuation of the near-infrared data associated with high atmospheric water-vapour concentration (Justice *et al.* 1991, Mpouza and Samba-Kimbata 1990). The largest discrepancies occur in the forest/savanna transition zone, where the forest is patchier (as in the Sananga oxbow 13° E, 5° N).

The general correspondence between previous maps and the satellite-derived maps gives an indication of the success in interpreting broad vegetation classes from the AVHRR, as illustrated in figure 11 (*a*), (*b*), (*c*).



(*a*)

(*b*)

(*c*)

Figure 11. (*a*) Vegetation map of the dense humid forest of Cameroon (from the LAC classification (1989). (*b*) Vegetation map of the dense humid forest of Cameroon from FAO/UN, 1980. (*c*) Vegetation map of the dense humid forest of Cameroon from Letouzey 1985.

5.2.2. *Quantitative validation*

For each Landsat scene, the LAC forest class was decomposed into forest, swamp forest, agriculture, degraded forest and savanna classes. For site 1 most of the area classified on LAC as forested (94·9 per cent) corresponds to the Landsat-MSS swamp forest (figure 12 (*a*)). For site 2, the area of forest on LAC is represented on Landsat by 51 per cent of forest, 16 per cent of degraded forest, 21 per cent of savanna and 11 per cent of agriculture (figure 12 (*b*)). For site 3, the LAC forest area corresponds to 56 per cent forest, 27 per cent degraded forest, 16 per cent savanna and 1 per cent agriculture on the Landsat classification (figure 12 (*c*)).

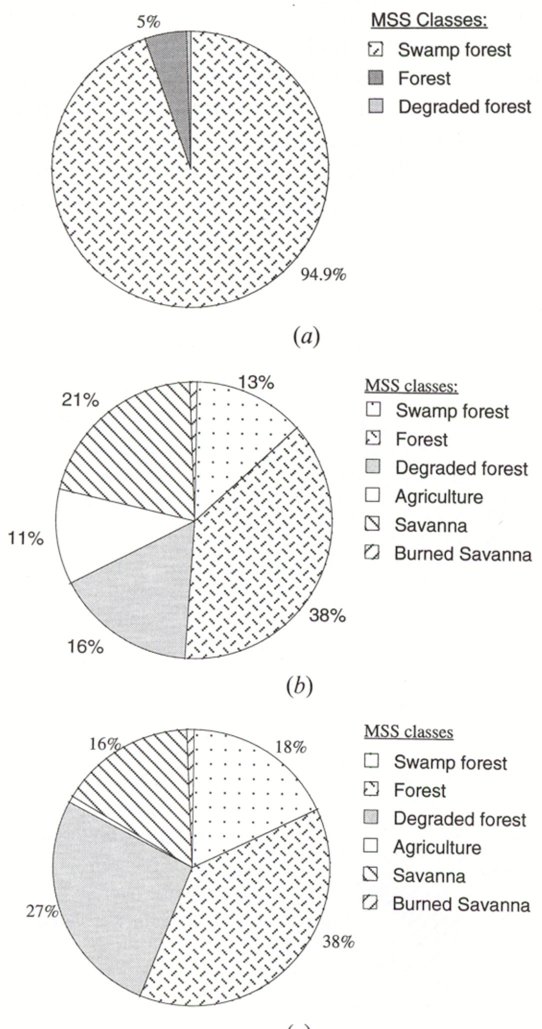


Figure 12. (*a*) Piegraph illustrating the confusion matrix for LAC-AVHRR forest class with the corresponding MSS classes for site 1. (*b*) Piegraph illustrating the confusion matrix for LAC-AVHRR forest class with the corresponding MSS classes for site 2. (*c*) Piegraph illustrating the confusion matrix for LAC-AVHRR forest class with the corresponding MSS classes for site 3.

The mixed forest-savanna areas which were identified in the LAC data occur on two of the Landsat images (site 2 and 3). This mixed class is represented in site 2 by 23 per cent forest, 22 per cent degraded forest, 8 per cent agriculture and 48 per cent savanna (figure 13 (*a*)). For the southern site 3, the area classified as mixed forest/savanna on LAC data is represented by 48 per cent savanna, 36 per cent degraded forest, 13 per cent forest and 3 per cent agriculture (figure 13 (*b*)). These estimates are preliminary and need to be compared with other MSS classifications located in the same type of interface.

To assess the percentage of error associated with the mapping of the dense humid forest we computed from the confusion matrix an error estimate (e). The errors associated with the estimation of the rain forest areal extent by type of forest/non-forest interface for the three Landsat-MSS sites are given in table 3. The largest errors are associated with the mapping of the dense humid forest (overestimation of 19 and 21 per cent) and occur in the forest/savanna transition zone (site 2 and 3), where the dense humid forest is highly fragmented in a savanna landscape. This overestimation is mainly due to misclassification between degraded forest and forest types. Even on MSS images radiometric differences between degraded forest and forested area can be very difficult to establish due to the low quality of the MSS

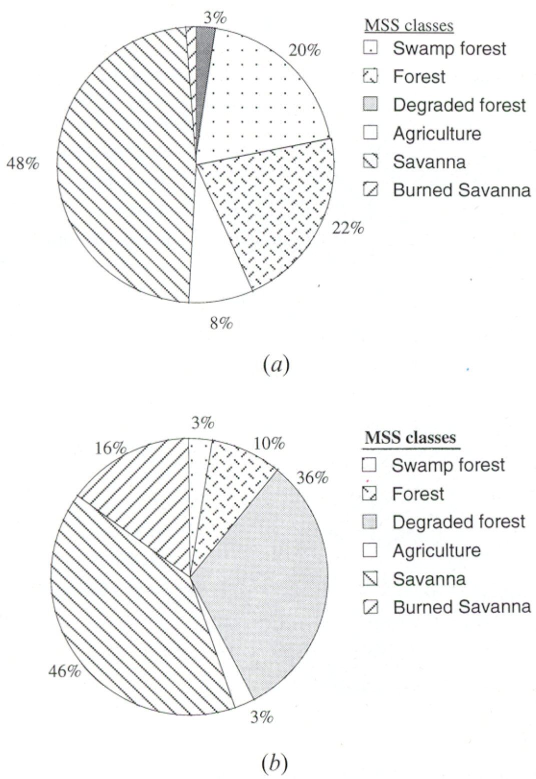


Figure 13. (*a*) Piegraph illustrating the confusion matrix for LAC-AVHRR mixed forest/savanna class with the MSS classes for site 2. (*b*) Piegraph illustrating the confusion matrix for LAC-AVHRR mixed forest/savanna class with the MSS classes for site 3.

Table 3. Results of forest extent errors for the 3 MSS sites from computed LAC/MSS confusion matrix.

Date	MSS (Path/Row)	Zone	(e) %
Forest/degraded forest interface			
20 June 1986	178/60	Forest Zone (S1)	+7·7
Forest/savanna—Forest/degraded forest—savanna degraded forest interface			
15 January 1986	174/58	Transition Zone (S2) (North)	−21
Forest/savanna interface			
20 June 1986	180/62	Transition Zone (S3) (South)	−19

$$e\ (\%) = \frac{\text{Forest class MSS area} - \text{Forest class LAC area}}{\text{Forest class MSS area}} \times 100.$$

dataset through the effects of atmospheric conditions such as the presence of haze. The lowest errors (+7·7 per cent) are found in the Cuvette Centrale where the forest is less fragmented.

6. Conclusions

The coarse resolution satellite-derived maps generated in this study provide the most recent vegetation maps of the central African region and show a good general correspondence with existing vegetation maps. The validation of the AVHRR vegetation classification maps using MSS data provide an indication of the errors in forest estimation by type of forest/non-forest interface. This validation is preliminary and can be improved by a better stratification of the central African region by type of forest/non forest interface and use of statistically representative high-quality high-resolution data.

Comparison of the Landsat and AVHRR classifications shows that the highest errors (19 to 21 per cent) are associated with the most complex spatial interfaces between forest and non-forest classes. The lowest errors (7·7 per cent) are found within the contiguous rain forest and are associated with a more simple forest/degraded forest interface (Site 1).

The higher proportion of boundary pixels between classes at the forest margin leads to a lower classification accuracy. Underestimation of forest area by the AVHRR classification is clearly linked to the discrepancy between the spatial size and distribution of forested areas and the spatial resolution of the sensor. Nevertheless it is our current conclusion that the AVHRR-derived vegetation maps are currently providing the most comprehensive and consistent maps of forest disturbances in central Africa. From the satellite mapping, 64 218 km^2 of Cameroon rain forest and 102 821 km^2 in Zaire are depicted using LAC data as degraded forest, which are mainly areas of shifting cultivation.

With the increasing availability of different satellite coverage over tropical areas the integration of multi-sensor, multi-scale data needs to be analysed in relation to problems associated with the stratification and validation of low-resolution global datasets. A coupled low- and high-resolution satellite image tropical forest monitoring system seems more reliable and feasible than single scale approach. Global world tropical forest monitoring programmes must pay special attention to data acquisition, archiving and the integration of validation procedures across the tropical belt.

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