Attempts to Use Satellite Data to Detect Vegetative Damage and Alteration Caused by Air and Soil Pollutants

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ABSTRACT

Data collected by a multispectral scanner on board the Earth Resources Technology Satellite was subjected to computer analysis in an attempt to detect vegetative damage primarily attributed to the atmospheric pollutant sulfur dioxide and the soil pollutant zinc emitted from a zinc smelter. Field observations and data collected by low-flying aircraft were used to verify the accuracy of the maps produced from the satellite data. An eastern white pine stand that was severely damaged by sulfur dioxide could not be differentiated from a healthy eastern white pine stand because spectral differences were not large enough. The damage was still undetectable when winter data were used to eliminate interference from herbacious and deciduous vegetation. However, the analysis did produce a character map that accurately delineated areas of vegetative alteration due to excessive zinc levels in the soil. The map depicted a distinct gradient of less damage and alteration as the distance from the smelter increased. The ERTS-1 system would be useful only on infrequent occasions when large areas of damage occur and the damage is severe enough to cause a high contrast between damaged and healthy vegetation. Even in such cases the resolution of the system would not allow an adequate evaluation of the amount of damage to the plants.

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Remote-sensing devices have been used to detect and monitor plant diseases (12, 13, 15, 18), insect problems (5, 18), air pollution damage to plants (9, 18), and other problems and conditions that change the normal reflectance and emittance of electromagnetic energy from plants. Cameras and related sensing devices such as multispectral scanners (MSS) and thermal infrared sensors are usually operated from aircraft, but the recent launch of the ERTS-1 (Earth Resources Technology Satellite) has provided a space platform for remote-sensing devices. Data collected by ERTS-1 have already been used in the areas of inventory and management of resources (11, 14), environmental problems (1, 3, 19), and the control of insect problems (6, 8). There are numerous uses for the ERTS-1 data in the fields of geology, oceanography, and photogrammetry.

The purpose of this study was to determine if the ERTS-1 data could be useful in detecting vegetative damage and altered plant communities resulting from pollutants emitted by a zinc smelter.

MATERIALS AND METHODS.—The ERTS-1 was launched in July 1972, and is now in a polar sun synchronous orbit 900 km above the surface of the earth. It passes over the same ground area every 18 days. The main functional sensor system on board the satellite is a multispectral scanner. The MSS divides reflected energy from the earth into four wavelength bands or channels by utilizing a prism. The four bands are 0.50-0.60, 0.60-0.70, 0.70-0.80, and 0.80-1.10 μm. A photoelectric sensor converts the energy into electronic signals which are transmitted to receiving stations on the earth. The data are then converted from analog to a digital form and stored on magnetic tapes (7). Data are also converted into 22.8×22.8 cm negative and positive transparencies. The digital and transparency formatted data were made available to us through the Goddard Space Flight Center, Greenbelt, Md.

Site.—The test area was near Palmerton, Pennsylvania, the site of a zinc smelter since 1898 (16). The roasting of zinc sulfide ores began in 1915 and since then oxides of zinc, lead, cadmium, copper, and sulfur have been released during the roasting and sintering process. Stack tests in 1970 by the Pennsylvania Department of Health measured a total sulfur dioxide emission rate of 635 to 681 kg/hour or 15.4 tonnes a day (4). The daily zinc emissions ranged between 6.3 and 9 tonnes. Within a 0.8 km radius of the smelter, zinc concentrations of up to 80,000 μg/g of air-dried soil occur in the surface layer of the soil (4).

Vegetation.—As a result of logging and burning, the forests surrounding Palmerton are all at least second-growth. Approximately 468 hectares (ha) of bare soil may be attributed to accumulations of high levels of zinc (4). Large acreages of altered plant communities exist because of sulfur dioxide pollution and zinc in the soil. Areas adjacent to bare soil sites support very little plant life. The only plant in relative abundance is the winter annual *Arenaria patula* Michx. In other areas, the only trees present near the bare soil and sparsely vegetated sites are sassafras (*Sassafras albidum* Nutt.) and black gum (*Nyssa sylvatica* Marsh.) with widely scattered scrub oak (*Quercus ilicifolia* Wangenh.) and chestnut oak (*Q. prinus* L.). The trees are stunted and there is very little undergrowth. At a distance beyond 0.8 km from the smelter, the hardwood forest exhibits a somewhat more normal appearance except the stands of oak are thinner, and there is less undergrowth.

A 4.86-ha eastern white pine (*Pinus strobus* L.) stand situated approximately 1.6 km northeast of the smelter is in a state of decline apparently due to the sulfur dioxide being emitted by the smelter. Most of the trees possess only the current year and 1-year-old needles both averaging 46 mm in length. At the time satellite coverage was obtained (8 July 1973), the 1-year-old needles displayed tip necrosis and chlorotic mottle. The current-year needles displayed a chlorotic mottle along the entire length of the needle.

A 3.64-ha eastern white pine stand located 2.73 km northeast of the smelter appeared to possess normal or healthy foliage. The trees possessed the current year needles, 1-year-old needles, and 2-year-old needles, all averaging 72 mm in length. The average needle length for eastern white pine in the eastern United States is between 60 and 140 mm (10). There was no apparent necrosis or chlorosis present on the needles.

Data analysis.—The primary hardware used for automatic processing of the digital tapes was an IBM System 370, Model 168, computer located at The Pennsylvania State University's Computation Center. The programs used to process the data are maintained by the Office for Remote Sensing of Earth Resources, The Pennsylvania State Univeristy, University Park, Pennsylvania.

The system used to process MSS data stored on tapes has been described by Borden (2) and Turner (17). All programs were stored in library files. We prepared control specifications for each program in the system; the program accepted the control specifications, processed the ERTS-1 data according to those specifications, and presented the results.

The first program utilized was NMAP, which produced a brightness map. Symbol patterns on this map were used to delineate areas of interest previously chosen. The next program in the system, UMAP, delineated areas possessing uniform spectral signatures. Spectral signatures for uniform areas were obtained by placing their coordinates into the STATS program. The spectral signatures were then placed into a classification program to produce a character map similar to Fig. 1. The classification program used in this study was DCLASS.

If areas of interest were small or nonuniform they could not be used in the STATS program to obtain spectral signatures. The DCLUS program used a cluster analysis technique to scan a whole set of data and place points with similar spectral signatures into clusters or groups. A character map was produced along with a table of spectral signatures for the groups. This program was used to obtain most of the signatures used to produce the map in Fig. 1.

A MERGE program allows the user to merge ERTS-1 data for up to six scenes of the same area. The merged data set can then be used in any of the other component programs in the system.

Data input.—ERTS-1 scene number 1350-15190 from 8 July 1973 was the primary data input for analyzing the Palmerton site. Transparencies of the scene contained no visible cloud coverage. Winter coverage of the test site was also analyzed (scene number 1116-15192, 16 November 1972).

The tape used for the map in Fig. 1 covers an area of 100 × 25 nautical miles and contains 1,881,360 data points. By dividing the number of data points into the area it was determined that each data point represents approximately 0.456 ha. This calculated value was used to determine the total area contained in each of the categories in Table 1. The number of data points for each category was provided as part of the output from the classification program. By multiplying the count for each category by 0.456 ha the associated area was obtained.

Underflight photographs were used to aid in the verification of the accuracy of the maps produced from the ERTS-1 data. Color and color-infrared photographs at a scale of 1:8,000 were obtained from low-flying aircraft. The coverage did not include the entire test site.

RESULTS AND DISCUSSION.—Ground truth revealed very striking differences between the two eastern white pine stands. However, the differences could not be discerned using the ERTS-1 data. Elimination of possible interference from herbaceous undergrowth and deciduous trees, obtained by use of a winter scene, still did not provide spectral signatures capable of recognizing the differences between the two stands. A cluster analysis of the two eastern white pine stands invariably produced nearly identical signatures for both stands. When the winter-scene data and the summer-scene data were merged and a cluster analysis performed on the merged data set again, no differences were apparent. The sulfur dioxide injury to the eastern white pine trees could not be detected.

A cluster analysis of the forested area on the mountain ridge south of the zinc smelter revealed that it could be divided into three distinct types. They were confirmed by

Fig. 1. A character map produced from satellite data that delineates areas of vegetation that are altered or damaged by pollutants emitted from a zinc smelter. The characters represent the following: "P" is the smelter site; "." is bare soil and areas of limited vegetative growth; "+" is an area of sassafras, black gum, and oak trees; "*" and "/" are areas of mild decline containing nearly healthy and normal forests; "#" is a waste pile of spent ore and coal; and "@" is healthy forest. The blank areas contain urban and agricultural areas that were intentionally left blank because too many symbols would render the map unreadable. Each character represents approximately 0.456 hectares (ha). The total ground area covered by the map is 4.41 ha.

TABLE 1. A list of the categories and symbols used to produce the classification map including: the count or number of data points in each category, the percentage of the total number of data points included in each category, and the total ground area (hectares) contained by each category

Number	Name	Symbol	Count	Percent	Area(ha)
1	Healthy forest	@	66.0	2.0	30.1
2	Healthy forest	@	37.0	1.0	16.8
3	Healthy forest	@	787.0	26.0	359.0
4	Healthy forest	@	19.0	1.0	8.6
5	Mild decline	*	202.0	7.0	92.1
6	Mild decline	*	111.0	4.0	50.6
7	Medium decline	+	131.0	4.0	59.7
8	Medium decline	+	363.0	12.0	165.6
9	Severe decline	.	306.0	10.0	139.5
10	Severe decline	.	304.0	10.0	138.6
11	Waste pile	#	191.0	6.0	87.1
12	Thin forest	/	67.0	2.0	30.5
13	Palmerton		71.0	2.0	32.4
14	Palmerton		65.0	2.0	29.6
15	Palmerton		94.0	3.0	42.8
16	Fields		6.0	0.0	2.7
17	Fields		13.0	0.0	5.9
18	Highway		75.0	2.0	34.2
19	Urban		62.0	2.0	28.2
20	Smelter	P	75.0	2.0	34.2
Unclassified			8.0	0.0	3.6

TABLE 2. Data used to produce the classification map including: categories, symbols, limits or critical values, and a set of signatures for each of the four channels or wavelength bands (μm)

				Relative reflectance[a] to wavelength band (μm)			
Number	Name	Symbol	Limit	.5-.6	.6-.7	.7-.8	.8-1.1
1	Healthy forest	@	10.0	38.27	26.55	56.53	30.89
2	Healthy forest	@	10.0	38.15	28.92	50.15	25.28
3	Healthy forest	@	10.0	35.66	23.90	54.49	29.37
4	Healthy forest	@	10.0	44.40	40.20	52.10	24.00
5	Mild decline	*	10.0	34.03	23.08	46.03	24.59
6	Mild decline	*	10.0	36.54	26.00	48.96	25.22
7	Medium decline	+	10.0	36.48	25.83	43.19	21.29
8	Medium decline	+	10.0	35.37	25.65	40.78	20.00
9	Severe decline	.	10.0	39.09	31.26	34.05	13.97
10	Severe decline	.	10.0	39.09	30.84	30.55	11.66
11	Waste pile	#	10.0	36.29	31.60	25.81	9.21
12	Thin forest	/	10.0	37.36	28.60	42.22	20.75
13	Palmerton		10.0	39.35	33.03	40.26	17.65
14	Palmerton		10.0	40.32	34.12	38.43	16.31
15	Palmerton		10.0	41.70	35.04	44.71	19.86
16	Fields		10.0	42.25	33.45	55.25	27.92
17	Fields		10.0	42.69	34.19	51.51	25.34
18	Highway		10.0	38.44	29.73	41.83	19.67
19	Urban		10.0	38.50	29.73	47.37	23.68
20	Smelter	P	10.0	41.87	36.25	33.15	12.26

[a]ERTS Data Users Handbook, Goddard Space Flight Center, Greenbelt, Md.

field trips to the area and by viewing aerial photographs which included portions of each type. The first and most abundant type was noted to be healthy forest. The second type was a mild decline area very similar to the first, except that the stands were thinner and the normal ericaceous undergrowth was absent. The canopy was noted to be discontinuous on aerial photographs. The third area was a medium-decline area containing mostly sassafras and black gum trees with a few scattered oaks. The trees were widely separated and there was no undergrowth. Due to the lack of vegetation and the steepness of the slope, erosion had taken place in some areas. In addition to these areas, a fourth distinct area of severe decline was discovered near the smelter itself. This was an area where zinc concentrations were so high that the soil supported practically no plant life. The only vascular plant species found in abundance was *Arenaria patula*. Much of the soil is completely barren of plant life and severe erosion had occurred in some areas.

Table 2 contains the spectral signatures used to produce the map in Fig. 1. The signatures for healthy forest, waste pile, and the city of Palmerton were obtained by defining uniform areas of known ground truth from the UMAP output and placing their coordinates into the STATS program. This initial set of signatures was used to produce trial maps of the Palmerton area. Areas on the trial maps which were unclassified were investigated and, by the use of the DCLUS program, signatures for the unclassified areas were accumulated.

It is important to note that the signatures produced by the altered plant communities are not specific for pollutant damage. Similar signatures could be caused by other factors that affect vegetation such as fire, soil conditions, lumbering, terrain and aspect, water relations, etc. It is therefore necessary to have some ground truth data to minimize errors when working with the satellite data.

The graph in Fig. 2 indicated that in the near-infrared wavelength bands 0.7 – 0.8 and 0.8 – 1.10 μm, the relative reflectance of electromagnetic energy decreased as the amount of vegetation decreased. This pattern was expected because healthy vegetation is highly reflective in the near-infrared portion of the electromagnetic spectrum, while bare soil areas are relatively unreflective. The decline in reflectance in the wavelength bands 0.7 – 0.8 and 0.8 – 1.10 μm displayed by the first 11 signatures in Table 2 was an indication that the signatures were correct. The healthy forest areas contained the most vegetation, while mild, medium, and severe decline areas contained progressively less vegetative growth. The waste pile of spent zinc ore and coal bore no vegetation.

Fig. 1 is the classification map that includes these categories. The small area denoted by the character "P" is the smelter site itself. The area denoted by the character "#" is a waste pile, approximately 1.93 km in length, of spent zinc ore and coal. The area adjacent to the waste pile denoted by the character "." is a bare soil and sparsely vegetated area. The area denoted by the character "+" contains sassafras, black gum, and oak tree species. The areas denoted by the characters "*" and "/" are areas of mild decline containing nearly normal hardwood forests, the only difference between the two areas is the color of the soil surface showing through the canopy. The area adjacent to these areas denoted by the character "@" is the healthy forest. The blank areas having no characters are areas that were not mapped by the program because characters were not assigned to their spectral signatures. These are areas containing roads, lawns, houses, gardens, and fields. These areas were left blank because too many symbols would render the map unreadable. Table 1 is a list of the ground areas associated with each of the categories on the map. The synoptic view (Fig. 1) of the Palmerton area displays a distinct gradient of less damage and alteration caused by accumulations of zinc in the soil as the distance from the smelter increases.

A problem arose that caused some confusion in the production of the map in Fig. 1. A large shadow present on the north slope of the mountain ridge caused by the steepness of the slope covered portions of the altered areas and healthy forest. This shadow caused areas of similar ground truth to produce two different spectral signatures with the ERTS-1 data, and therefore the areas appeared to be different on the maps produced by the cluster analysis procedure. To produce an accurate classification map, both signatures were assigned the same character. For instance, portions of the healthy forest in shadowed and nonshadowed areas produced different spectral signatures. The shadow effect was eliminated from the final map (Fig. 1) by assigning the same character @ to both signatures in the classification program.

The results show both the usefulness and weakness of the ERTS-1 remote-sensing capabilities. The data do not appear useful for evaluating the condition of small acreages of vegetative damage similar to that investigated herein. An area as small as 2.4 ha can be detected by computer analysis of the satellite data, if the spectral signatures for that area contrast with the spectral signatures for surrounding areas. Air pollution damage is often restricted to small acreages of scattered susceptible plants or to damage around local sources. The differences in spectral signatures from such damaged and healthy foliage are not large enough to be detected by the ERTS-1 remote-sensing systems. The ERTS-1 system would be useful only when large areas possess contrasting spectral signatures.

The ERTS-1 data did however, produce a map which accurately delineated areas surrounding a zinc smelter which may be limited in vegetative production due to the zinc emitted by the smelter. Herein lies the strength of the ERTS-1 system. The management of resources usually involves a three-step process of inventory, analysis, and allotment. This study has re-emphasized the usefulness of the capability of the ERTS-1 system in inventorying present and potential resources. It provides synoptic

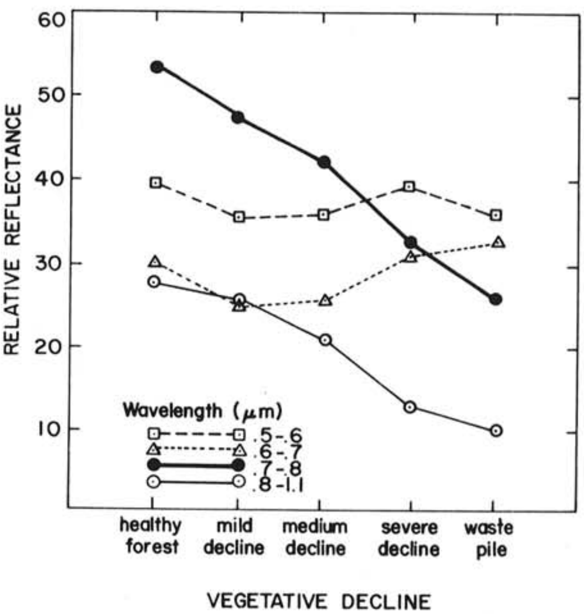

Fig. 2. Relative reflectance in relation to the amount of vegetative decline for all four of the wavelength bands. Values are means for all of the vegetative classes except the waste pile. The relative reflectances in Table 1 were used to obtain the values.

views of the earth's resources that includes a temporal factor because the satellite passes over the same area every 18 days. Rapid estimations of the ground area contained in each category are possible. In the future, the ERTS-1 may possibly be used as a detection system capable of inventory, but not particularly useful in evaluation.

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