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Short Communication

Fragmentation and clearance of Liberia's forests during 1986-2000

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Abstract We report estimates of the area and rate of loss and fragmentation of Liberian forests from 1986 to 2000. These estimates are based on comprehensive mapping using Landsat satellite imagery, which has a resolution of 28.5 m. We estimate a total forest cover of 4.65 million ha in 1986 and 4.33 million ha in 2000. Most of Liberia's remaining forest is in two large regions. These forests are very important biologically because they are the largest remaining forest areas in West Africa. The average deforestation rate was low at 0.2% per year during 1986–2000. Although the fragmentation of Liberia's forests is also relatively low, most of the remaining forest is readily accessible as it is within a few km of existing roads. This ease of accessibility suggests that the present low deforestation rate could increase if conservation planning is not effectively implemented.

Keywords Clearance, deforestation, fragmentation, Landsat, land use change, Liberia, remote sensing.

The Guinean Forest region extending from Guinea to Cameroon north of the Sanaga River is one of the world's Biodiversity Hotspots (Mittermeier *et al.* 2004). The forests in this region are separated into two areas by the Dahomey gap, with the Upper Guinea Forests extending from Benin west to Guinea. Almost half of what remains in the Upper Guinea Forests is in two large blocks of mostly continuous forest in Liberia (Kunkel, 1965; Mittermeier *et al.* 2004). Combined, these forests contain >2,000 flowering plant, 150 mammal, 620 bird, and 125 reptile and amphibian species (Kunkel, 1965; Gatter, 1997).

Civil conflict during 1989-1997 and 2002-2003 prevented field studies from being undertaken in Liberia, placing a greater reliance on remote sensing data, including satellite imagery and aerial photography, for habitat monitoring. The project reported here utilized satellite data and aerial surveys to provide the first map of deforestation patterns. We estimate deforestation by providing a high resolution assessment of the remaining forests and patterns of forest loss, and discuss deforestation and the relationship of this to proximity to roads.

Slash-and-burn agriculture has historically posed the greatest threat to Liberia's forests. Logging increased this threat by opening up new access roads in the 1970s and 1980s when timber became the country's third largest export commodity (Mittermeier *et al.*, 2004). Deforestation slowed during the civil war of 1990-1997 and resurged again in 1999 with the new arrival of foreign logging companies, primarily the Oriental Timber Company (Global Witness, 2003). This Company, along with Ivorian and Liberian companies, intensified logging operations, fragmenting the forest through road building to increase timber production to unprecedented levels estimated at 1 million m^3 for 2002. This provided over half of Liberia's foreign exchange, as well as USD 20 million in government revenue, or 22% of GDP (UNSC Expert Panel, 2003). Liberia's forest sector grew until most forest was under the control of rebel factions. In 2003, UN Sanctions (UNSC Resolution 1478) were imposed to prevent logging revenue from funding conflict.

Estimates of Liberian forest area are 20,000-73,000 km^2 before 1980 and 20,000-47,900 km^2 thereafter (Mayer, 1951; FAO, 1981a,b, 1990, 2000; Hammermaster, 1985; Fairhead & Leach, 1998). Two continental maps of forest cover produced from NOAA AVHRR satellite data produced estimates of Liberian forest cover of 42,600 km^2 and 45,500 km^2 for the late 1980s (Päivinen *et al.*, 1989; Stibig & Baltaze, 1993). This range of estimates is caused by varying definitions of forest cover and differing data sources and methods. Because of this, and because there were no previous data on spatial patterns of deforestation for Liberia, there was a need for an accurate, validated map of forest cover and change as a baseline for monitoring of deforestation and logging.

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We obtained 28.5 m resolution Landsat-5 data from 1985-90 for a *c*. 1986 epoch (~1986) and Landsat-7 data from 1998-2001 for *c*. 2000 epoch (~2000), covering all of Liberia. The cited locational accuracy of these data is <100 m (Tucker *et al.*, 2004). Image pairs, each 180-km wide, were co-registered to reduce this error to within one pixel width (28.5 m). Data from all six shortwave channels from both epochs were merged into a single multi-date image for each Landsat tile. Each tile was classified, via iterations of a maximum-likelihood classifier, to produce an estimate of forest cover and change. Classes of cover and change were mapped in a single process (Harper *et al.*, 2007), reducing potential errors in change estimation caused by differences between dates in leaf cover phenology, atmospheric conditions and image interpretation. The resulting land cover classes are forest, non-forest, cloud or cloud shadow, water, and transitions between these types. Each classified tile was filtered using a three-by-three majority filter followed by a 2-ha sieve and merged to produce a single national mosaic.

Aerial surveys in March 2002 produced >2,000 vertical and oblique digital photographs of south-east Liberia that were visually interpreted to assist classification. We acquired triplicate photos with 60% overlap every 11 km along transects spaced at 11 km, as well as continuous vertical video, both time-coded to a global positioning system unit. Over 250 of these aerial photographs were used as reference points to validate the land cover classification. Photographs showing >80% cover of closed-canopy forest or >80% non-forest cover were labeled as forest and non-forest control points, respectively. Comparison between the labeled photos and the image classifications produced error estimates for these two cover types. Fragmentation was assessed by calculating the proportion of remaining forest near a non-forest edge or in small, isolated patches. Roads could be observed in the Landsat images and were digitized on-screen, enabling calculation of the percentage of remaining forest within specified distances from roads.

We estimated a total forest cover of 4.65 million ha in ~1986 and 4.33 M ha in ~2000 (Fig. 1, Table 1). Excluding areas obscured by clouds and using an average time lapse of 14 years between image pairs, we estimated an average deforestation rate of 0.2% per year and a total forest loss of 2.9% over the 14-year period. We extrapolated this rate to forest areas obscured by clouds in the second epoch (0.20 M ha) minus the cloud-obscured areas within Sapo National Park (0.04 M ha of its 0.10 M ha area that we assume is all forest) where clearance is assumed to be minimal, as was the case in the areas not obscured by clouds. This produced an estimated additional forest clearance of only 4,173 ha and additional forest cover of 0.19 M ha, yielding an estimate of Liberia's total forest cover in ~2000 of 4.52 M ha. Deforestation rates averaged over the 14-year period were greatest in Margibi (26%), Bomi (13%) and Grand Bassa (9%) counties, and rates in remaining counties were 0.5-8%.

Table 1 Area, forest cover, and area obscured by clouds in 1986 and 2000, and forest loss, for individual counties in Liberia, and within four bands of distance to roads, as calculated from the satellite data (Fig. 1).

	Area (km^2)	~1986 known forest (km^2; %)	~2000 known forest (km^2; %)	~1986 cloud (km^2; %)	~2000 cloud (km^2; %)	Forest loss (km^2; %)
County						
Bomi	2,154	66 (3.1)	58 (2.7)	61 (2.8)	0	9 (13.0)
Bong	8,312	1,109 (13.3)	1,044 (12.6)	48 (0.6)	0	65 (5.9)
Gbarpolu	9,285	7,009 (75.5)	6,894 (74.2)	233 (2.5)	0	115 (1.8)
Grand Bassa	7,408	1,356 (18.3)	1,224 (16.5)	15 (0.2)	12 (0.2)	120 (8.9)
Grand Cape Mt	4,804	1,801 (37.5)	1,772 (36.9)	463 (9.6)	0	29 (1.7)
Grand Gedeh	10,525	7,715 (73.3)	7,588 (72.1)	216 (2.1)	99 (0.9)	34 (0.5)
Grand Kru	3,658	2,063 (56.4)	1,739 (47.5)	161 (4.4)	328 (9.0)	73 (4.4)
Lofa	10,647	5,539 (52.0)	5,417 (50.9)	91 (0.9)	2 (<0.1)	122 (2.2)
Margibi	2,840	182 (6.4)	135 (4.8)	213 (7.5)	0	47 (25.9)
Maryland	2,219	932 (42.0)	780 (35.1)	19 (0.9)	115 (5.2)	54 (7.7)
Montserrado	1,784	30 (1.7)	29 (1.6)	121 (6.8)	0	1 (3.7)
Nimba	12,057	4,280 (35.5)	4,080 (33.8)	41 (0.3)	41 (0.3)	200 (4.7)
River Ghee	6,005	4,447 (74.1)	3,640 (60.6)	169 (2.8)	789 (13.1)	75 (2.4)
Rivercess	5,216	2,792 (53.5)	2,665 (51.1)	39 (0.7)	0	127 (4.6)
Sino	9,321	7,215 (77.4)	6,287 (67.4)	542 (5.8)	809 (8.7)	120 (2.1)
Total	96,235	46,537 (48.4)	43,351 (45.0)	2,431 (2.5)	2,196 (2.3)	1,192 (2.9)
Distance to road						
0.4 km	11,694	4,234 (36.2)	3,877 (33.2)	404 (3.5)	159 (1.4)	210 (5.1)
1 km	26,854	11,580 (43.1)	10,808 (40.2)	874 (3.3)	431 (1.6)	369 (3.6)
3 km	59,027	27,274 (46.2)	25,538 (43.3)	1,728 (2.9)	1,095 (1.9)	716 (2.9)
5 km	75,381	35,445 (47.0)	33,164 (44.0)	2,089 (2.8)	1,506 (2.0)	900 (2.9)

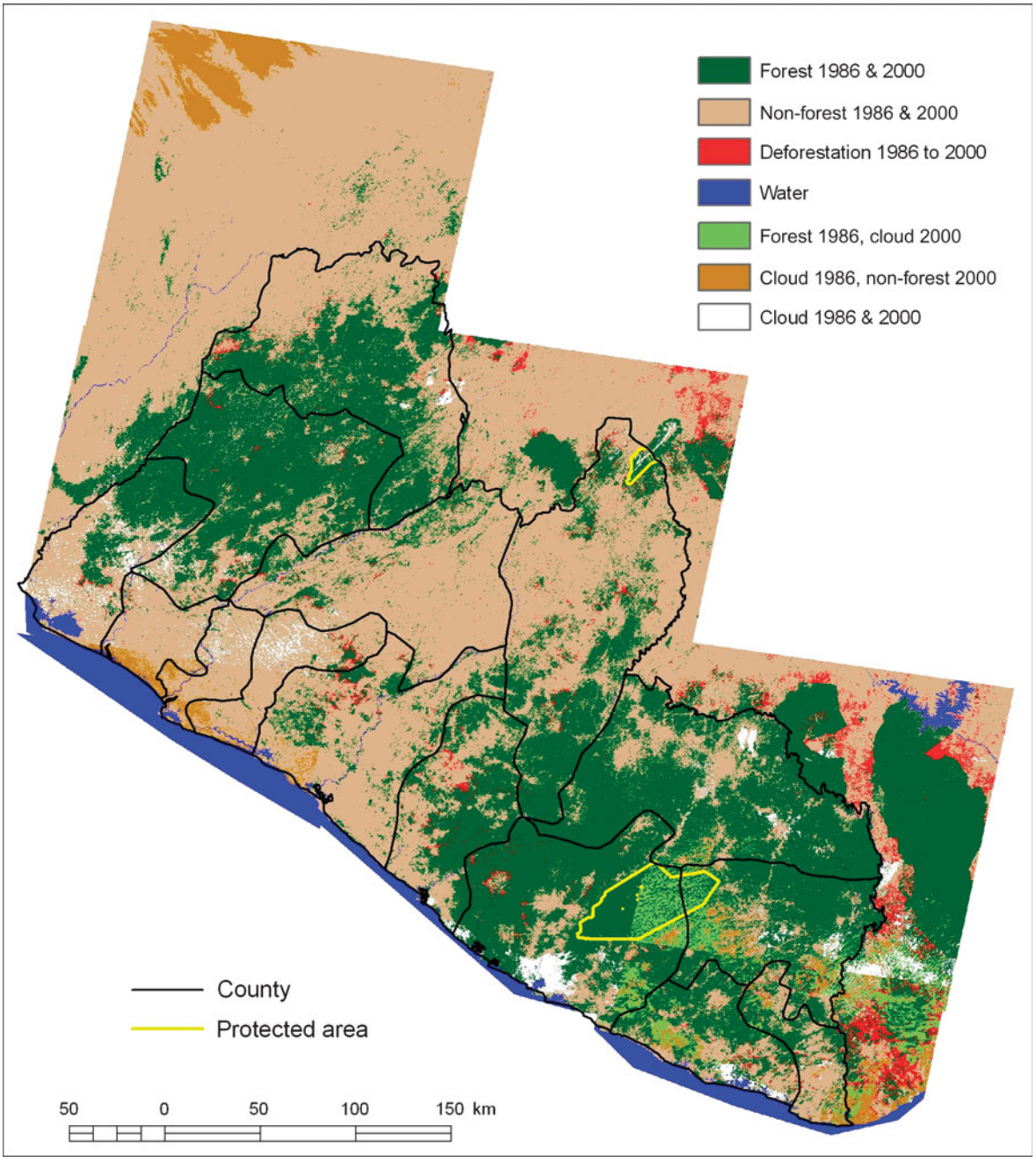

Fig. 1 Distribution of forest and forest clearance in Liberia from 1986 to 2000.

Although we have not completed a national analysis of Côte d'Ivoire, we mapped deforestation for the portion that was within the view of the Landsat images used for this study, which extended as much as 65 km from the Liberian border. We observed a forest cover of >0.96 M ha in this border area in 1986, over half which was within Tai National Forest. The rate of deforestation was 20% over the 14-year period, i.e. much higher than in Liberia.

Validation with aerial photography yielded an estimated average accuracy of 83% for forest cover in ~2000. We believe that the majority of the errors are in areas of secondary or degraded forest in central Liberia. The error estimate also includes that caused by imperfect co-registration between the aerial survey data and satellite images, and thus we believe this to be a conservative estimate of classification accuracy for the country-wide estimate.

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In both ~1986 and ~2000 80% of forests were concentrated in two large patches >1 M ha, whereas the remaining 20% were in patches of <0.1 M ha. However, 75, 93 and 96% of Liberia's forests were within 1, 3 and 5 km, respectively, of a non-forest edge, indicating the potential vulnerability of forests due to ease of access. These values increased to 75, 94 and 97%, respectively, in ~2000. Liberia contains only 657 km of paved roads (CIA World Factbook, 2003) yet our analysis detected >13,500 km of roads in the satellite imagery of the forest zone alone. These are mostly secondary dirt and gravel roads for logging and travel to rural settlements. We found that 44% of all forest in ~2000 occurred within 5 km of a detected road (Table 1). Forest clearance between the two epochs was closely associated with roads, with over 60 and 75% of deforestation within 3 and 5 km of roads, respectively. Deforestation in Sapo National Park was very low (<0.1%) over the study period.

Liberia's deforestation rate, as defined in this study, was less than those for many other tropical countries (FAO, 2000). However, clearings <2 ha in size were not mapped in this study, nor was selective logging. Much of the remaining forest is unprotected and is easily accessible to hunting and other forms of exploitation via the road network. Most forest is near existing roads and farmlands. Field surveys undertaken during the Liberia Forest Reassessment project, after the war, indicate species vulnerability resulting from extensive hunting (E. Waitkuwait, pers. comm.) and that access via roads has increased.

Liberia may provide the last remaining opportunity to protect significant habitat for Upper Guinean biodiversity. The high rate of deforestation in neighbouring Côte d'Ivoire, probably due to expansion in cocoa and oil palm production, is cause for concern as Liberia emerges from conflict and reconstitutes its agricultural sector. Further satellite and field monitoring is needed to assess the degree of degradation from logging. This should be conducted in coordination with a deforestation update using more recent satellite data. The data in this study forms a national baseline for regular monitoring.

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Biographical sketches

T. Christie helped found the Conservation International Liberia office and is interested in natural resource governance and reform. M.K. Steininger studies biogeography, land-use change, tropical forest ecology, and satellite applications in these fields. D. Juhn's interests include technical applications and technology transfer in conservation. A. Peal was formerly in the Bureau of Forest and Wildlife Conservation of Liberia, now the Forestry Development Authority, and is co-founder of the Society for the Conservation of Nature in Liberia and the Society for the Renewal of Nature Conservation in Liberia. He helped create Sapo National Park in Liberia and was a 2000 winner of the Goldman Environmental Prize for the Environment.

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