REMOTE SENSING OF SUBSURFACE WATER RESOURCES IN THE U.S. VIRGIN ISLANDS

by

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Project No. A-016-VI
Agreement No. 14-34-0001-1150

September 1983

The work upon which this report is based was supported in part by funds provided by the United States Department of the Interior, as authorized by the Water Research and Development Act of 1978

Technical Report No. 14
Caribbean Research Institute
College of the Virgin Islands
St. Thomas, USVI 00802

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ABSTRACT

Location of areas for groundwater exploitation has been a long standing problem in the Virgin Islands. In response to this need a project was designed to briefly assess the possibility of using plant pigments surveyed from aircraft or satellites to locate aquifer. The results of this project indicate that: (a) plant pigments can indeed be used to detect soil moisture changes, (b) the chlorophyll/carotinoid ratio is especially useful, (c) technical difficulties prevent the type remote sensing tried from being useful. Recommendations are made for design changes.

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I. Introduction and Background

St. Thomas, a Caribbean Island in the U.S. Virgin Islands, relies on a variety of sources for its domestic water supply. In the early 1970s, these sources included wells on the eastern part of the island, three desalinization plants, water barged from Puerto Rico, and a large number of individual household cistern systems. At one time, large municipal cisterns were operating; however, these systems have not been maintained; and were functioning at the College of the Virgin Islands only at the time of the study.

St. Thomas is 4.8 km (3 miles) wide and 19 km (12 miles) long. It has a backbone ridge of mountain which rises to approximately 456 m (1,500 ft.) above sea level. The climate of St. Thomas is essentially marked by constant easterly trade winds and maximum average temperatures about 27°C (80°F) in the winter and 30 to 32°C (87-89°F) during the summer. Average relative humidity is above 80%. Rainfall ~~frequently~~ generally occurs in the form of brief showers, with the higher elevations on the island tending to receive greater amounts of rainfall, on the order of 102-187 cm (40-80 in.), per year. Average monthly rainfall for the month of December though June is 5 to 7.5 cm (2-3 in.), while for July through

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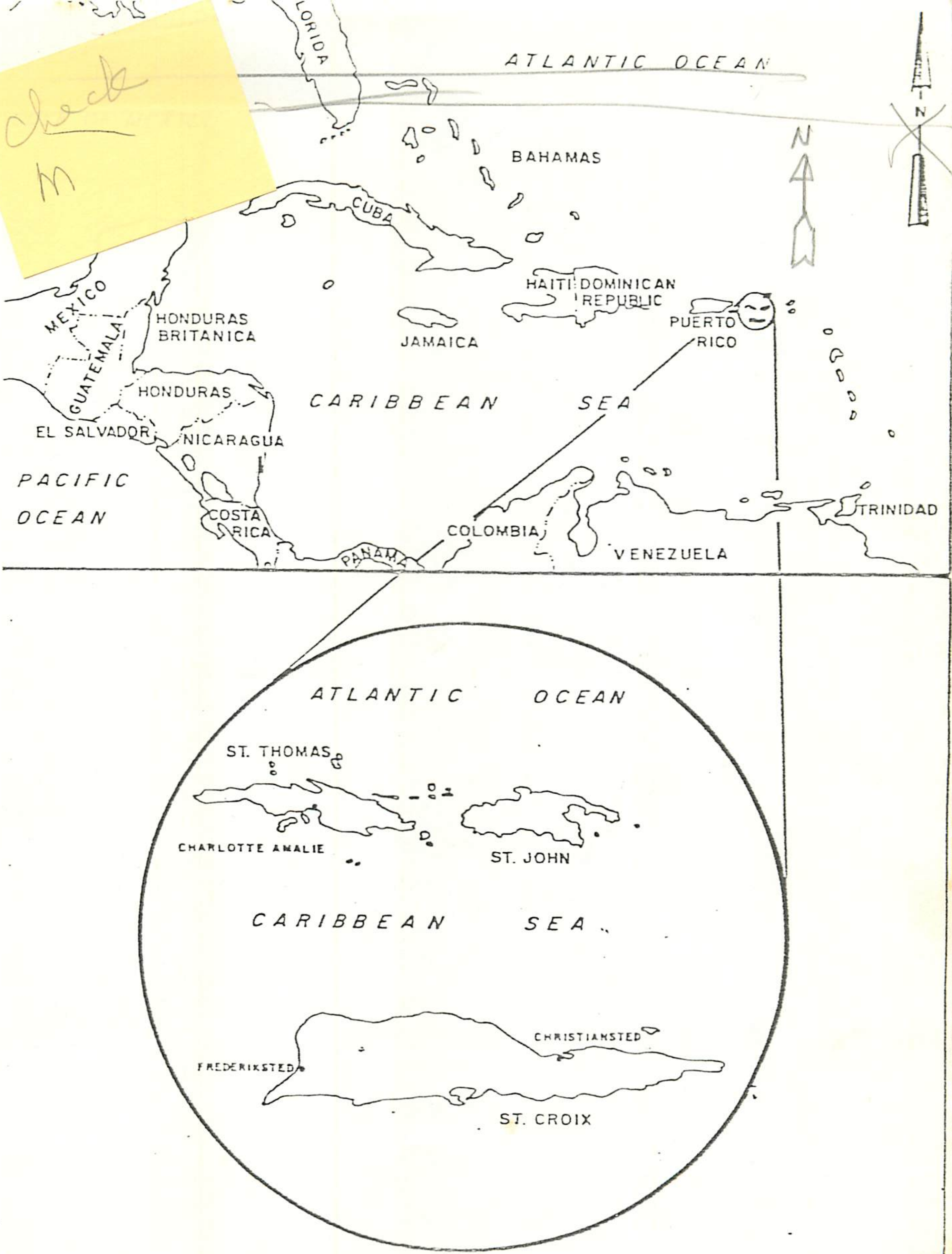

THE U.S. VIRGIN ISLANDS
LOCATION MAP
FIGURE I

November it is on the order of 10 to 12.5 cm (4-5 in.) of which 80% is during July and November.

The population of the Virgin Islands is approximately 110,000 persons, having doubled in 15 years and being expected to double again in the next 10 years. The water problem is expected to parallel this.

Fresh water has always been in critical supply in St. Thomas. Rain collected on roofs and stored in cisterns is still the source of water for most rural and urban domestic supplies. Before 1960 hillside rain catchments and a few dug wells were the major source of water for public supplies. Since then, desalted water has become the major source of water for public supplies, and water barged from Puerto Rico is a close second.

Charlotte Amalie has a dual public water system. Fresh water is used for drinking and general household needs, and salt water is used for sanitary and fire-control purposes. The fresh-water supply, obtained from salt-water distillation plants, hillside rain catchments, and wells, is supplemented by water barged from Puerto Rico. Potable water use and the sources of the water not only show the increasing demand for water but also the shift in sources of the water. Barged water became the major source of supply in the early 1960s, but by the late 1960s, desalted water became the principal source of supply.

II. Thesis

The technological explosion stimulated by military and space research has made available a diversity of airborne sensors to record information about ecosystems. These sensors capture energy from various portions of the electromagnetic spectrum. The information ~~so garnered by~~ from remote sensors may be primarily a function of plant surfaces, o~~r~~f the environment or of a complex interaction of both. In any case, the biological implications of the signals received must be interpreted, and THERE IS ? therfe is a little prior experience to guide the interpreter. Three basic types of sensor systems for remote sensing from airborne or satellite platforms are available; all three are processed to present two-dimensional or pictorial displays. Photography is used in the visible and far-red spectrum, 300 to 1000μm; optical-mechanical scanners are employed in the infrared wavelengths, 1 to 40μm; and passive microwave and radar are developed for selected bands from .1μm up to 1μm. To date, by far the greatest amount of information about vegetation has been derived from photography. Among the most promising wavelengths are 700μm to 900μm in which plants reflect 80% to 90% of the impinging light. Frequently information from several spectral bands surpasses the sum of each band considered separately. Ecological research with remote sensors is predicated on the necessity of developing these tools for the study of entire populations and ecosystems to understand and manage the consequences of our technology.

(Canoy, 1978) ~~NOT LISTED IN THE REFERENCES~~

OK

Water resources have been evaluated by remote sensing for years in terms of surface water, submerged lands or wetlands, or snow cover. In the dry tropics, however, most water resources are subsurface and often in rugged terrain. This makes it attractive to have a method for remote sensing of subsurface moisture, or at least an elimination of certain areas in water prospecting.

This study was designed as a quick survey to determine if there is a quick and easy way to use remote sensing for this purpose.

III. Methods

A. Soil Moisture at the surface and three (3) foot depth were determined in the 4 study sites. Moisture was read from a Bouyoucos Moisture Meter, Model BN-2B, Beckman Cedar Grove, N.J.

Three (3) sets of samples were taken September 22-26, 1982 December 21-28, 1982 and April 18-24, 1983. Leaf samples for pigment analysis were taken at the same time from mature trees within a 10 meter radius of the moisture meter site.

B. Plant Pigments were analysed on fresh material from the site. Extraction and chlorophyll per gram of leaf were determined as follows.

Chlorophyll Estimati[illegible]

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The determi[illegible]phyll content is frequently required in [illegible]s always better to extract fresh tissue and [illegible]ments immediately, although extracts can be st[illegible] in the dark in acetone containing ? traces of Na_2CO_3 at -20 to -30° F without appreciable loss. As a general precaution, it is advantageous to work in dim light to avoid pigment losses. The fresh tissue is ground in a mortar or macerator in the presence of excess acetone or methanol until all the colour is released from the tissue. Mg a $MgCO_3$ is added to prevent pheophytin formation and the extract is filtered on a Buchner funnel, the bre~~i~~ being washed with fresh acetone until colorless. The extract and washings are then made up to a known volume and stored in the refrigerator.

Measurement of chlorophylls a and b can then be made by direct determination of the absor~~b~~PTance at different wavelengths, using a standar~~s~~D spectrophotometer. Assuming an 90% acetone extract, the absor~~bace~~PTANCE should be measured at 663 and 645 nm in 1 cm cells. The concentrations can then be calculated from the following fomulae:

$$\text{Total chlorophyll (mg/l)} = 20.2\,A_{645} + 8.02\,A_{663}$$

$$\text{Chlorophyll a (mg/l)} = 17.7\,A_{663} - 2.69\,A_{645}$$

$$\text{Chlorophyll b (mg/l)} = 22.9\,A_{645} - 4.68\,A_{663}$$

These can be converted to chlorophyll content on a fres~~s~~h weight basis as follows:

$$\text{Chlorophyll a (mg/g)} = \frac{12.3\,A_{663} - 0.86\,A_{645}}{\alpha \times 100 \times W} \times V$$

To be completed

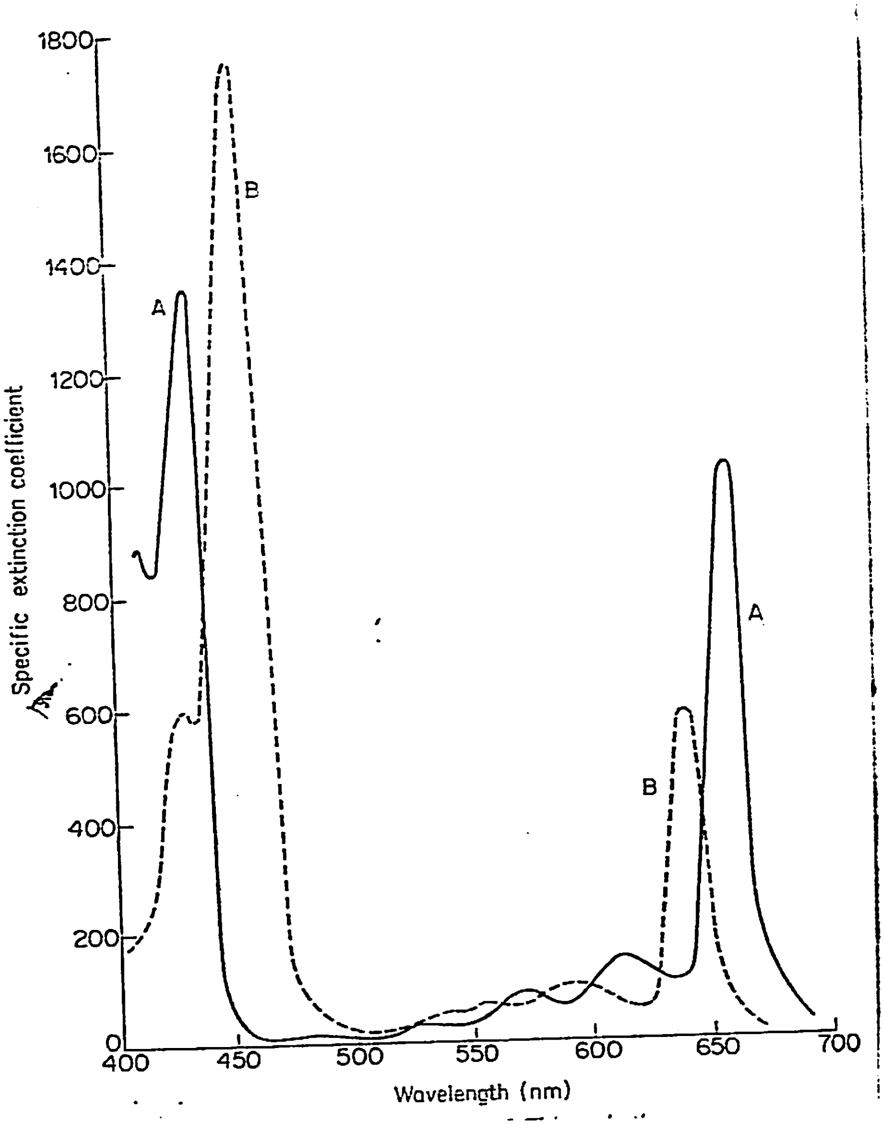
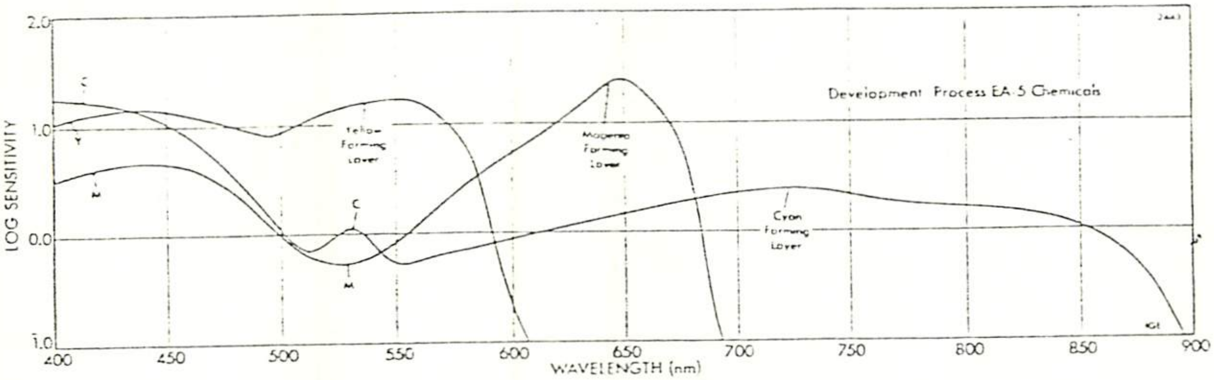


FIGURE2: *Absorption Spectra of Chlorophylls a and b*
Curve A, chlorophyll a; curve B, chlorophyll b
in 90% acetone

(From Phytochemical Methods, 1979)

Spectral Sensitivity Curves
Process EA-5



Sensitivity = Reciprocal of the exposure (ergs/cm²) required to produce a density of 1.0 above D-min.
Measurements were confined to the 400- to 700-nanometer region.

FIGURE 3

From: Eastman Kodak "Aerial Photography as a Planning Tool". 1976, M-128

C. Carotinoids were extracted into chloroform and read at 450 nm. This wave length was arbitrarily chosen because the majority of the over 400 carotinoids are found in the range of 400-530 nm.

Margalef (1959) found the ratio of carotinoids to chlorophyll to correlate well with primary production in several ecosystems. Odum et al. (1970) applied this method to productivity and reaction to stress in a tropical rainforest.

In this study we found that carotinoids ranged from 2.3 mg/g to 2.9 mg/g and were consistent per species where chlorophyll varied rather widely according to plant conditions.

D. Remote sensing of reflected light was accomplished using Nikon F Camera loaded with Kodak Ektachrome Infrared film (false color). Initially a 135 mm lens was used, but this proved to have too poor resolution, and in the last two sample periods an 80 mm lens was used. The film required a Wratten 12 filter to exclude blue wave lengths. Films were developed locally according to the manufacturer's specifications.

IV. Results

Soil moisture levels were measured on three occasions, once, a week after a 4 inch rain. The moisture blocks and samples were at the surface and 36 inch depth. It was found that the surface soils varied considerably according to soil composition, rainfall, and environmental factors (Table 3) but

~~THERE IS NO TABLE 5~~

TABLE I

TROPICAL TREES AND SHRUBS - ST. THOMAS
Chlorophyll ~~A~~ lc (mg/g)

	Species	Sun Leaves	Shade Leaves	Top/Bottom Leaf Variation in color
1.	*Sloanea berteriana*	4.5	5.3	-
2.	*Picteta aculeata*	5.5	6.1	+
3.	*Exostrema caribaeum*	7/2	7.6	+
4.	*Prosopsis juliflora*	4.3	4.6	+
5.	*Guaicuma officinale*	4.9	5.5	+
6.	*Amyris elemifera*	6.1	6.1	-
7.	*Andropogon* sp.	4.3	4.3	-
8.	*Bucida buceras*	5.5	6.3	+
9.	*Canella winterana*	4.9	5.7	-
10.	*Thouinia* sp.	5.5	5.5	+
11.	*Rhizophora mangle*	5.0	6.0	+
12.	Luceana glauca	4.3	4.8	+

that at 36 inches there was little difference in moisture even after moderately heavy rains. There was no apparent correlation between deeper soil moisture and aquifers Table 21 (Dorethea vs. Lameshur).

~~NOT LISTED IN REFERENCES~~

not a Reference

Soil moisture measured at 0.15-0.37 parts/~~of~~ dry weight (15-37%) at the surface and 0.5-0.13 parts/dry weight (5-13%) at 36 inch depth. The available moisture was both lower and less variable at the depth feeding most shrubs and small trees.

SEE NEXT LINE

<u>Plant pigments</u> were found to vary with species, sun adaptation and age of the leaf. Chlorophyll ~~A~~ a (spectrum maxima at 665 na~~n~~nometers, nm) ranged from 4.5-9.3 milligrams per gram (mg/g). Of the 400 known carotinoids, over 80% have spectrum maxima between 425 and 480 nm. Following Margalef, 1962 and Odum, et al, 1970 an arbirary median spectral point, 450 nm of carotinoids in chloroform, was used as a reference. Total chloroform-soluble carotinoids measured at this point were calculated at 2.3-2.8 mg per gram of leaf. These measures were not so variable as the chlorophyll contents and seemed to remain within 15-20% of a mean regardless of the situation of the plant.

NOT LISTED IN REFERENCES

<u>Aerial and satellite photos</u> of the watersheds were evaluated in terms of known plant pigment ratios. The 10 satellite Infra-red photos and 72 aerial false-color infra-red photos showed no discernable pattern in plant/pigments despite

TABLE 2

SOIL MOISTURE, AS PARTS OF DRY WEIGHT

Sample Site		Sample Number	DEPTH	
			3-6 inches	35-38 inches
Dorothea I	SET I	1	0.15	0.05
		2	0.28	0.08
Elevation; + 18 MSL Soil Sandy Roam		3	0.25	0.07
		4	0.23	0.07
	SET 2	5	0.17	0.05
		6	0.24	0.08
	SET 3	7	0.34	0.12
		8	0.33	0.10
		9	0.37	0.13
		Mean -	0.26	0.08
Dorothea II		1	0.23	0.08
	SET I	2	0.16	0.06
		3	0.18	0.07
		4	0.21	0.07
	SET 2	5	0.27	0.09
		6	0.15	0.05
		7	0.19	0.07
	SET 3	8	0.22	0.08
		9	0.18	0.06
		Mean -	0.20	0.06
Lameshur I		1	0.12	0.05
Sandy Loam	SET I	2	0.09	0.03
+ 15' MSL		3	0.13	ND

(continued...)

Sample Site		Sample Number	DEPTH	
			3-6 inches	35-38 inches
	SET 2	4	0.07	0.02
		5	0.09	0.03
		6	0.10	0.03
	SET 3	7	0.08	0.05
		8	0.09	0.07
		9	0.11	0.03
		Mean -	0.09	0.03
Lameshur II Rocky clay, Loam	SET I	1	0.13	0.06
		2	0.12	0.04
		3	0.15	0.07
	SET 2	4	0.13	0.05
		5	0.11	0.05
		6	0.10	0.02
	SET 3	7	0.09	0.04
		8	0.11	0.05
		9	0.08	0.07
		Mean -	0.11	0.05

on site differences which were measured. Possible reasons for this will be brought forth during the discussion section of this paper.

V. Discussion

Remote sensing has become a more and more common tool for resource studies (USGS/NASA, 1980 NOT LISTED IN THE REFERENCES; Jensen and Meyer, 1976). This includes various estimates of water resources (U.S. Nat. Research Council, 1980; Striffler and Fitz, 1980). This technique~~s~~ is especially attractive to planners where large areas or distant and difficult terrain is involved.

In the case of tropical ecosystems plant pigment indices were suggested by Margalef as indicators of primary production and stress in 1959 and 1962. Odum, McConnell, and Abbott (1959) NOT LISTED IN THE REF., verified these findings in temperate systems and Odum, et al, (1970) using the Richards and Thompson methods NOT LISTED IN THE REF. (1952) for chlorophyll analysis, extended the study to a tropical rainforest. Here they applied the Margalef ratios to the El Verde research site in Puerto Rico in a study which combined actual measurement of pigments with estimates from remotely sensed data. The agreement between remote data and actual measurements on a spot by spot comparison was not conclusive; but, if the chlorophyll measurement was converted to an areal value (multipling the amount per gram of lea~~ve~~f to the calculated leaf biomass per meter) of chlorophyll per square meter, the agreement was quite good.

NOT LISTED IN THE REFERENCES

Studies by Canoy (1970, 1972) showed that the plant pigment ratio per m^2 was a g~~ii~~ood indicator of stress, production, and biochemical potential (as DNA) in rainforests, tropical dry forests, and mangrove forests.

The present study attempted to relate on-site pigment analysis directly to aerial data and soil moisture. The plant pigment analyses (Table 2) compare well to those previously found in Puerto Rico (Table 4) and are probably accurate. The direct measure of free soil moisture was checked against samples dried in the labl and these measures seem accurate. Furthermore the mean soil moisture data correlated well ($\gamma = 0.93$) with the plant pigment ratios. There is however no discernable pattern in the remote photographs relative to soil moisture or aquifers. The aim of this study IS TO to ~~scope~~ define the limits of the question of remote sensing for aquifers and therefore did not cover some expensive or time consuming studies such as biomass or potentiometric sensing for really deep (over 36") water sources.

TABLE 2 SHOWS SOIL MOISTURE

~~MEASURE~~ ?

The new data ha~~s~~ve yielded several results. 1) Plant pigment ratios for 12 common trees in St. Thomas can serve as indicators of water deficiency or adequacy. 2) The plant pigment ratio is a good indicator for agricultural purposes. 3) There is , at this point, no simple way to relate water availability to remote data via plant pigments.

TABLE 3

SOIL MOISTURE AND PLANT PIGMENTS

Site	Set	Mean Deep Soil Moisture	Chlorophyll ~~A~~:a mg/g	Cartonoids (@ 450 nm) mg/g	Ratio
Dorothea I	1	0.07	5.5	2.8	0.51
	2	0.07	6.2	2.3	0.37
	3	0.11	9.3	2.3	0.25
Dorothea II	1	0.07	6.2	2.5	0.40
	2	0.08	6.3	2.5	0.40
	3	0.09	7.8	2.4	0.31
Lameshur I	1	0.03	4.5	2.9	0.63
	2	0.03	4.5	2.6	0.58
	3	0.05	5.1	2.3	0.45
Lameshur II	1	0.06	6.0	2.6	0.43
	2	0.04	4.8	2.8	0.58
	3	0.05	5.3	2.5	0.47

TABLE 4

REPRESENTATIVE CHLOROPHYLL ~~A~~ lc AND ~~B~~ lc FOR SELECT TROPICAL SPECIES

Tree and leaf data	Tree No.	Sample No.	Beckman 645	Beckman 630	Beckman 665	Chlorophyll a ~~A~~, mg/liter	Ba~~y~~usch & Lomb (665)	Chlorophyll ~~B~~ lc, mg/liter
Dacryodes excelsa	2695							
Sun leaves, new		1	0.185	0.179	0.462	6.7	0.600	0.83
Sun leaves, new		8	0.154	0.143	0.396	5.6	0.570	0.70
Shade leaves, new		22	0.118	0.108	0.325	4.6	0.422	0.45
Shade leaves, old		39	0.378	0.334	0.978	14.2	1.10	1.86
Manilkara bidentata	2680							
Shade leaves, old		47	0.375	0.357	0.925	13.2	1.00	1.78
Sun leaves, new		51	0.254	0.245	0.641	9.2	0.725	1.14
Sun leaves, old		67	0.285	0.275	0.742	10.7	0.850	0.84
Euterpe globosa	2421							
Sun leaves, new		98	0.253	0.245	0.650	9.4	0.780	1.04
Shade leaves, new		105	0.353	0.334	0.950	13.8	1.05	1.35
Sun leaves, old		113	0.153	0.145	0.415	6.0	0.520	0.57

*Ratio of chlorophyll ~~A~~ lc to ~~B~~ lc is 8.9
From: Odum and Pigeon, 1970. "A Tropical Rain Forest." USAEC.

The parameters necessary to clearly define the use of remote data for water "prospecting" include:

1) Leaf biomass per square meter
2) Root, particularly tap root, depth.
3) The species diversity index (species/acre)
4) Other physiological reactions of these species to water stress such as leaf folding, leaf abcission, or release of gums, oils, etc.

As a result of this study it is shown that Virgin Islands foresters or agriculturalists can use plant pigment ratios as an indicator of productivity or stress. It has further indicated that remotely sensed pigment data can be used, given the data listed above, to locate shallow aquifers during dry periods.

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