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RELATIONSHIP BETWEEN FOREST CLEARING AND BIOPHYSICAL FACTORS IN TROPICAL ENVIRONMENTS: IMPLICATIONS FOR THE DESIGN OF A FOREST MONITORING APPROACH

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The location of forested areas at four reference dates (1940, 1950, 1961, and 1977) as derived from aerial photography and Landsat MSS data was digitized and entered into a geographically-referenced data base. Ecological zones as portrayed by the Holdridge Life Zone Ecology System, and the location of roads and railways were also digitized from maps of the entire country as input to the data base. Information on slope gradient and soils was digitized from maps of a 21,000 square kilometer area, corresponding to the San Jose 1:200,000 Quadrangle map. The total area of forest cleared over four decades as related to biophysical factors, was analyzed within the data base and deforestation rates and trends were tabulated. The relationship between forest clearing and ecological zone and the influence of topography, soils, and transportation network are presented and discussed. Quantitative information on these relationships and data from other countries will form the basis for predictive modeling of changes in the forest environment in tropical and subtropical regions.

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ABSTRACT

The scope of the work embodied in this paper was to analyze the relationship between forest clearing, biophysical factors (e.g., ecological zones, slope gradient, soils) and transportation network. The country of Costa Rica was selected as a study site because of the ecological diversity present within a relatively small area, and the availability of maps depicting biophysical information.

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predictive modeling of changes in the forest environment in tropical and subtropical regions.

Introduction

Tropical forests have great importance with respect to the global energy balance, climate, geochemical cycle and various beneficial resources they provide to mankind. Although considerable economic and human resources have been allocated to study the environmental impacts of forest clearing or "deforestation" in tropical regions (U.S. Department of State, 1978 and 1980, World Bank, 1978, Zerbe et al., 1980 and Barney, 1980), there are many uncertainties concerning actual rates and trends of tropical deforestation. Tropical deforestation estimates differ by 100% or more (Brown and Lugo, 1980).

A National Academy of Sciences report (Myers, 1978) has been cited in many U.S. Government reports as the most complete work on "tropical deforestation", although some authors dispute Myer's deforestation estimates and related conclusions concerning environmental impacts (Sedjo and Clawson, 1983). A Food and Agricultural Organization (FAO) report (Lanly, 1982) sponsored by the UNEP Global Environmental Monitoring Program (GEMS), may have replaced the Myers report as the "best available data" concerning tropical deforestation. However, like the Myers report that preceded it, there is no quantifiable basis to determine the reliability of the FAO estimates. The FAO report could serve as a baseline against which future tropical forest change can be measured in the 76 countries targeted by the document, but a more standardized, quantifiable approach is needed to derive current deforestation estimates.

Several authors have demonstrated the utility of remotely sensed data for detecting forest change (Sader 1980; Joyce et al., 1980; Miller et al, 1979 and Novaes, 1980). Remote sensing techniques coupled with computer technology and appropriate sampling methodology may offer the best opportunity to systematically monitor changes and trends in the tropical (frost-free) environments.

NASA's Remote Sensing Research in Tropical Environments

A research program entitled "Remote Sensing of Forest Dynamics in Tropical Regions" is being conducted at the NASA-Earth Resources Laboratory of the National Space Technology Laboratories in Mississippi. The research addresses two general objectives: (1) to develop an ecologically-oriented stratification scheme and (2) to design a tropical forest inventory and monitoring system utilizing remotely sensed and biophysical (terrain, soils, etc.) data analyzed in a computerized Geographic Information System (GIS). The ultimate goal of the projected 4 year research program is to develop globally applicable sampling/inventory methodologies to increase the precision of biomass estimates, timber volume, organic carbon and CO_2 flux, and current deforestation rates and trends.

Approach

The first task of NASA's investigation was to build a data base and analyze the relationship between forest clearing and biophysical landscape characteristics. The country of Costa Rica was selected as a study site because of the ecological diversity present within a relatively small area and the availability of published maps depicting biophysical information. The major hypothesis set forth in this investigation was that the propensity of a forest landscape to be cleared of primary forest is related to various biophysical characteristics of the landscape and other man-induced factors. Specific hypotheses concerning forest change by life zone, soils and slope class will be investigated to address the major hypothesis stated above.

Furthermore, by quantifying these relationships and identifying important "predictors" of forest change, an improved forest change inventory and monitoring approach can be implemented utilizing remotely sensed (orbital satellites) and corrollary data.

Methods

Forest maps depicting the location and extent of all primary, dense, (>80% crown closure) forest in Costa Rica at four reference dates were acquired from the Costa Rican National Planning Agency (Perez and Protti, 1978). The forest maps were derived through interpretation of aerial photos (1940, 1950, 1961) and image analysis of Landsat MSS data (1977). The forest boundaries of each date were transferred to a base map, digitized and reformatted to raster data in the ERL computer.

Also ecological zones of the entire country as portrayed by the Holdridge Life Zone System (Holdridge, 1967) and transportation network (roads and railroads) were digitized from published map sources. Information on slope gradient, soils and geomorphology were acquired from the Instituto Geografico National. In addition, data were entered into the data base for a 21,000 square kilometer area that was selected for detailed study, corresponding to the San Jose 1:200,000 quadrangle map sheet.

All digitized data were transformed to raster image files in a common georeferenced data base. In this form, individual files could be queried to generate tabular summaries of land area occupied by each class of information. Manipulation and merging of the data files was performed to examine the relationship of various biophysical and man-induced factors to the phenomena of forest clearing.

Results and Discussion

At the country level, tabular summaries of the total extent of forest area were obtained at each reference date. These data indicate that total primary forest remaining in 1940, 1950, 1961, and 1977 was 67%, 56%, 45%, and 32%, respectively. Assuming that Costa Rica was originally 99.8% forested (Tropical Science Center, 1982), approximately 2/3 and 1/3 of the primary forest remained in 1940 and 1977, respectively. Average annual rates of deforestation in primary forest increased slightly from the 1940-50 period (1.6%/year) to the 1950-61 period (1.8%/year) and again in the 1961-77 period (1.9%/year). Specific relationships and trends in forest clearing will be examined in the following series of data analyses.

Forest Clearing vs. Life Zone

The Life Zone map of Costa Rica contained 20 life zones with 8 being transitional from one zone to another. Each life zone is characterized by the integration of 3 climatic parameters: potential evapotranspiration, precipitation and biotemperature (Holdridge, et al., 1971; Tosi, 1969). Forest clearing rates and trends by life zone (excluding Subalpine Rain) were examined for four time periods (pre 1940, 1940-50, 1950-61, and 1961-77). For all time periods except 1961-77, the largest amount of forest area was removed in the Tropical Moist Life Zone, followed by the Premontane Wet Zone (Table 1). For the 1961-77 period, the Premontane Wet Forest was highest (2665 km^2 removed) and the Tropical Wet was second highest in forest land cleared. Primary forest occupied only 11% of the entire Tropical Dry Life Zone as of 1940. Maps depicting forest area prior to 1940 were not available to allow estimates of forest clearing rates in the Tropical Dry and other Life Zones

Table 1. Forest Area by Life Zone at Four Reference Dates - Costa Rica

Life Zone	Life Zone Area (km^2)	% of Total Country	Forest Area 1940 km^2	Forest Area 1940 % Life Zone	Forest Area 1940 km^2 Loss	Forest Area 1950 km^2	Forest Area 1950 % Life Zone	Forest Area 1950 km^2 Loss	Forest Area 1950 % yr	Forest Area 1961 km^2	Forest Area 1961 % Life Zone	Forest Area 1961 km^2 Loss	Forest Area 1961 % yr	Forest Area 1977 km^2	Forest Area 1977 % Life Zone	Forest Area 1977 km^2 Loss	Forest Area 1977 % yr	Loss, Total km^2	% Loss/ Life Zone
Tropical Dry	3733	7	427	11.4	3306	4	-	423	9.9	-	-	4	9.1	-	-	-	-	3733	100
Tropical Moist	990	19	5205	52.6	4698	3562	36.0	1643	3.2	1722	17.4	1840	4.7	593	6.0	1129	4.1	9310	94
Tropical Wet	11517	23	9726	84.4	1791	8867	77.0	859	.8	7582	65.8	1285	1.3	5331	46.3	2251	1.9	6186	54
Tropical Premontane Moist	3659	7	847	23.2	2812	181	4.9	666	7.9	110	3.0	71	3.6	6	.02	104	5.9	3653	99
Tropical Premontane Wet	12005	24	8799	73.3	3206	7363	61.3	1436	1.9	5710	47.6	1653	1.8	3045	25.4	2665	2.9	8960	75
Tropical Premontane Rain	4341	9	4100	94.4	241	3890	89.6	210	.5	3514	80.9	376	.9	3039	70.0	475	.8	1302	30
Tropical Lower Montane Moist	127	<1	<1	-	127	-	-	-	-	-	-	-	-	-	-	-	-	127	100
Tropical Lower Montane Wet	925	2	515	55.7	410	329	35.6	186	3.6	215	23.2	114	1.2	191	20.6	24	.7	734	79
Tropical Lower Montane Rain	3576	7	3446	96.4	130	3341	93.4	105	.3	3114	87.1	227	.6	2925	81.8	189	.4	651	18
Tropical Montane Wet	38	<1	18	47.4	20	10	26.3	8	4.4	-	-	10	9.1	-	-	-	-	38	100
Tropical Montane Rain	1165	2	1123	96.4	42	1095	94.0	28	.2	1067	91.6	28	.2	1023	87.8	44	.3	142	12
TOTAL COUNTRY	51078	100.00																	
Total Primary Forest	50990	99.8	34206	67.1	16784	28642	56.2	5564	1.6	23034	45.2	5608	1.8	16154	31.7	6880	1.9	34836	68

for that period. The highest average annual rates[1] of forest clearing occurred in the Tropical Dry (9.9%) and the Premontane Moist Forest (7.9%) between 1940 and 1950. The Premontane Moist and Tropical Moist Life Zones had the highest annual rates of deforestation in the last three time periods.

Tosi (1980) reported that between 1971 and 1977, among Life Zones with a large total land area, the Tropical Moist Life Zone had the highest annual rate of deforestation (7.6%), followed by the Premontane Wet (3.7%) and the Tropical Wet (2%). Our computations (1961-77) show the same three life zones in the same order as having the highest deforestation rates, although our annual rates are slightly lower over the longer period. Tosi's estimates include both primary and secondary forest where our computations relate only to clearing of primary forest.

Forest clearing within the land area represented by the San Jose 1:200,000 scale quadrangle show similar trends to the entire country results (Table 2). Of the Life Zones with a larger land area, the Tropical Moist Forest had the highest annual forest clearing rate for the 1940-50 and 1950-61 periods. The Tropical Moist was one of 4 life zones that were totally cleared of primary forest by 1961. The Tropical Wet and Premontane Wet life zones had the greatest amount of forest area cleared in the last 3 time periods. Annual forest clearing rates were slightly higher for the San Jose quadrangle as compared to the country level. For the 1950-61 period, the annual rate was 2.7% for the San Jose quadrangle compared to 1.8% for the entire Country. The San Jose quadrangle contains the majority of the urbanized area and population within Costa Rica. Population density by Life Zone according to Tosi and

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[1]The Montane Wet and the Tropical Dry Life Zone had a 9.1%/year rate of clearing but the total area cleared was only 10km^2 and 4km^2, respectively.

Table 2. Forest Area by Life Zone at Four Reference Dates - San Jose 1:200,000 Quadrangle

Life Zone	Life Zone Area (km^2)	% of Total Country	Forest Area 1940			Forest Area 1950				Forest Area 1961				Forest Area 1977				Loss, Total km^2	% Loss/Life Zone
			km^2	% Life Zone	km^2 Loss	km^2	% Life Zone	km^2 Loss	% yr	km^2	% Life Zone	km^2 Loss	% yr	km^2	% Life Zone	km^2 Loss	% yr		
Tropical Dry	171	1.5	-	-	171	-	-	-	-	-	-	-	-	-	-	-	-	171	100
Tropical Moist	1746	15.2	178	10.2	1568	51	2.9	127	7.1	-	-	51	9.1	-	-	-	-	1746	100
Tropical Wet	2160	18.8	1896	87.8	264	1522	70.5	374	2.0	1021	47.3	501	3.0	702	32.5	319	2.0	1458	68
Tropical Premontane Moist	1309	11.4	61	46.6	1248	22	1.7	39	6.4	5	.4	17	7.0	5	.4	0	0	1304	99
Tropical Premontane Wet	2753	23.9	1212	44.0	1541	832	30.2	380	3.1	486	17.7	346	3.8	198	7.2	288	3.7	[illegible]	93
Tropical Premontane Rain	1263	11.0	1176	93.1	87	1073	85.0	103	.9	910	72.1	163	1.4	808	64.0	102	.7	455	36
Tropical Lower Montane Moist	127	1.1	<1	-	127	-	-	-	-	-	-	-	-	-	-	-	-	127	100
Tropical Lower Montane Wet	697	6.1	305	43.8	392	152	21.8	153	5.0	56	8.0	96	5.7	31	4.4	25	2.8	666	96
Tropical Lower Montane Rain	1078	9.4	1004	93.1	74	927	86.0	77	.8	752	69.8	175	1.7	675	62.6	77	.6	403	37
Tropical Montane Wet	39	.3	18	46.2	21	12	30.8	6	1.3	-	-	12	9.1	-	-	-	-	39	100
Tropical Montane Rain	148	1.3	129	87.2	19	114	77.0	15	1.2	97	65.5	17	1.4	70	47.3	27	1.7	78	53
Total Primary Forest	11491		5980	52.0	5512	4705	40.9	1274	2.1	3326	28.9	1379	2.7	2489	21.7	833	1.6	8997	78

Voertman (1964) was highest in the Lower Montane Moist (238.5 persons/km^2). The Premontane Moist Life Zone had the next highest population density (216.2/km^2). Table 1 and 2 indicate total forest loss in the Lower Montane Moist and greater than 99% loss in the Premontane Moist Life Zone by 1961.

Up to this point we have discussed the Life Zones that have experienced the highest forest clearing rates. There are some interesting trends in Life Zones that have experienced low amounts and rates of forest clearing that may be correlated with the life zone parameters. The hypothesis concerning these data are that forest clearing decreases as the potential evapotranspiration (PET) to precipitation (P) ratio decreases[2]. Climates are increasingly humid as the ratio decreases. Although country-wide, the three life zones with the lowest PET/P ratio were the three that had experienced the lowest amount of forest clearing, the Montane Rain was the least deforested in 1977 (12% loss) but had a slightly higher PET/P ratio than both the lower Montane and Premontane Rain forest (Table 1). For the intensive study area corresponding to the San Jose 1:200,000 quadrangle map sheet, the hypothesis appears to be especially valid, although not tested in the rigid statistical sense in this preliminary examination. The Premontane Rain Forest was the least deforested Life Zone in 1977, followed by the Lower Montane Rain and Montane Rain Forest. Likewise, the Premontane Rain Life Zone represents the lowest PET/P ratio of all life zones in Costa Rica followed by Lower Montane Rain and Montane Rain Forest, respectively (Table 2).

A corollary hypothesis to be investigated at a later stage in the research is that the probability of abandonment (and secondary succession) following

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[2]The reader is referred to Holdridge (1967), Holdridge, et. al. (1971), and Tosi (1969) for more information on life zone characteristics.

forest clearing will increase as the PET/P ratio decreases because the wetter, more humid zones are less suitable for non-forest uses and are prone to degrade quickly. Brown and Lugo (1980) have reported that mean plant biomass (in relatively undisturbed forest conditions) was linearly correlated to the PET/P ratio. Deforestation estimates by life zone would be a particularly useful statistic if biomass levels can be correlated with the PET/P ratio as Brown and Lugo suggest.

Forest Clearing vs. Slope Gradient

The digitized slope map contained six slope gradient classes. Computations performed by computer indicated that 61% of the San Jose quadrangle was composed of greater than 30% slopes and only 5% of the slopes were nearly level. By 1940, the 30-45% slope class had the largest forest area cleared (Table 3). Between 1940 and 1950, the highest forest clearing rate occurred on 5-15% slopes (3.0%/year) and the lowest rate occurred on the 0-5% slope class (.4%/year). Between 1950 and 1961, the 0-5% slope class had only .6%/year clearing rate while the next lowest rate jumped to 2.3%/year for 15-30% slopes. The rest of the slope classes were near 3%/year. Between 1961 and 1977, the forest clearing rate dropped considerably on the steeper slope classes and increased substantially on the nearly level slopes (4.4%/year).

The high rate of clearing on the steeper slope classes during the 1950-61 period may be explained by the expansion of the cattle ranching industry during the same period (Tropical Science Center 1982, Tosi 1980). The decrease in forest land cleared on the steeper slopes may have been a result of conservation awareness that materialized in the 1970's and the designation of new national parks, and forest protection zones (e.g., Braulio Carrillo, Rio Macho reserve and Zona Protectora South of La Selva Biological Reserve).

The total forest loss in relation to slope class by 1977 (Table 3), was generally a linear decrease in the percentage of forest cleared as slope gradient increased. The trend was subtle up to the 60% and greater slope gradient class where an abrupt decrease occurred (e.g., 79% loss on 45-60% slopes compared to 54% loss on greater than 60% slopes). This relationship between forest clearing and slope gradient does not approach linearity until the last period. The steepest slope class (>60%) could be considered critical management areas; because the soils are prone to erosion, degradation and subsequent abandonment after the protective forest cover is removed.

Forest Clearing vs. Soils

Seven soil orders and 39 subgroups were present in the San Jose quadrangle. The seven soil orders were: 1) Alfisols, 2) Entisols, 3) Histosols, 4) Mollisols, 5) Ultisols, 6) Vertisols, and 7) Inceptisols. The Alfisols and Vertisols had been totally cleared of forest cover by 1940. By 1977, no primary forest remained on the Mollisols. The total area represented by Alfisols, Vertisols and Mollisols was small and they occur in the Tropical Dry and Moist Life Zones which were favored for agricultural and grazing uses.

The largest amount of land area and some of the highest annual rates of forest clearing occurred on two soil subgroups (Typic Dystrandept-I6 and Typic Dystropept-I26). They are also the two largest in terms of total land area (Table 4). The lowest rates of clearing occurred on Typic Placandepts (I4), Typic Hydraquents (E1) and Oxic Palehumults (U1) which had moderate to strong use limitations for cultivated crops and pasture as a result of either rocky, shallow soils, high rainfall, poor internal drainage or high soil acidity. The Typic Placandept was the only soil unit that experienced no loss in forest cover. It was learned by pinpointing the soil location that the reason for

Table 3. Forest Area by Slope Class at Four Reference Dates - San Jose 1:200,000 Quadrangle

Slope Class %	Slope Class Area km^2	% of Total Map	Forest Area 1940 km^2	Forest Area 1940 % Slope Class	Forest Area 1940 km^2 Loss	Forest Area 1950 km^2	Forest Area 1950 % Slope Class	Forest Area 1950 km^2 Loss	Forest Area 1950 %/yr.	Forest Area 1961 km^2	Forest Area 1961 % Slope Class	Forest Area 1961 km^2 Loss	Forest Area 1961 %/yr.	Forest Area 1977 km^2	Forest Area 1977 % Slope Class	Forest Area 1977 km^2 Loss	Forest Area 1977 %/yr.	Loss Total km^2	% Loss/ Slope Class
0 - 5	532	4.6	327	61.5	205	314	59.0	13	.4	294	55.3	20	.6	88	16.5	206	4.4	444	83.5
5 - 15	2183	19.0	1190	54.5	993	838	38.4	352	3.0	554	25.4	284	3.1	286	13.1	268	3.0	1897	86.9
15 - 30	1843	16.0	786	42.7	1057	576	31.3	210	2.7	428	23.2	148	2.3	324	17.6	104	1.5	1519	82.4
30 - 45	3461	30.1	1458	42.1	2003	1065	31.3	373	2.6	747	21.6	338	2.8	646	18.7	101	.8	281[illegible]	81.3
45 - 60	1800	15.6	883	49.1	917	693	38.5	190	2.2	456	25.[illegible]	237	3.1	373	20.7	83	1.1	1427	79.3
>60	1695	14.7	1336	78.8	359	1200	70.8	136	1.0	846	50.0	354	2.7	776	45.8	70	.5	919	54.2
Total Primary Forest	11514		5980	51.9	5534	4705		1275	2.1	3326		1379	2.7	2493		833	1.6		

Table 4. Forest Area by Soil Class at Four Reference Data - San Jose 1:200,000 Quadrangle

Soil Association Code*	Soil Area km^2	% of Map Area	Forest Area 1940 km^2	Forest Area 1940 km^2 Loss	Forest Area 1950 km^2	Forest Area 1950 km^2 Loss	Forest Area 1950 %/yr.	Forest Area 1961 km^2	Forest Area 1961 km^2 Loss	Forest Area 1961 %/yr.	Forest Area 1977 km^2	Forest Area 1977 km^2 Loss	Forest Area 1977 %/yr.	Loss Total km^2	% Loss Soil Ass.
$H_{2}O$	1128	9.0	-	-	-	-	-	-	-	-	-	-	-	-	-
V-1	5	<1.0	1	4	-	1	10.0	-	-	-	-	-	-	5	100
I-33	617	5.0	-	617	-	-	-	-	-	-	-	-	-	617	100
M-2	2	<1.0	-	2	-	-	-	-	-	-	-	-	-	2	100
A-1	2	<1.0	-	2	-	-	-	-	-	-	-	-	-	2	100
I-17	733	6.0	7	726	5	2	2.8	-	5	9.1	-	-	-	733	100
I-5	124	1.0	25	99	5	20	8.0	-	5	9.1	-	-	-	124	100
I-6	3708	29.0	2692	1016	2212	480	1.8	1759	453	1.9	1491	268	1.0	2217	60
I-2	449	4.0	126	323	102	24	1.9	96	6	.5	34	62	4.0	415	92
I-24	20	<1.0	9	11	8	1	1.1	-	8	9.1	-	-	-	20	100
E-6	74	1.0	-	74	-	-	-	-	-	-	-	-	-	74	100
I-16	1	<1.0	1	0	-	1	10.0	-	-	-	-	-	-	1	100
E-5	562	4.0	99	463	63	36	3.6	-	63	9.1	-	-	-	562	100
M-3	23	1.0	5	18	-	5	10.0	-	-	-	-	-	-	23	100
I-26	1775	14.0	699	1076	474	225	3.2	59	415	8.0	59	0	0	1716	97
I-35	718	6.0	562	156	440	122	2.2	354	86	1.8	321	33	.6	397	55
U-5	402	3.0	227	175	155	72	3.2	151	4	.2	82	69	2.9	320	80
I-28	88	1.0	52	36	6	46	8.9	1	5	7.6	-	1	6.2	88	100
U-4	179	1.0	174	5	135	39	2.2	52	83	5.6	52	0	0	127	71
I-34	62	<1.0	9	53	2	7	7.8	<1	2	9.1	-	-	-	62	100
I-31	503	4.0	485	18	392	93	1.9	234	158	3.7	131	103	2.8	372	74
V-2	106	1.0	-	106	-	-	-	-	-	-	-	-	-	106	100
I-30	291	2.0	124	167	118	6	.5	108	10	.8	94	14	.8	197	68
I-7	80	1.0	-	80	-	-	-	-	-	-	-	-	-	80	100
I-11	57	<1.0	4	53	3	1	2.5	1	2	6.1	1	0	0	56	98
E-1	20	<1.0	18	2	18	0	0	18	0	0	14	-	.1	6	30
I-15	54	<1.0	3	51	-	3	10.0	-	-	-	-	-	-	54	100
I-14	201	2.0	161	40	123	38	2.4	98	25	1.9	82	16	1.0	119	59
I-9	328	3.0	258	70	243	15	1.6	211	32	1.2	46	165	4.9	282	86
I-12	111	1.0	41	70	3	38	1.3	2	1	3.0	-	2	6.2	111	100
E-4	79	1.0	78	1	77	1	.1	77	0	0	10	67	5.4	69	87
H-1	7	<1.0	4	3	3	1	2.5	3	0	0	1	2	4.2	6	86
I-4	26	<1.0	26	0	26	0	0	26	0	0	26	0	0	0	0
U-1	76	1.0	71	5	71	0	0	65	6	.8	40	25	2.4	26	34
I-8	25	<1.0	23	2	19	4	1.7	11	8	3.8	3	8	4.5	22	88
Total (includes water)	12636														
Total Primary Forest (includes Subalpine Rain)	11508		5984	5524	4703	1281	2.1	3326	1377	2.7	2493	832	1.6		

(*Soil Association descriptions are by Perez, et al. 1979) it's unique status (zero deforestation) was probably not because there were inherent soil limitations for use, but because the mapping unit was totally enclosed by the boundaries of Rio Macho Forest Reserve. The significance of soils to forest clearing and the relationship of soils to other biophysical landscape characteristics will be investigated in more detail as the research progresses into the next stage.

Forest Clearing vs. Transportation Network

The transportation map depicts the road and railroad system as of 1977 when the map was revised. A hypothesis concerning these data are that forest clearing increases immediately adjacent to new road (or railroad) construction and out to an undefined distance from the nearest road or railroad access. The approximate dates and sequence of road construction in Costa Rica can be deduced by observing the 1977 transportation network with each date of forest location. Point A and B (Figure 1) show roads crossing forest in 1940 but the forest adjacent to the road is gone in 1950. It is likely that the section of road at point A and B was constructed after 1940 but before 1950. Using the same logic, the road at point C and D was constructed between 1961 and 1977. Without attempting to separate cause and effect, there appears to be a definite relationship between transportation infrastructure and forest clearing as of 1977.

This simple example demonstrates how historic information (transportation infrastructure development) can be derived from remotely sensed data if adequate records are not available in other forms. Our interest concerning these data is to determine the relationship between transportation infrastructure and the phenomena of forest clearing. Once additional maps can be

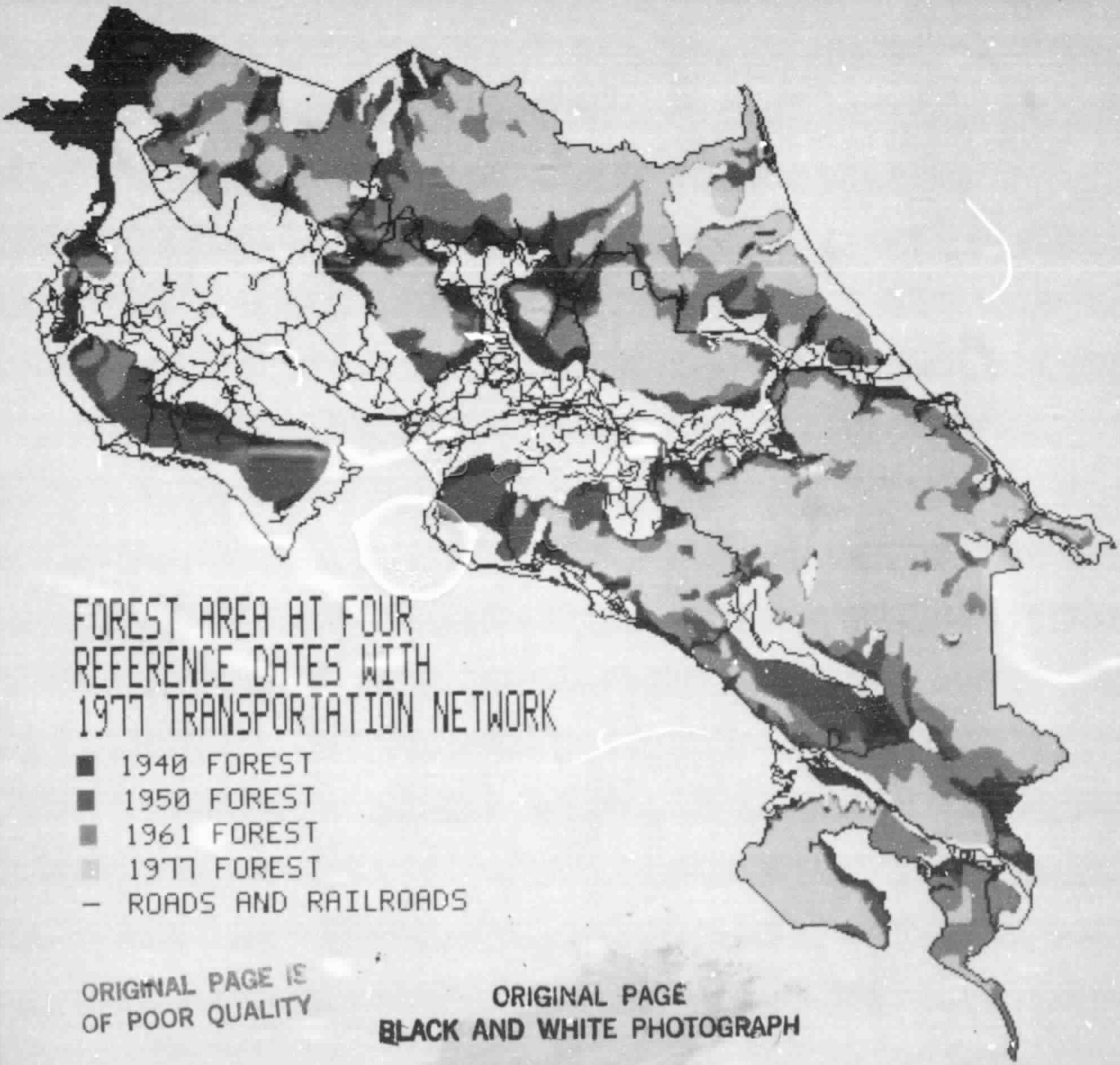

FIGURE 1.

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acquired depicting the transportation system at earlier dates, a distance-to-road spatial analysis criteria will be investigated as a possible component of a "deforestation event probability" model. Also, as we have attempted to demonstrate, the terrain, climate and various demographic variables will have significant influence on the amount of forest cleared adjacent to roads and railroads.

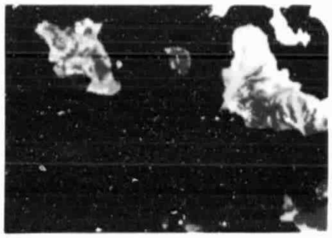
Summary and Conclusions

The relationship of biophysical landscape characteristics to the phenomena of forest clearing in Costa Rica was investigated. Various published maps depicting forest area, life zone, soils, slope gradient, and transportation network were acquired and entered into a common geographic information system (see Figure 2). Tabular summaries generated by combining the forest area files with biophysical and transportation data files revealed specific rates and trends of forest clearing over a 4 decade period. In the most simplistic description of these results, we learned that less forest land was cleared (as of 1977):

1. In Life Zones with the lowest PET/P ratios, and in Life Zones with lower population densities.
2. As the slope gradient increased.
3. At locations not adjacent to roads or railroads.
4. On soils with strong inherent limitations for crop and pasture uses.
5. In areas assigned forest protection status such as national parks and biological reserves.

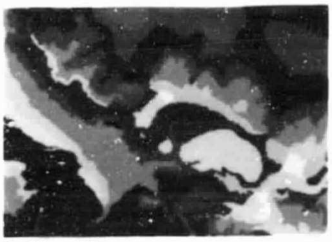
The results are not particulary surprising and most would appear to be intuitively obvious. The value of the automated GIS as demonstrated here was the ease in which data files could be combined and compared to isolate import-

Slope Gradient



Forested Slopes-1977

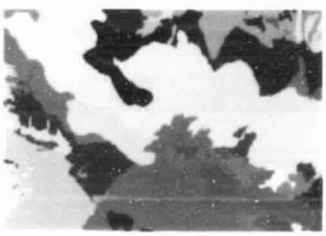
Six slope classes are represented. Yellow hues are lower slope gradients and green hues are steeper. The slope image was combined with the 1977 forest area image that still supported primary forest in 1977.



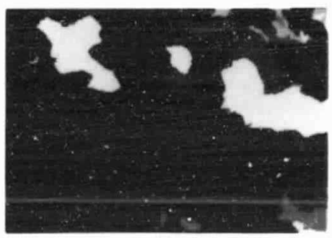
Life Zones

Forested Life Zones-1977

Each life zone is identified by the integration of three climatic parameters. The wetter, more humid life zones (purple and dark green hues) had the lowest clearing rates and were still forested in 1977.

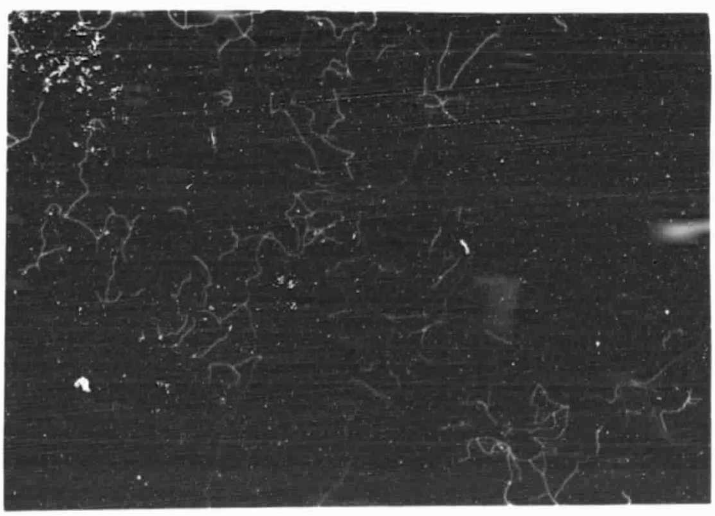


Soils



Forested Soils-1977

In general, the least amount of deforestation by 1977 occurred on soils that had inherent limitations for nonforest uses (e.g., crops and pastures).



1940 forest is shown in blue and 1977 is shown in green. Roads and railroads are red. There was an obvious relationship between the transportation system and forest clearing. A distance-to-road spatial analysis technique is being investigated to quantify this relationship.

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BIOPHYSICAL LANDSCAPE RELATIONSHIPS TO TROPICAL FOREST CHANGES—SAN JOSE QUADRANGLE

FIGURE 2

ant predictors of forest or land use change, quantify their relationships, and pinpoint their location on the ground. Many of the variables affecting forest change are interrelated and others were not evaluated in this preliminary analysis. Because the accuracy of the forest area maps are unknown, we present the area of primary forest cleared and deforestation rates only as approximations for comparative purposes. Also, the deforestation rates had to be averaged over each reference period. Actual rates could have been higher or lower in intermediate years depending on economic factors and population migrations.

The interactions of biophysical variables and their relationship to forest change will be further examined at the next stage in the research where "predictors" of forest change will be determined quantitatively and applied in a regression model using statistical programs similar to those reported by Hamilton and Wendt (1975) and Hamilton (1974). A "deforestation event probability" model will be based on empirical relationships between biophysical variables and other predictors of forest change as derived from the Costa Rica data and data bases generated for other tropical and subtropical areas.

The deforestation model will be applied and tested in other tropical regions where the "sampling frame" can be generated through the acquisition of satellite-acquired data and good quality maps depicting the biophysical landscape and other data necessary as input to the model. In an operational mode, forest change statistics compiled by forest type, life zone, slope gradient, and soils, would be accompanied by confidence limits. Critical areas (e.g., steep slopes, erodible soils, endangered habitat) and secondary forest succession could be monitored systematically with long-term environmental changes and trends documented through the use of data collected by satellite-borne sensors to update the GIS.

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