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E7.7-10.16.5 CR-152666

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Detection of short-term changes in vegetation cover by use of Landsat imagery		5. Report Date June 1975 6. Performing Organization Code
7. Author(s) Raymond M. Turner and Frederick M. Wiseman		8. Performing Organization Report No.
9. Performing Organization Name and Address U.S. Geological Survey National Center Reston, VA 22092		10. Work Unit No. 11. Contract or Grant No. SR 342-8
12. Sponsoring Agency Name and Address GODDARD SPACE FLIGHT CENTER TECHNICAL MONITOR GREENBELT, MARYLAND 20771		13. Type of Report and Period Covered Final Report for July 1, 1972 - June 30, 1974 14. Sponsoring Agency Code
15. Supplementary Notes	Original photography may be purchased from: EROS Data Center 10th and Dakota Avenue Sioux Falls, SD 57198	

16. Abstract

A ratioing technique was used to map the changing pattern of plant growth from August 1972 to March 1974 near Tucson, Arizona. Black-and-white 70-mm positive transparencies were analyzed by the Electronic Satellite Image Analysis Console at Stanford Research Institute. Imagery in two spectral bands, MSS-5 and MSS-6, was used to detect areas of dense foliar cover. Binary thematic masks, created electronically by displaying all vidicon picture elements where the band-6 to band-5 radiance ratio exceeded 1.25, were used to map areas with dense vegetation. The foliar cover threshold represented by the ratio was not accurately determined but field measurements show that the threshold lies in the range of 10 to 25 percent foliar cover.

Montane evergreen forests with constant dense cover were correctly shown to exceed the threshold on all dates. The summer-active grassland exceeded the threshold in the summer unless rainfall was insufficient. Desert areas exceeded the threshold during the spring of 1973 following heavy rains; the same areas during the rainless spring of 1974 did not exceed the threshold. Irrigated fields, parks, golf courses, and riparian communities were among the habitats most frequently surpassing the threshold. Eroded areas and mine tailing dumps were among the areas which never exceeded the threshold.

17. Key Words Suggested by Author	18. Distribution Statement
Remote Sensing Phreatophytes Phenology Arizona Ecological distribiton	1342H

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Not applicable	52	

Figure 2A. Technical Report Standard Title Page. This page provides the data elements required by DoD Form DD-1473, HEW Form OE-6000 (ERIC), and similar forms.

INT: 2090-72

PREFACE

A. Objective.--Seasonal change in vegetation growth activity is a terrestrial feature of great importance that should be easily detected and mapped by Landsat. The U.S. Geological Survey has used Landsat multispectral scanner imagery to detect areas of dense plant growth in the semiarid region in the vicinity of Tucson, Arizona. The objective of this study is to develop techniques for measuring changes in the foliar cover of plants within broadly defined wildland communities. The techniques sought were narrowly circumscribed by the following constraints: black-and-white, 70-mm, transparent Landsat imagery was to be employed; no field radiometric data were to be used; and analysis was to be performed by the Electronic Satellite Image Analyses Console at the Stanford Research Institute.

B. Scope of Work.--The study was designed to develop techniques for detecting dynamic vegetation features within a semiarid region where the temporal and spatial variability in plant cover is probably near maximum. The image analysis involved a ratioing technique between two Landsat multispectral scanner (MSS) bands. The bispectral ratioing used Landsat multispectral scanner bands 5 and 6. The rationale for using these bands depends upon the unique spectral response, compared to other common earth features, that vegetation possesses in the two spectral regions represented by these bands.

C. Conclusions.--By using a constant band-6 to band-5 radiance ratio of 1.25, the changing pattern of areas of relatively dense vegetation cover was detected for the semiarid region in the vicinity of Tucson, Arizona. Electronically produced binary thematic masks were used to map areas with dense vegetation. The foliar cover threshold represented by the ratio was not accurately determined but field measurements show that the threshold lies in the range of 10 to 25 percent foliar cover.

Montane evergreen forests with constant dense cover were correctly shown to exceed the threshold on all dates. The summer-active grassland exceeded the threshold in the summer unless rainfall was insufficient. Desert areas exceeded the threshold during the spring of 1973 following heavy rains; the same areas during the rainless spring of 1974 did not exceed the threshold. Irrigated fields, parks, golf courses, and riparian communities were among the habitats most frequently surpassing the threshold. Eroded areas and mine tailing dumps were among the areas which never exceeded the threshold.

D. Summary of recommendations.--It is recommended that additional studies of vegetation growth dynamics be undertaken using the ESIAC analysis described in this report. The technique should be applied to other areas with different rainfall and plant growth regimes. For many applications, more precise plant coverage values than currently obtainable are not needed. The technique in its present stage of development can contribute significantly to the solution of many resource problems. For those applications requiring greater precision, it is recommended that additional studies be undertaken utilizing computer compatible tapes in conjunction with ESIAC analysis. Ground-truth data gathered in a new study should include radiometric measurements.

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I. INTRODUCTION

With the launch of Landsat, an important change in the approach to synoptic vegetation mapping became possible. Traditionally, vegetation mapping had been used to record static plant occurrences. The products of pre-Landsat mapping were usually vegetation maps showing ranges of plant communities or floristic maps showing distributions of individual species. Now that Landsat is in orbit, synoptic mapping of short-term vegetation phenomena has become feasible. The progressive greening of the earth's surface, as its mantle of foliage seasonally comes to life, is a temporally variable phenomenon of great importance easily detected by Landsat.

Knowledge of the seasonal changes in plant cover can be used by agriculturalists to pinpoint likely areas for grazing by livestock, to anticipate locust migration areas (a recurring problem over millions of square miles in Africa), or to help identify crop types and woodland communities. Seasonal change in foliation has been an elusive parameter of great importance to hydrologists studying water use within croplands as well as in riparian and phreatic communities. Information about locations of dense plant growth can also be used to determine likely areas of subsurface water availability.

The objective of this Landsat investigation was to develop techniques for semi-quantitatively measuring seasonal changes in plant foliar cover within broadly defined plant communities using only bulk Landsat imagery and without field radiometric measurements. Several studies have used ratios between visible and reflective infrared (IR) bands to measure the green biomass of plants. Culler and others (1972) used color infrared film as the source of radiometric data for the ratioing procedure. Aircraft optical mechanical scanners (Stoner and others, 1972), two channel radiometers (Pearson and Miller, 1972), and Landsat computer compatible tapes (Wiegand and others, 1973) have also been employed in ratioing techniques. This report describes a method for detecting areas of heavy plant cover by using bulk Landsat imagery in 70-mm format. We employed a ratio between two of the four spectral bands (MSS-5 and MSS-6) to which the Landsat multispectral scanner is sensitive. The ratioing technique relies on the fact that green plants, among all the common features of the earth, respond uniquely to light—they reflect heavily in the near-IR but reflect little in the visible range. Leaf reflectance in the two bands used, 0.6 to 0.7 μm (MSS-5) and 0.7 to 0.8 μm (MSS-6), is influenced by two distinct plant systems, one involving pigment chemistry, the other, mesophyll anatomy. Both of these systems are closely tied to the parameter being measured, foliar cover.

II. ACKNOWLEDGMENTS

The task of extracting data from the imagery was performed by scientists at Stanford Research Institute: W. E. Evans was especially helpful through his knowledge of the many processes intervening between scene detection and image display. Terry Gustafson gathered the field data during the first months of the study.

III. DESCRIPTION OF STUDY SITES

A. Tucson Test Site.--The primary study area, the Tucson Test Site (Fig. 1), is the region that routinely includes Tucson, Arizona, on Landsat images. The area studied was 81 mi (130 km) by 131 mi (210 km) in size, somewhat smaller than a full Landsat frame. The center of the rectangular area lies at lat. 31° 56' N., long. 110° 50' W. Altitudes at the test site vary from about 2,000 ft (600 m) to about 9,500 ft (2,900 m) (Fig. 2). The vegetation varies from dense evergreen conifer forests on the mountains to sparse desert vegetation on the basal plains. Riparian vegetation occurs at all altitudes. Irrigated crops such as cotton, barley, and pecans are grown in several valleys. Average annual rainfall within the test site varies from near 10 in (250 mm) to more than 30 in (750 mm) (Fig. 3).

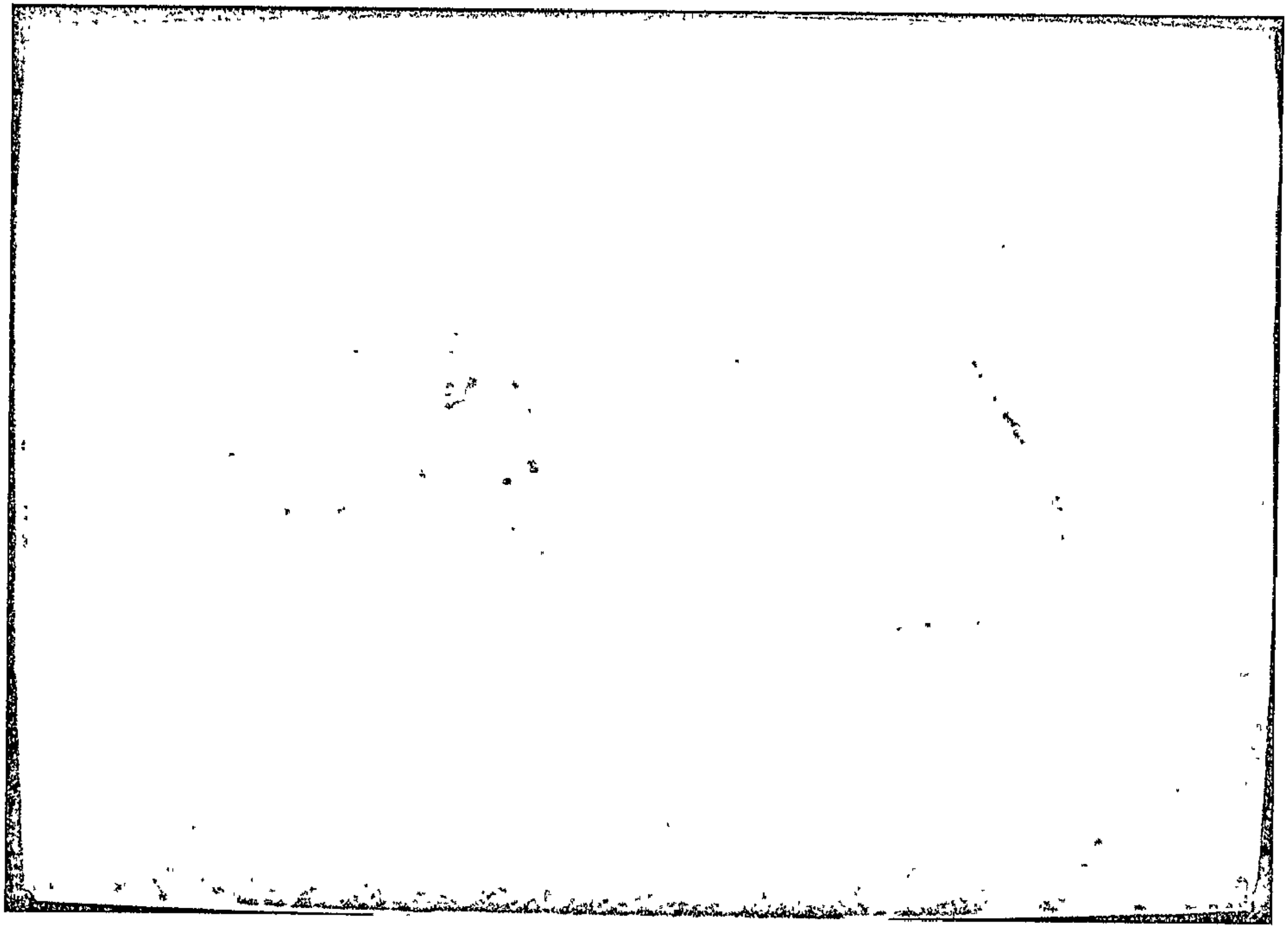


Figure 1.--ESIAC vidicon display of the Tucson Test Site (from image no. 1246-17283-5, March 26, 1973).

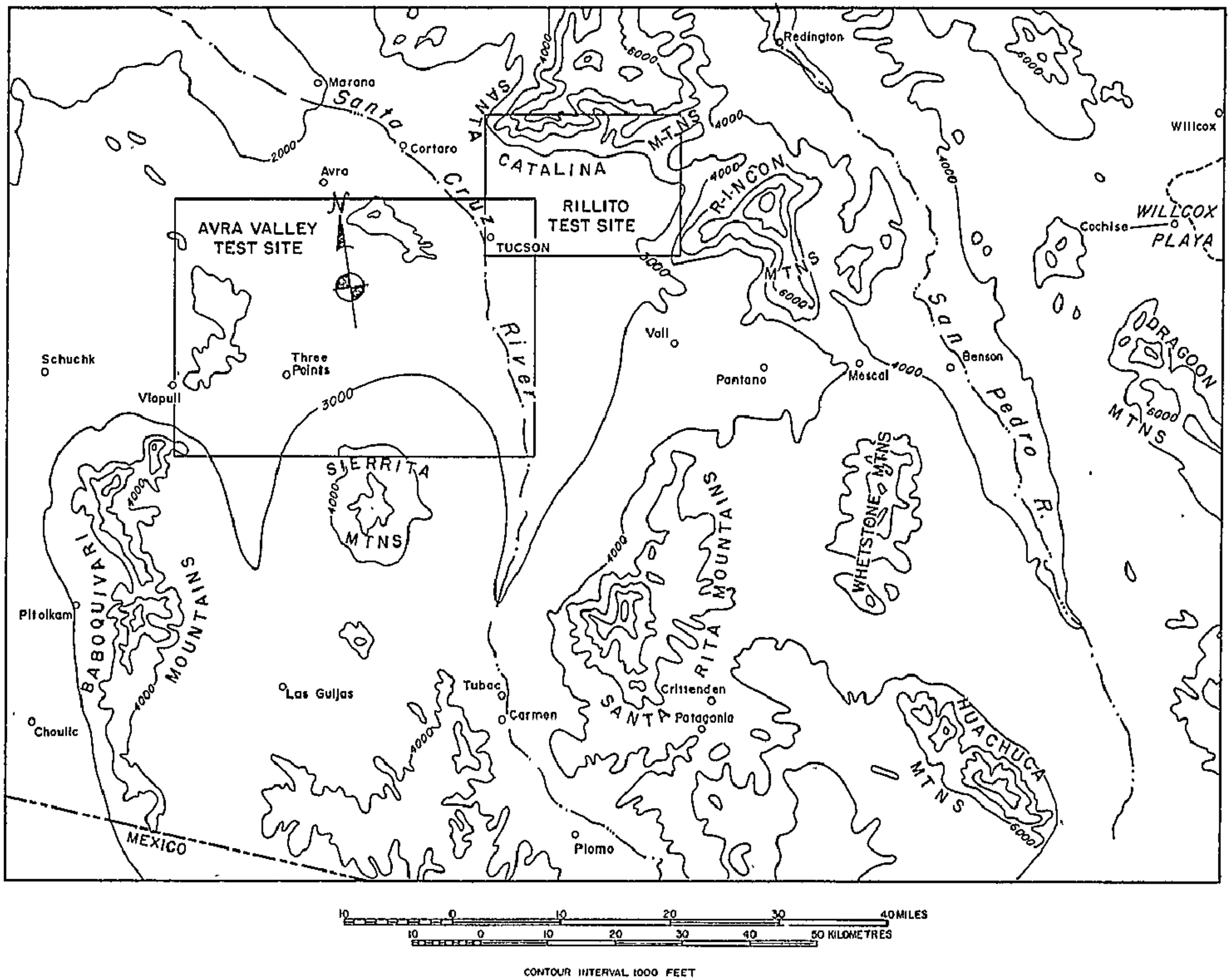


Figure 2.--Topographic map of Tucson Test Site showing location of Avra Valley and Rillito Sites.

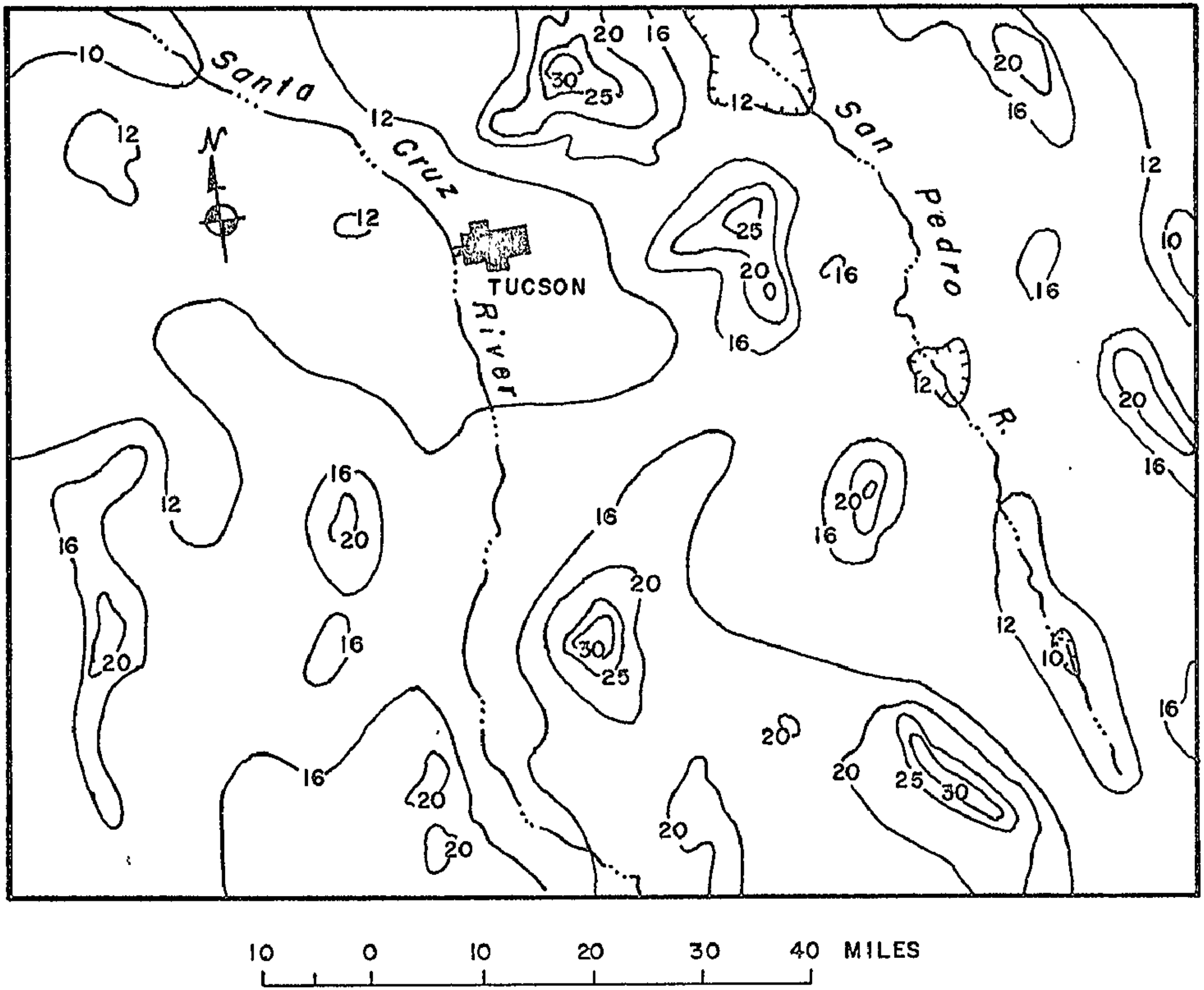


Figure 3.--Average annual precipitation (inches) of Tucson Test Site.

As with most arid regions, a dense cover of ephemeral plants develops quickly within certain desert communities during years of favorable rainfall. The plants reach maturity and complete their life cycles during a period of only a few weeks—any method of measuring these plants must be based on frequent observations. At the other extreme of plant phenologic response in the Tucson region are the evergreen conifers found at high altitudes on the isolated mountains—these plants will change little through the year. To successfully monitor the variable vegetation, the technique to be developed should detect the following seasonal trends in plant cover in the Tucson region:

(1) Small mountainous areas of evergreen conifer forests above about 7,000 ft (2,100 m) will show dense plant cover at all seasons, unless there is a covering of snow.

(2) Many areas between 5,000 and 7,000 ft (1,500 and 2,100 m) altitude are dominated by evergreen oaks and will show dense plant cover at all seasons except during a brief spring period (usually in April and May) when the oaks are leafless.

(3) Plant growth activity in grassland areas between about 3,000 and 5,000 ft (900 and 1,500 m) altitude will be at a maximum during the July to October period of summer-autumn rains. By contrast, the grassland is dormant during the winter.

(4) In general, the persistent perennial vegetation of the desert (areas below about 3,000 ft [900 m]) is not dense enough to mask the reflectance from desert soils; the plants of these communities will usually be too sparse to be detected by the satellite. If rainfall is adequate, there will be a detectable spring maximum of plant activity in the desert corresponding to the time when a dense growth of ephemeral plants develops among the widely spaced shrubs and trees.

(5) Riparian vegetation is winter deciduous at all elevations. At altitudes below about 3,500 ft (1,100 m), the winter leafless season is short, extending roughly through December and January. At higher altitudes the leafless season is longer.

(6) Certain areas will lack significant plant cover at all seasons. Mine tailing dumps, large shopping centers, residential areas with closely spaced houses, and highly eroded areas are among these unproductive sites.

(7) Within and about the City of Tucson, large areas with irrigated lawns such as housing projects, parks, school grounds, and golf courses will support dense plant cover. These are green most of the time if both summer-growing and winter-growing grasses are used.

Two small areas within the Tucson Test Site were studied in enlarged view. One, west of Tucson, includes the Avra Valley and is called the Avra Valley Test Site; the other includes most of the City of Tucson and the foothills of the Santa Catalina Mountains to the north. This site is centered over Rillito Creek and is called the Rillito Test Site (Fig. 2).

B. Rillito Test Site.--The Rillito Test Site (Fig. 2) is 18 mi by 14 mi (29 km by 21 km) and covers an area approximately 1/40 the size of the Tucson Test Site. This small area, encompassing much of the City of Tucson, includes Rillito Creek as a prominent feature. Because of its largely urban setting, this site includes parks, golf courses, and school yards, which if large enough should provide plant response part of the time. Additional areas of dense plant growth such as irrigated fields, phreatophyte communities, and perennial montane vegetation are also included. Many areas of little or no plant growth are represented. These include large paved lots, high density residential areas, and cleared construction sites.

C. Avra Valley Test Site.--The Avra Valley Test Site (Fig. 2) is an area of about 770 mi^2 (2,000 km^2) lying in the northwest quarter of the Tucson Test Site. Most of this site is below an altitude of 3,000 ft (900 m), although small areas (Tucson Mountains and Sierrita Mountains) approach or exceed 4,000 ft (1,200 m). The vegetation of the low-lying desert areas is predominantly creosote bush, desert sage, and degraded grassland. Large areas are badly eroded. Extensive areas are irrigated in the northwest part of the site. Irrigated crops are also raised near the Santa Cruz River south of Tucson.

Five locations within the Avra Valley Test Site were selected for intensive study. Three of the five stations were located along Milewide Road which extends down a bajada to the west of the Tucson Mountains and on to the valley floor. The station designated as Milewide 1 is on the west side of Brawley Wash on an alluvial soil at an altitude of 2,220 ft (675 m). The vegetation is simple, comprising mainly one dominant perennial plant, creosote bush (*Larrea tridentata*). The perennial plant cover is sparse but in favorable seasons the cover of ephemeral plants, especially filaree (*Erodium cicutarium*), is almost complete.

Milewide 3 lies approximately 5 mi (8 km) east of Milewide 1 at an altitude of 2,540 ft (770 m) and is on the upper bajada of the Tucson Mountains. The perennial plant with greatest coverage is triangle bursage (*Ambrosia deltoidea*). Other perennial plants in this complex community are foothill paloverde (*Cercidium microphyllum*) and saguaro (*Carnegiea gigantea*).

Milewide 2 lies between the other two stations at an altitude of 2,300 ft (700 m). The perennial vegetation of this lower bajada site is composed of the same dominants as at Milewide 3 but total coverage is less at the former. Milewide 2 and 3 were located on contrasting soils: Milewide 3 on a dark basaltic soil and Milewide 2 on a lighter granitic soil.

The other two stations within the Avra Valley Test Site were along the bajada of the Sierrita Mountains. Sierrita Mountain 1, the lower of the two stations, is at an altitude of 2,540 ft (770 m). The vegetation is overgrazed, degraded, desert grassland. A small shrub, snakeweed (*Gutierrezia sarothrae*), is the dominant plant, rather than grasses. Other perennial dominants include mesquite (*Prosopis juliflora*) and jumping cholla (*Opuntia fulgida*). The area has a high albedo as seen on Landsat images because of the high degree of soil erosion.

Sierrita Mountain 2 is higher on the bajada at an altitude of 2,890 ft (880 m). More grasses occur here compared to Sierrita Mountain 1 as well as more snakeweed. Minor perennial constituents are mesquite, jumping cholla, desert hackberry (*Celtis pallida*), and Mormon tea (*Ephedra trifurca*). Erosion at this site is much less than at the previous site and the albedo is lower as a consequence.

IV. METHODS

A. Field Studies.--At the time of each satellite overpass, records were made at several locations within the Tucson Test Site. Five stations (all within the smaller Avra Valley Test Site) were studied more intensively than the others. At these five stations, foliar coverage measurements were made and photographs taken. At the other stations that were routinely visited within the Tucson Test Site, only photographs were taken to document vegetation condition. The photographic stations were located at three riparian plant communities, one in Avra Valley and two within the Rillito Creek drainage. In addition, photographs were taken at irregular intervals within several montane communities (Santa Catalina Mountains and along the San Pedro River).

A series of four transects was established at each of the five intensively studied sites. The four transects extended out from a common point in the four cardinal directions. Along each transect, fifteen rectangular plots, 8 in (200 mm) by 20 in (500 mm), were established at 3 ft (1 m) intervals. Foliar cover was measured by estimating the percentage of the soil surface obscured by green plant organs when viewed vertically (Daubenmire, 1959). A mean coverage for the area was derived from the resulting sixty plots.

Photographs were taken at each Avra Valley station, looking north from the intersection of the four transects. In this way, replicated photographs, one satellite cycle apart, were used for qualitative assessment of foliar change as a supplement to the transect data.

B. Image analysis.--By combining radiance data from two spectral bands in which plants have a unique response, it is possible to create thematic masks showing all areas within a Landsat scene where plant foliage cover exceeds a selected threshold. The Electronic Satellite Image Analysis Console (ESIAC), developed and operated by scientists at Stanford Research Institute, was used to generate thematic masks of the Tucson sites. Basically, the technique involves a ratioing procedure utilizing scene radiance values across paired Landsat scenes (Serebreny and others, 1974).

In analyzing the imagery, paired MSS-5 and MSS-6 70-mm black-and-white positive transparencies were viewed by a television camera and recorded on the ESIAC magnetic discs. With the image grey scales as guides, appropriate adjustments in camera response were first made on the console to standardize the grey-scale step versus voltage response for all images. Thematic masks, showing areas of heavy plant development were generated by electronically "slicing" areas that exceeded some preselected ratio. The masks were displayed on a television monitor and recorded photographically for future analysis and study.

C. Selecting a ratio.--Plant reflectance values given by Billings and Morris (1951) for plant communities show that green plant tissue (foliage) will reflect approximately 50 to 60 percent of the incident light within the 0.7 to 0.8 µm (MSS-6) range and roughly 10 percent within the 0.6 to 0.7 µm (MSS-5) range. Where plants grow densely, such as in irrigated fields, the characteristic reflectance in these two bands can be used jointly to distinguish the plants from nearby soil, rock, bodies of water, and other natural surfaces. Because natural plant communities in arid and semi-arid regions rarely attain such dense growth, foliage reflectance is masked to some degree by soil, litter, and rocks. To examine the effect that background reflectance might have on measurements of vegetative cover in desert areas, a set of hypothetical curves (Fig. 4) has been derived by assuming various mixtures of soil and foliage cover and by calculating the corresponding MSS-6 and MSS-5 radiance ratios. These curves show that for a given MSS-6/MSS-5 ratio a decrease in soil reflectance coincides with a decrease in foliage cover. Because of the variability in soil reflectance within the test site, the vegetative cover percentage represented by a given ratio is variable. If a single ratio is selected as a threshold value for estimating coverage, a spurious decrease in community reflectance would occur following rains because of the reduced reflectance of soils when moist (Condit, 1970). Furthermore, the amount of plant cover required to exceed the critical threshold value would be less on dark basaltic soils than on light granitic soils of equal moisture content.

The foregoing material suggests that the technique might be improved by providing field measurements of radiation at the time of each satellite pass over. Such field data, taken from large uniform features such as playas or mine tailing dumps, might be useful in removing sampling errors resulting from variation in soil moisture conditions. This refinement was beyond the scope of the present program. Other difficulties with the technique were related to variations in photographic processing of the Landsat images used (Serebreny, and others, 1974). These problems would be circumvented if the data were entered from tape, an approach not covered by the objectives of this study.

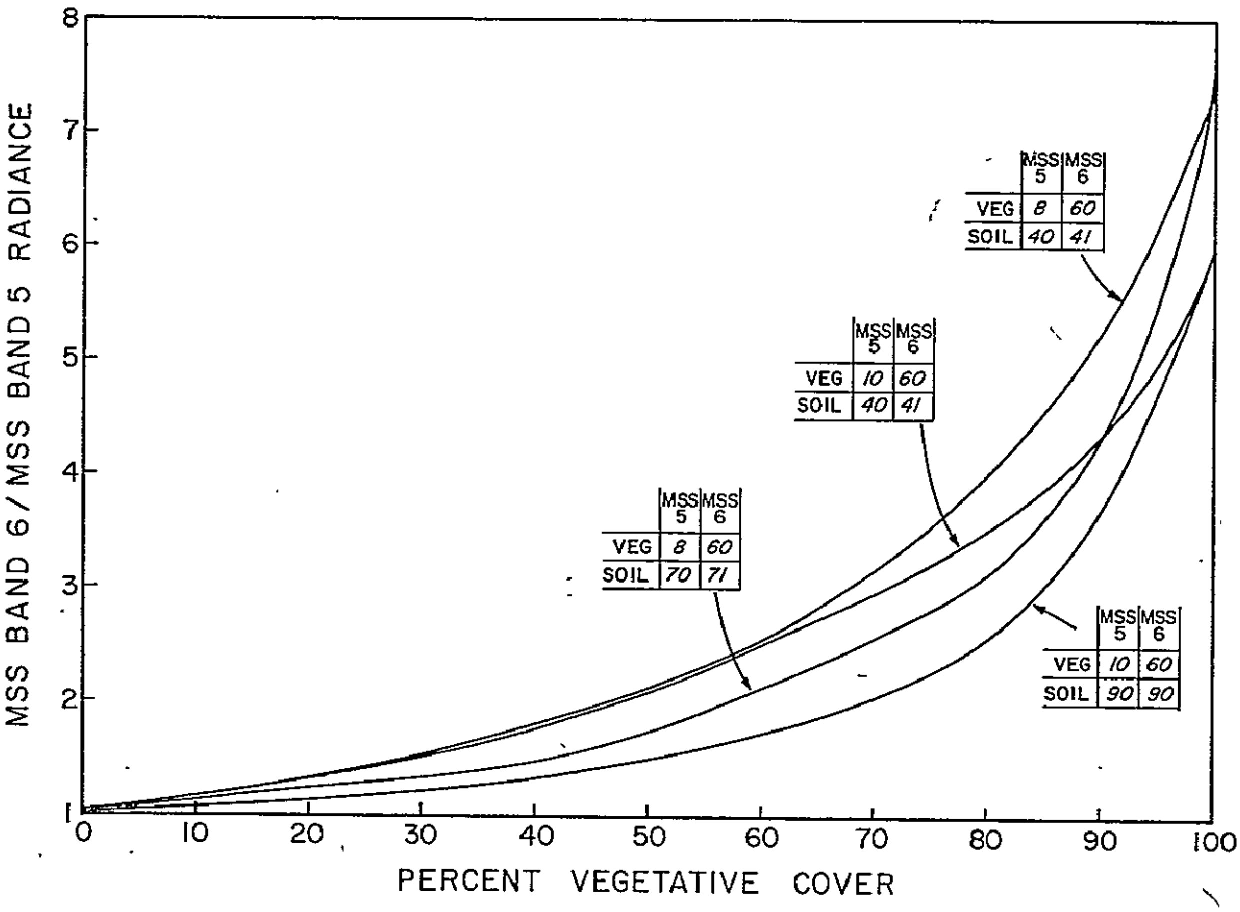


Figure 4.--Change in the ratio of MSS-6/MSS-5 radiance values with change in plant coverage. The four curves represent hypothetical combinations of soil and vegetation reflectances (as percent) in the two spectral bands represented by MSS-5 and MSS-6.

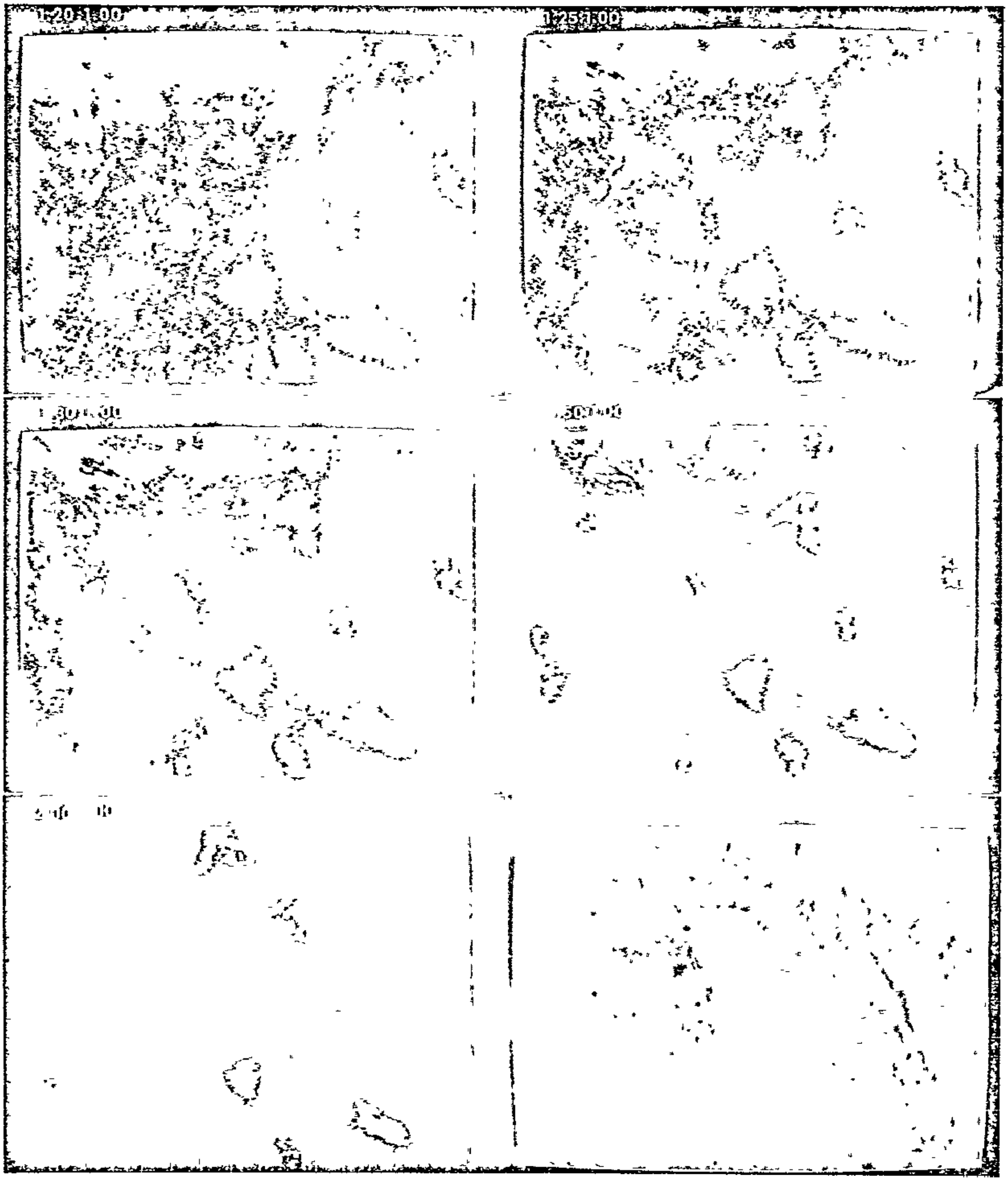
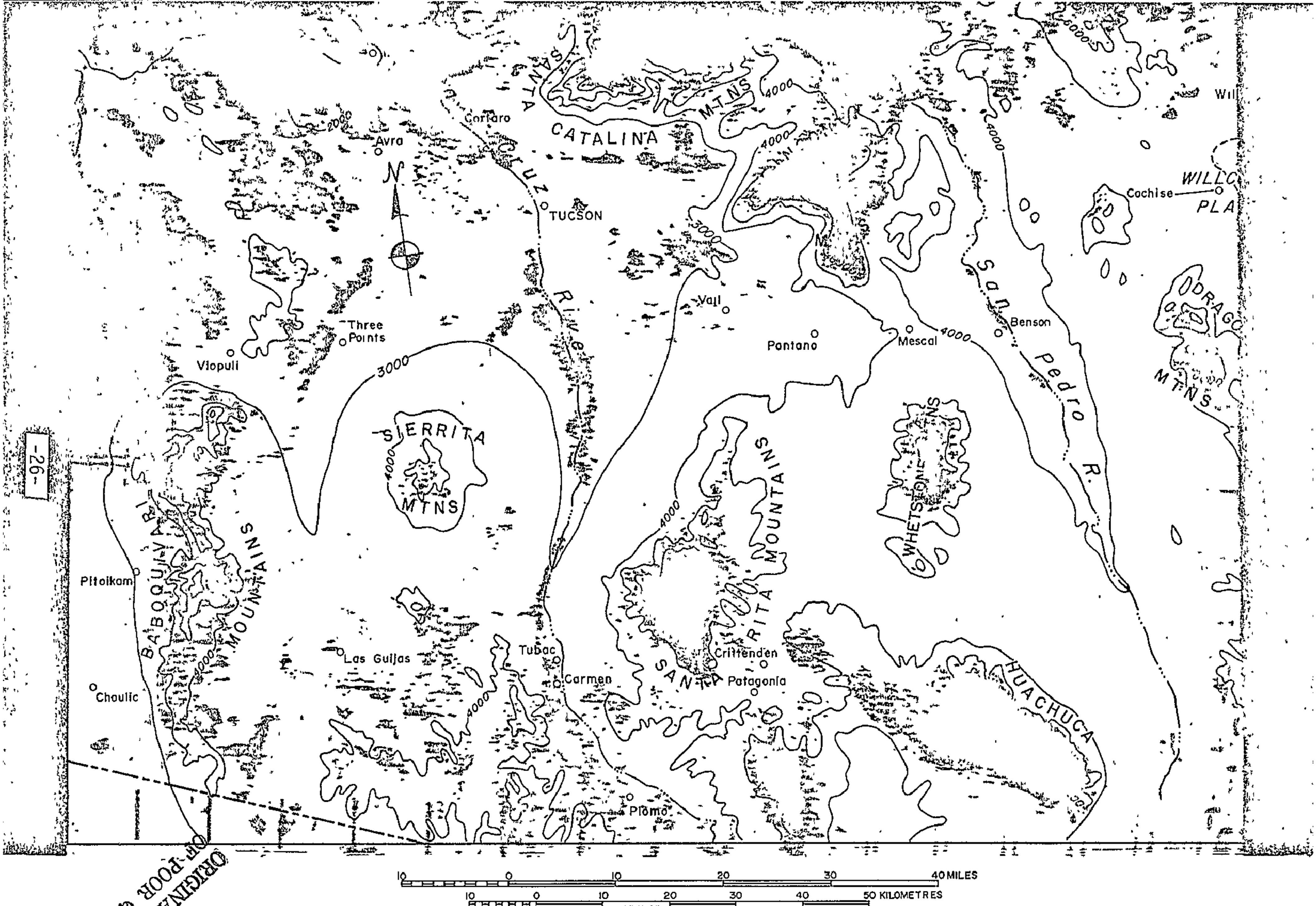


Figure 5.--Thematic masks representing five MSS-6/MSS-5 ratios from images of the Tucson Test Site for February 18, 1973 (image nos. 1210-17282-5 and -6). For comparison a view of the Test Site is shown at lower right (see fig. 1).



CONTOUR INTERVAL 1000 FEET

Figure 6.--Superimposed binary masks for five dates (cycles 9, 10, 12, 14, and 15) during a wet winter-spring period, Tucson Test Site.

In selecting a ratio to represent areas of relatively dense plant cover, imagery for a date of known heavy desert plant growth was used and a series of thematic masks representing various ratios was displayed on the console. Figure 5 shows a series of masks for the following MSS-6/MSS-5 ratios: 1.20/1.00; 1.25/1.00; 1.30/1.00; 1.50/1.00; and 2.00/1.00. The date of the imagery was February 18, 1973 (image numbers 1210-17281-5 and -6). (Areas which exceed the threshold values are shown as white in this series of thematic masks; in subsequent displays, for example Fig. 6, such areas are dark against a light background.) Scene reflectance on this date was strongly influenced by vegetation in four different locations: (1) low-lying desert areas with dense ephemeral plant cover, (2) riparian communities below about 3,500 ft (1,100 m) altitude where ephemeral plants and early foliating trees such as cottonwood grow densely, (3) croplands, and (4) dense evergreen vegetation of the highest mountains. Plants at intermediate elevations were winter dormant on this date. It can be seen that at a ratio setting of 2.00/1.00 most areas were deleted; only the silhouettes of mountains and a few fields remain. At a low setting of 1.20/1.00 most of the low desert area was included along with the mountains. A ratio value of 1.25/1.00 was finally selected as the value that would yield the most information about the various plant communities in the scene. Study of two other series of similar masks representing imagery from contrasting seasons bore out the conclusions that a ratio value between 1.20/1.00 and 1.30/1.00 would probably provide maximum information.

V. RESULTS

A. Tucson Test Site.--Thematic masks from 13 Landsat cycles have been analyzed for the Tucson Site (Table 1). The 13 images were cloud-free, or nearly so, and represent all seasons through approximately 16 months during the period from late August 1972 to late January 1974. Groups of these masks have been superimposed over a map of the Tucson Site. The transparent masks can be combined to show conditions for a variety of seasons and dates. When masks for consecutive cycles are combined, the resulting patterns represent maps of foliage duration, the darkest portions of the map representing areas that exceeded the threshold for the longest time. For illustrative purposes, only one composite is presented (Fig. 6); this includes five dates during a relatively wet winter-spring period (cycles 9, 10, 12, 14, and 15).

On the composite in figure 6, areas exceeding the ratio threshold lie primarily in the mountains, low elevation desert areas, and along the bottoms of valleys. On a composite of summer-fall cycles (not shown), areas exceeding the threshold also lie in the mountains and along the valleys but at this season high valleys, which support grassland, show a response; less response is found in the desert areas. Thus, the main difference between the two sets of data lies in the location of dense intermontane vegetation: for the summer-fall season the response is in areas of grassland; for the winter-spring season, in desert areas where a dense growth of spring annuals occurs.

Table 1.--Imagery data, Tucson Test Site.

LANDSAT CYCLE NO.	DATE	IMAGE NO.
2	22 Aug 1972	1030-17271-5 & -6
6	2 Nov 1972	1102-17280-5 & -6
9	26 Dec 1972	1156-17280-5 & -6
10	14 Jan 1973	1174-17275-5 & -6
12	18 Feb 1973	1210-17282-5 & -6
14	26 Mar 1973	1246-17283-5 & -6
15	13 Apr 1973	1264-17283-5 & -6
17	19 May 1973	1300-17281-5 & -6
19 1/	24 June 1973	1336-17275-5 & -6
23 2/	4 Sept 1973	1408-17265-5 & -6
27	15 Nov 1973	1480-17253-5 & -6
29	21 Dec 1973	1516-17250-5 & -6
31	26 Jan 1974	1552-17235-5 & -6

1/ Southern 1/4 of frame has 10 percent cloud cover.

2/ Clouds over Huachuca Mountains.

Individual masks derived from all 13 cycles are shown in figures 7, 8, 9, and 10. By examining the series of masks, seasonal changes are readily apparent, including the seasonal progression of plant growth from grassland areas in August and November 1972 (Fig. 7), to desert areas in February, March, and April 1973 (Fig. 8). The mask for September 1973 shows little response in the grassland areas although this is the season when greatest grassland growth activity should occur. The low level of response is attributable to the poor rainfall recorded throughout most of the region during the 2 months prior to the September 4 Landsat cycle.

B. Rillito Creek Test Site.--The area examined in the preceding section is so large that many vegetation details are lost because of the small scale. The ESIAC vidicon camera is equipped with zoom optics so that enlargement and analysis of but a small part of a single Landsat frame is possible. Accordingly, a small area approximately 1/40 the size of the Tucson Test Site (Fig. 2) was selected for study. The procedure for analyzing the imagery was the same as before except, with the vidicon camera adjusted for enlarged viewing, only part of a 70-mm transparency was seen. The scale of the Rillito Creek Site as seen on the 17-in (43 cm) ESIAC screen was approximately 1:90,000.

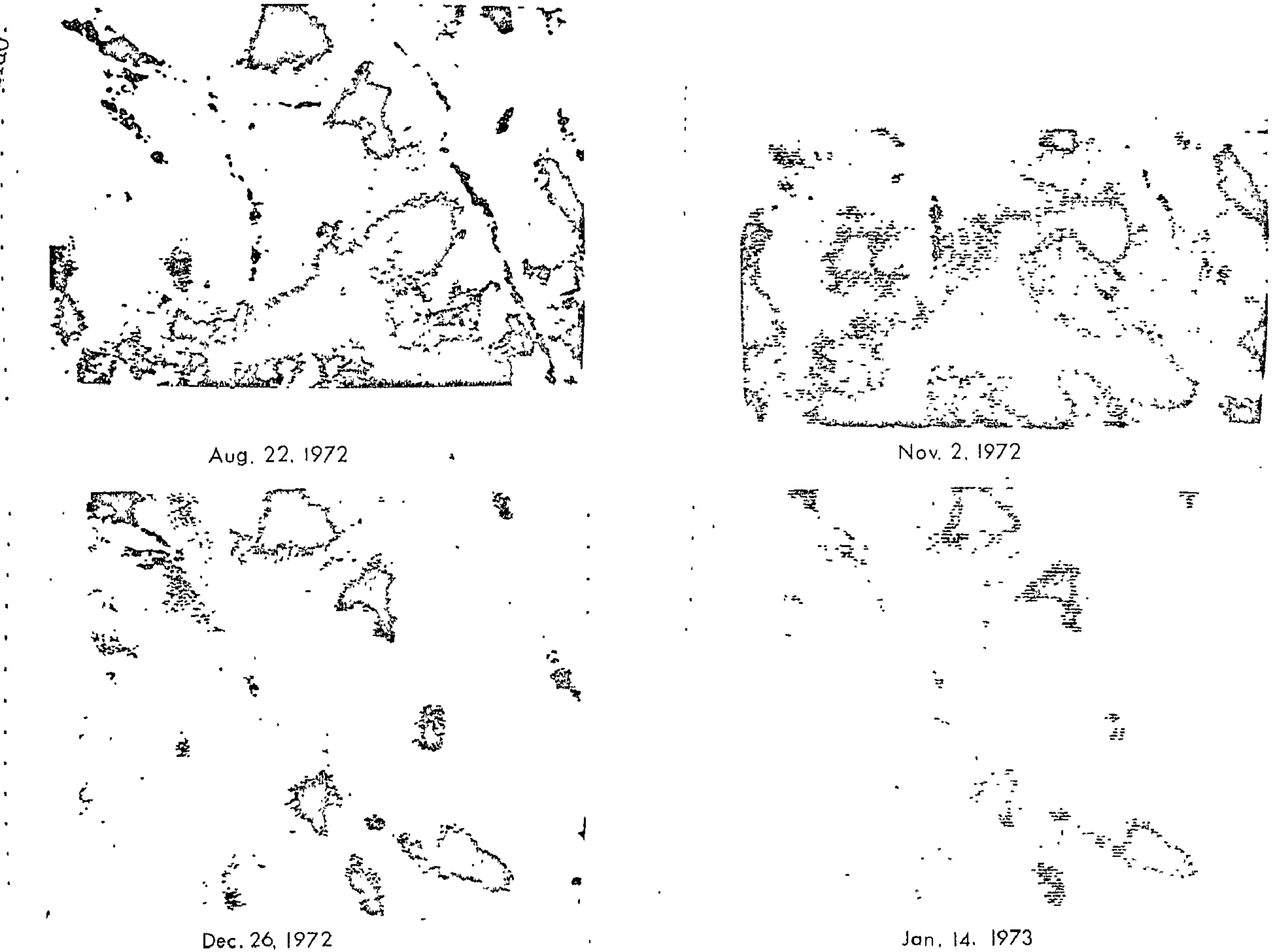


Fig. 7 Binary masks showing areas of dense vegetation on four dates. Tucson Test Site.

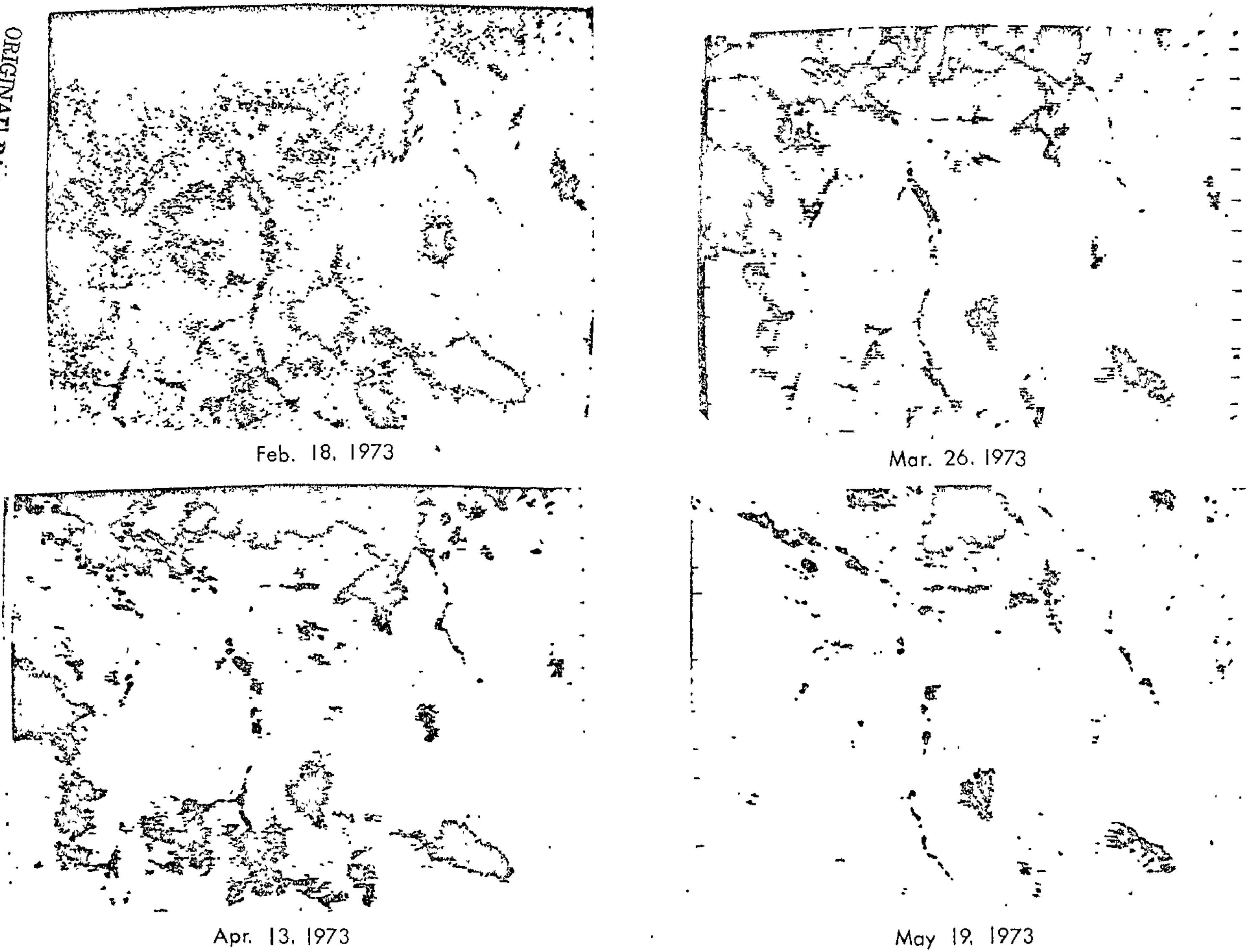


Fig. 8 Binary masks showing areas of dense vegetation on four dates. Tucson Test Site.

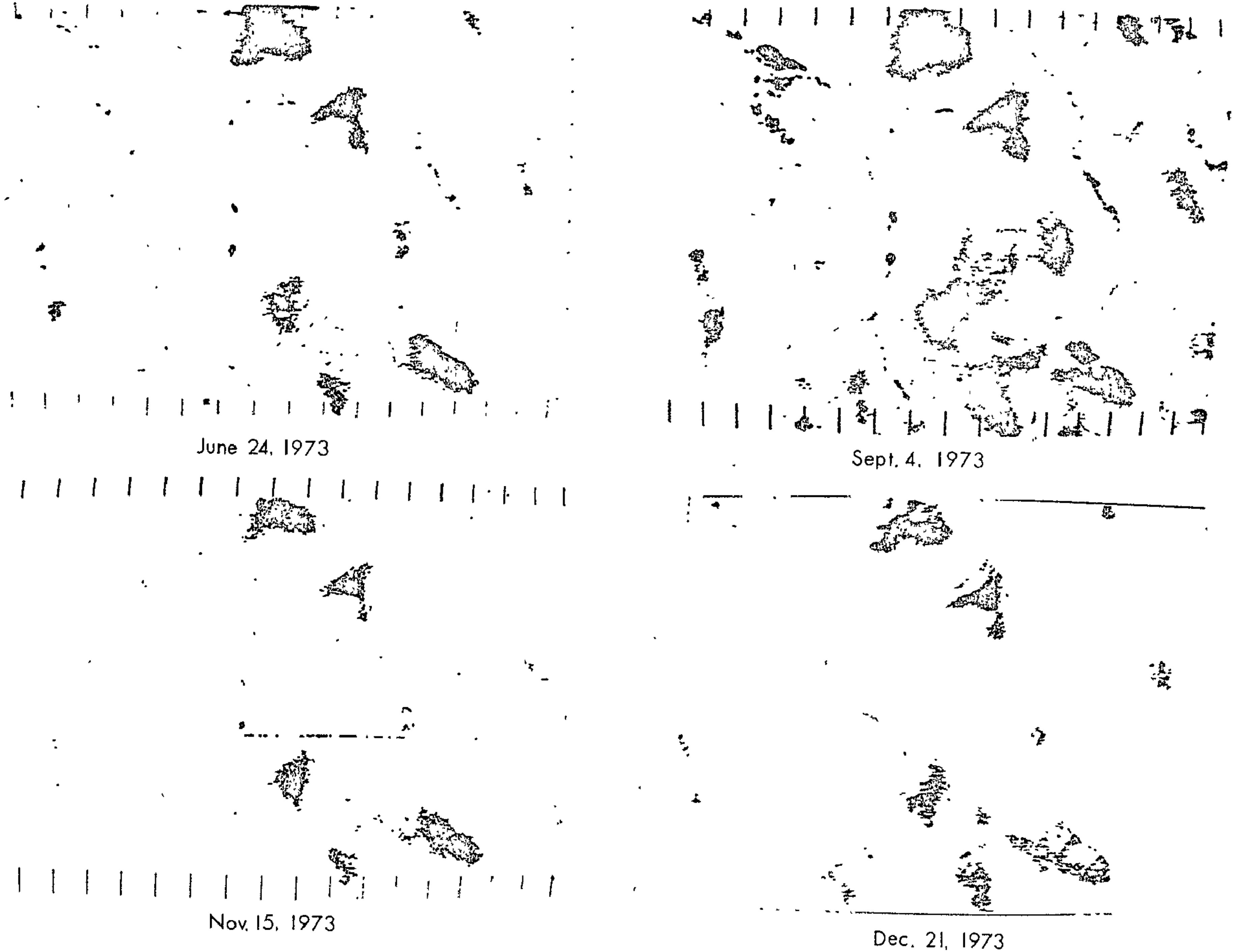


Fig. 9 Binary masks showing areas of dense vegetation on four dates. Tucson Test Site.

Jan. 26, 1974

Fig.10 Binary mask showing area of dense vegetation on one date. Tucson Test Site.

Imagery of the Rillito Site for 13 Landsat cycles was examined (Table 2). A composite of masks from the 13 cycles, superimposed over a map of the Rillito Test Site is shown in figure 11. The composite of 13 images shows the following salient features: parks, such as those at A and D, exceed the threshold on many dates (A includes a golf course). Schools and many housing developments (especially those with golf courses) are also electronically sliced; among the latter are Vandenberg Village (B), Rolling Hills Country Club Estates (C), Tucson Country Club Estates (H), and Skyline Country Club Estates (G). Irrigated farms (E), mesquite forests along Rillito Creek (right center), and natural vegetation in the Santa Catalina Mountains (F) also have dense plant cover.

Table 2.--Imagery data, Rillito Test Site.

LANDSAT CYCLE NO.	DATE	IMAGE NO.
2	22 Aug 1972	1030-17271-5 & -6
6	2 Nov 1972	1102-17280-5 & -6
10	14 Jan 1973	1174-17275-5 & -6
12	18 Feb 1973	1210-17283-5 & -6
14	26 Mar 1973	1246-17283-5 & -6
15	13 Apr 1973	1264-17283-5 & -6
16	1 May 1973	1282-17283-5 & -6
17	19 May 1973	1300-17281-5 & -6
19	24 June 1973	1336-17275-5 & -6
23	4 Sept 1973	1408-17265-5 & -6
27	15 Nov 1973	1480-17253-5 & -6
29	21 Dec 1973	1516-17250-5 & -6
31	26 Jan 1974	1552-17235-5 & -6

Figure 11.--Composite of binary masks for thirteen cycles showing areas of dense vegetation, Rillito Test Site. (Scale 1:126,720)

Toward the right side of figure 11 is a discontinuous north-south strip of presumed heavy vegetation about two miles wide (between Houghton Road on the west and Freeman Road-Soldier Trail Road on the east). Most response in this area was during only three cycles: February 18, 1973; March 26, 1973; and April 13, 1973. These dates coincide with a period of heavy growth of annual plants in surrounding desert areas. Although field checks in this area were not made at the time of the satellite overpasses, a check during the spring of 1974 suggests that this strip probably supported large numbers of desert annuals during the spring of 1973. The relatively sharp eastern boundary is possibly determined by a change to a soil that did not support a rank growth of annuals. The western boundary is probably determined in part by disturbance resulting from urbanization.

A cycle-by-cycle examination of the 13 masks shown in figure 11 reveals that several areas consistently exceeded the ratio threshold. In general, these were the high elevations in the Santa Catalina Mountains (labeled F in Fig. 11), where the native evergreen oaks and conifers form a dense canopy even during periods of little rainfall, and large areas receiving supplemental water. Among the latter were Randolph Park (A), Tucson Country Club Estates (H), Skyline Country Club Estates (G), and Rolling Hills Estates (C). Vandenberg Village (B) exceeded the threshold on all but one cycle (Dec. 21, 1974). The University of Arizona farm (E) lacked response on two dates, November 2, 1973 and January 26, 1975.

Masks for two cycles (2 and 6) are superimposed to represent conditions during a relatively dry period (Fig. 12). The total area with plant coverage great enough to exceed the slicing threshold is now low. The few areas sliced include parks (A and D), golf courses (A, B, and C), irrigated fields (E), mesquite forests (elongate area, middle right), and vegetation of the mountains (F).

C. Avra Valley Test Site.--Studies at the Avra Valley Test Site were aimed primarily at defining the foliar coverage threshold detected by the ratioing procedure. Foliar coverage was measured in the field within 2 days of each satellite overpass; measurements were obtained from August 1972 to June 1974 (Fig. 13). Precipitation data were obtained from the Arizona-Sonora Desert Museum which lies within the northwestern quadrant of the Test Site only 1.7 mi (2.7 km) from Milewide Road 3. Rainfall data in figure 13 represent total amounts falling during each 18-day cycle. Precipitation during the autumn of 1972 was unusually high throughout southern Arizona. This heavy rainfall stimulated early development of winter annuals, especially at Milewide Road 1. Continued development of the plants was promoted by small amounts of rain during cycles 10, 11, and 12, and by abundant rain during the next several cycles. As a consequence, the growth of ephemeral "wild-flowers" was heavy within the Test Site (Fig. 13) and throughout much of the region.

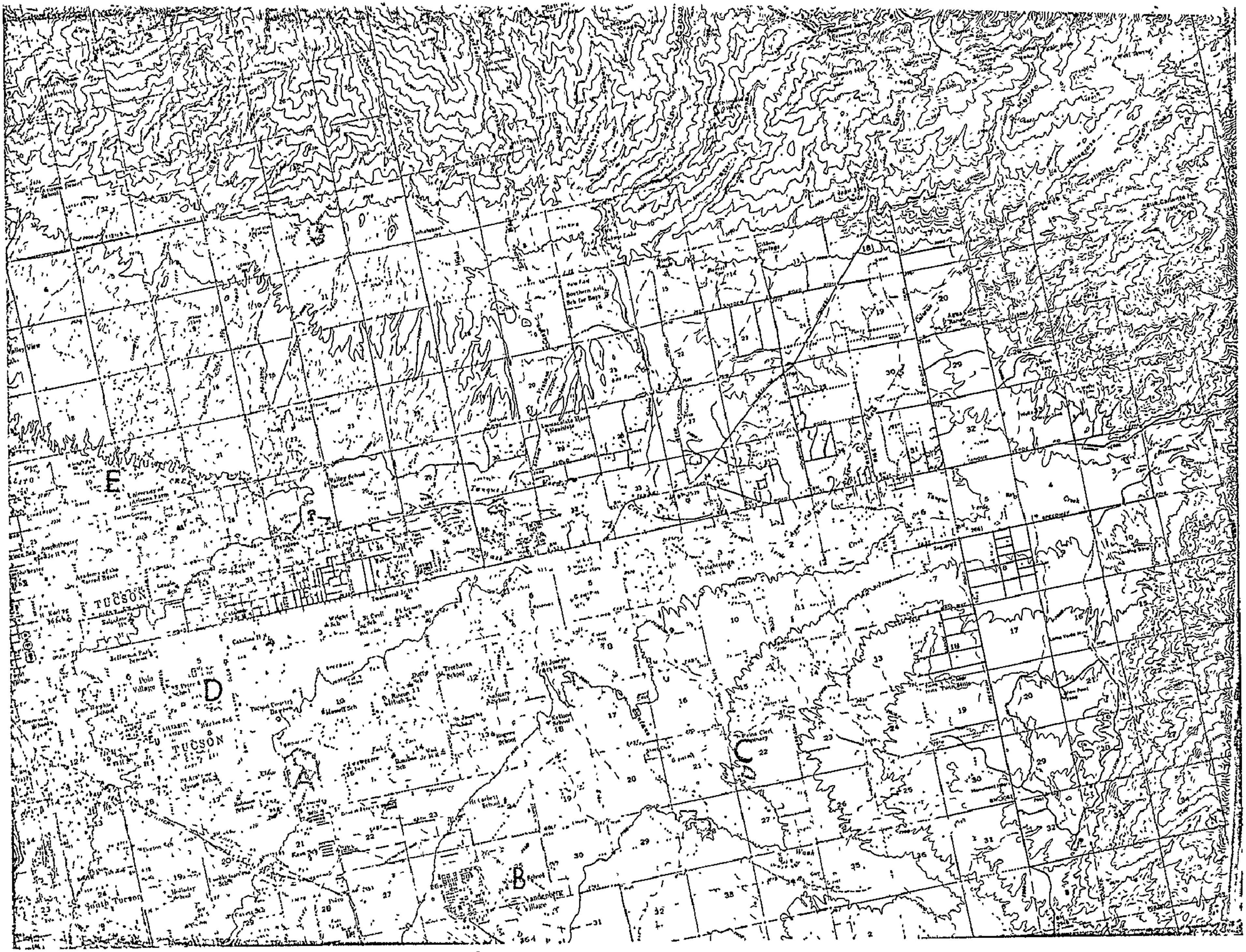


Figure 12.--Binary mask for cycles 2 and 6 (August 22 and November 22, 1972) superimposed over map of Rillito Test Site (Scale 1:126,720).

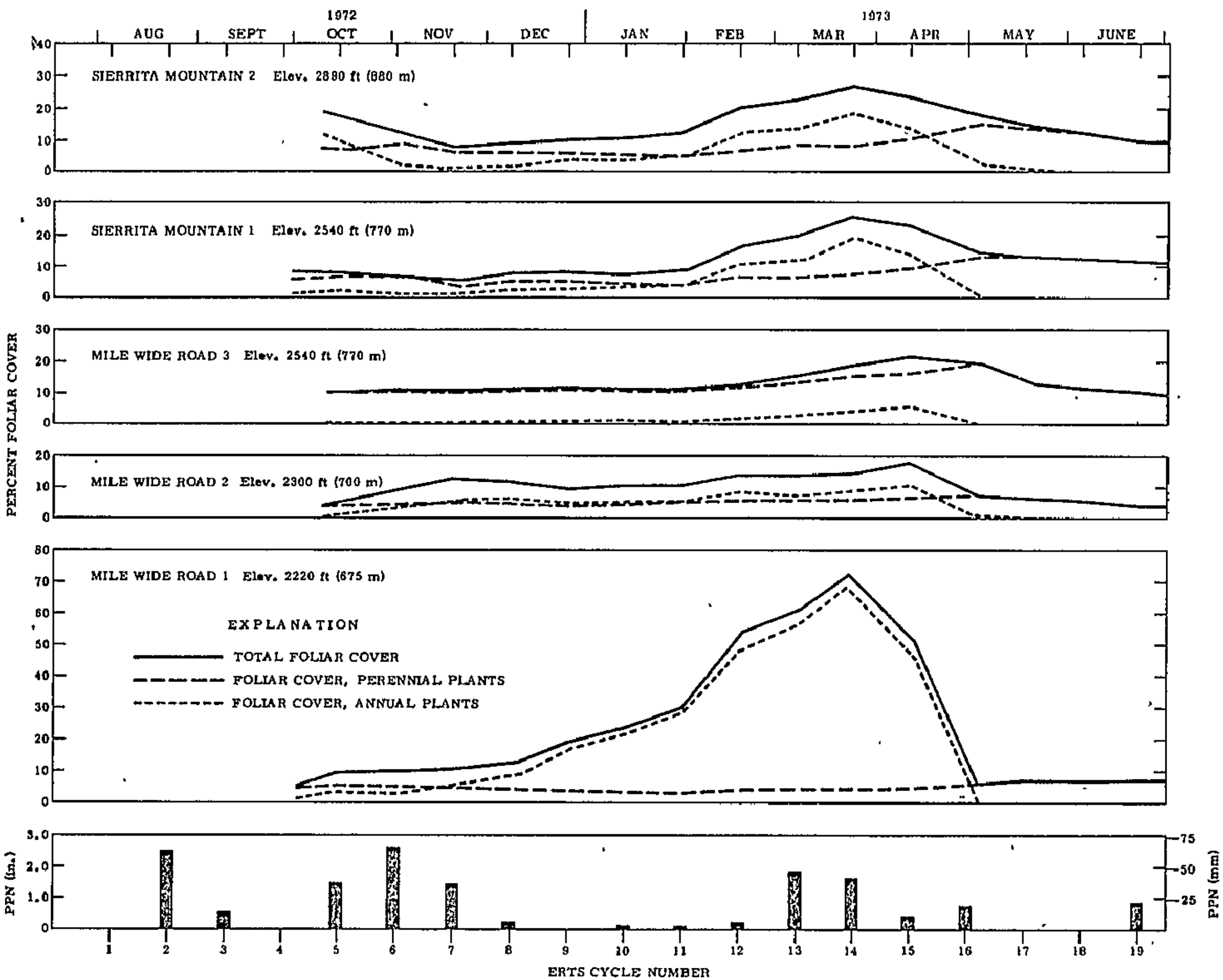


Figure 13.--Changes in foliar cover at five stations, Avra Valley Test Site. Precipitation values are from a single locality within the Test Site.

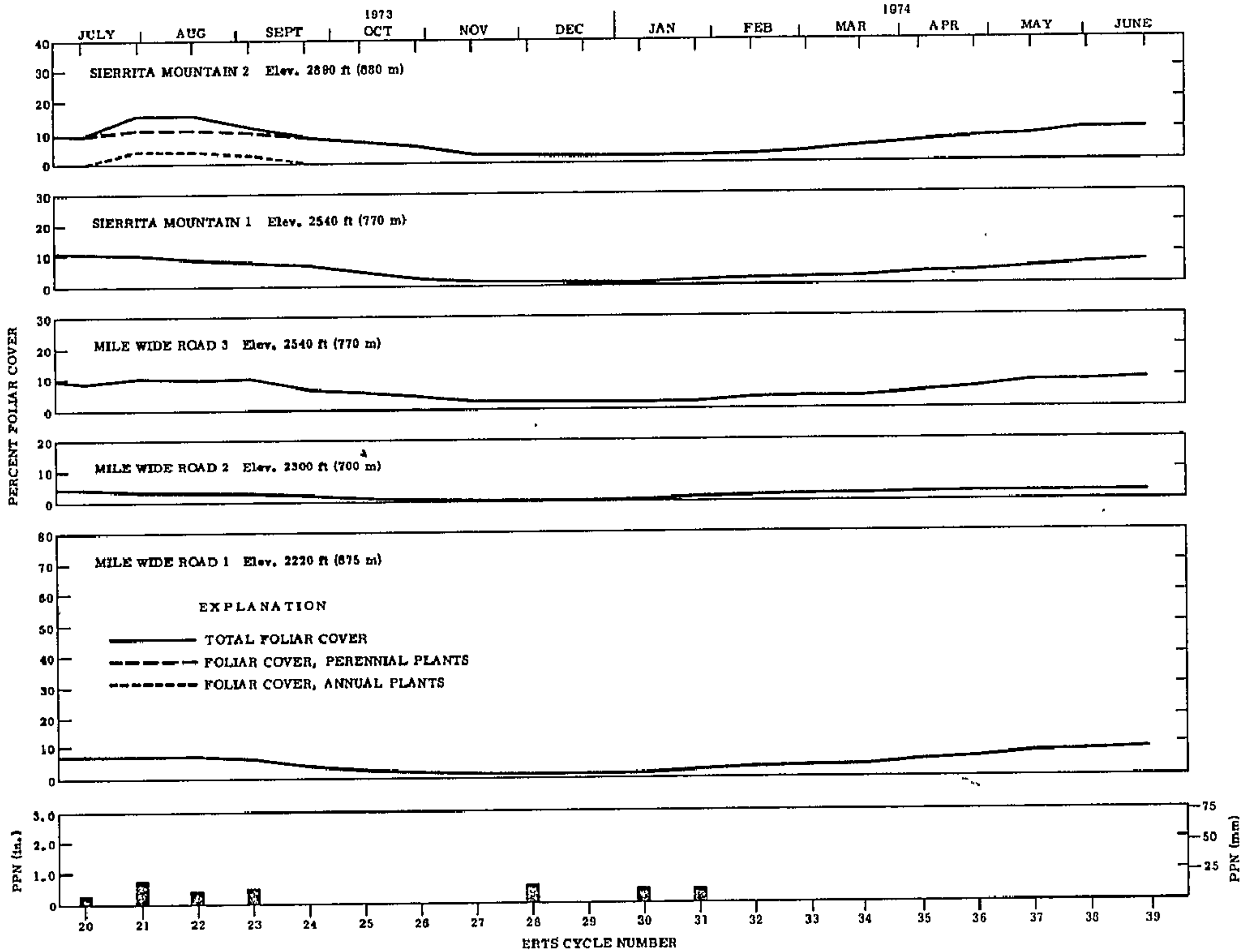


Figure 13.--Changes in foliar cover at five stations, Avra Valley Test Site. Precipitation values are from a single locality within the Test Site. (Continued).

Plant-coverage measurements made near the date of each Landsat cycle have been compared with the thematic masks generated by the ESIAC. Images from 19 dates have been used in this analysis. By superimposing thematic masks over a map showing the five intensively studied Avra Valley stations, the dates when the ratio was exceeded can be readily determined for most dates (Table 3). Cycle 12 data are ambiguous for two stations—Milewide 2 and Milewide 3. On that date, these stations coincide with small, patchy, irregular mask patterns. Because the location of the stations cannot be pinpointed on the map, where they lie within the binary mask pattern is in doubt.

Two stations, Milewide 2 and Sierrita Mountain 1, coincided with areas where the threshold was never exceeded (except doubtfully at Milewide 2, cycle 12, as noted above). Sierrita Mountain 1 is in an area of low plant density and high erosion; as a conseuqence, the albedo is high. The nearby station at Sierrita Mountain 2 exceeded the threshold twice—at the time of cycles 5 and 12. Significantly, this station is in an area of greater plant density, less erosion, greater average rainfall, and lower albedo than Sierrita Mountain 1.

Table 3.--Imagery data and record of dates when ratio threshold was exceeded, Avra Valley Test Site

Landsat Cycle No.	Station					Image No.	Date
	Milewide			Sierrita Mountain			
	1	2	3	1	2		
2	no	no	no	no	no	1030-17271-5 & -6	22 Aug 72
3	no	no	no	clouds	clouds	1048-17272-5 & -6	9 Sep 72
4	no	no	no	no	no	1066-17272-5 & -6	27 Sep 72
5	no	no	yes	no	yes	1084-17274-5 & -6	15 Oct 72
6	no	-	-	no	no	1102-17280-5 & -6	2 Nov 72
9	no	no	no	no	no	1156-17280-5 & -6	28 Dec 72
10	yes	no	no	no	no	1174-17275-5 & -6	14 Jan 73
11	yes	no	no	no	no	1193-17335-5 & -6	1 Feb 73
12	yes	?	?	no	yes	1210-17283-5 & -6	18 Feb 73
14	yes	no	no	no	no	1246-17283-5 & -6	26 Mar 73
15	yes	no	no	no	no	1264-17283-5 & -6	13 Apr 73
17	no	no	no	no	no	1300-17281-5 & -6	19 May 73
18	no	no	no	no	no	1318-17280-5 & -6	6 June 73
19	no	no	no	no	no	1336-17275-5 & -6	24 June 73
23	no	no	no	no	no	1408-17265-5 & -6	4 Sep 73
27	no	no	no	no	no	1480-17253-5 & -6	15 Nov 73
29	no	no	no	no	no	1516-17250-5 & -6	21 Dec 73
31	no	no	no	no	no	1552-17235-5 & -6	26 Jan 74
33	no	no	no	no	no	1588-17231-5 & -6	3 Mar 74

Milewide 1 exceeded the threshold on five dates, corresponding with cycles 10 through 15. These dates fell within a period when ephemeral plant growth at low-lying desert areas reached values greater than for any other time during the study. Coverage values during this winter-spring period reached a maximum of about 75 percent at Milewide 1. The high values, largely attributable to the heavy production of ephemeral plants, occurred at a time when rainfall amounts were above normal. Much of the area received roughly four times the long-term average precipitation. The following year, when rainfall was lacking during the spring, no ephermeral plants developed at the five stations (Fig. 13).

An example of the data obtained at the Avra Valley Site is shown in figure 14. In this illustration, representing conditions for an unusually wet spring, binary masks for cycles 14 and 15 (March 26, 1973 and April 13, 1973) have been superimposed over a map of the site. Of the five stations, only Milewide 1 exceeded the threshold on these dates. Other areas that exceeded the threshold were irrigated fields, golf courses, and parks. Heavily eroded areas and mine tailing dumps were among the features that did not exceed the threshold.

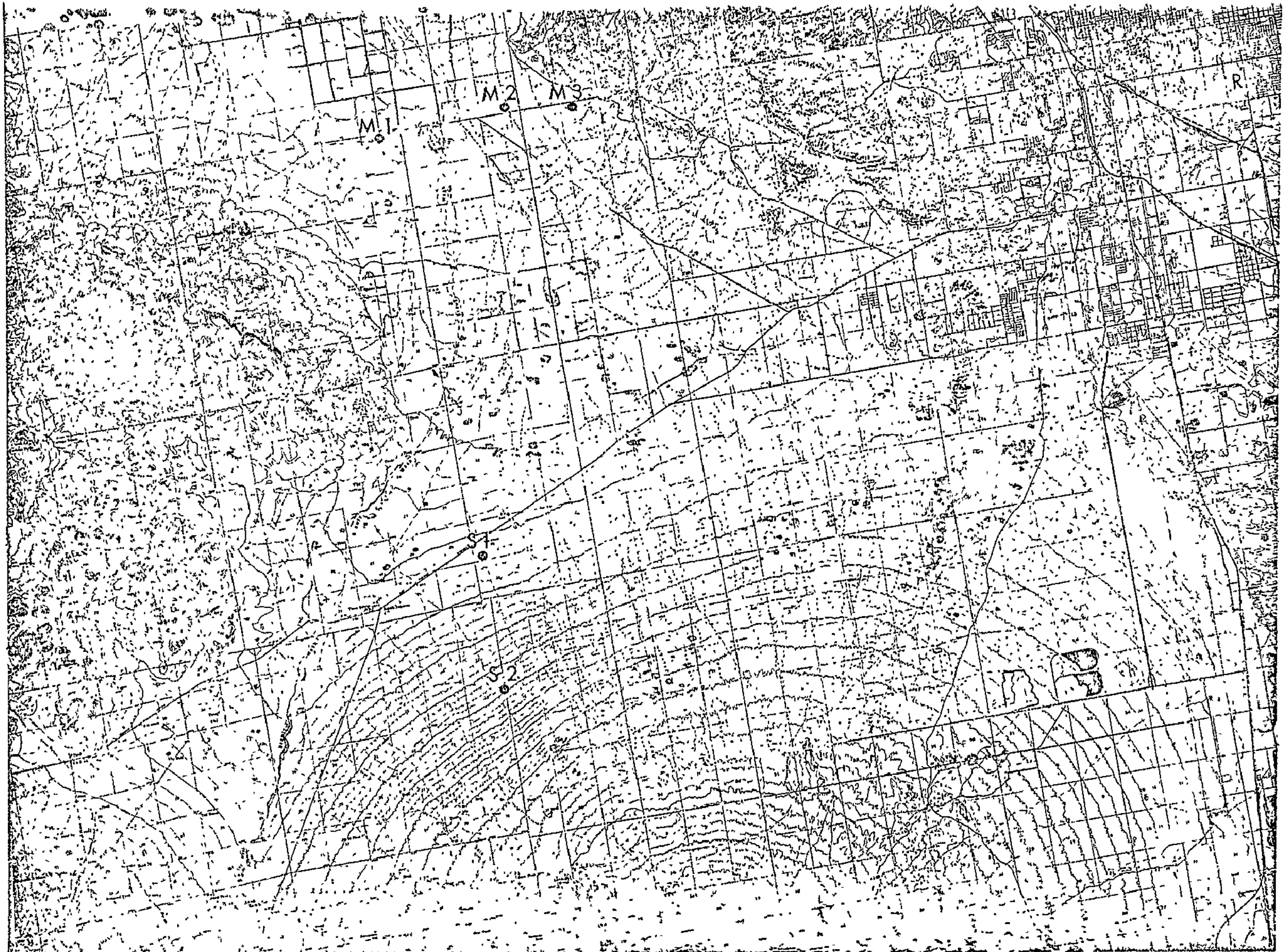


Figure 14.--Superimposed binary masks for cycles 14 and 15 (March 26 and April 13, 1973), Avra Valley Test Site (Scale 1:209,740). Explanation of symbols: M = Milewide Road; S = Sierrita Mountain; E = El Rio Golf Course; R = Randolph Park and Golf Course.

Binary masks of the Avra Valley Site for the dry spring of 1974 bore little resemblance to the masks based upon spring 1973 imagery. The 1974 masks (for examples cycles 31 and 33; not presented) showed few areas exceeding the ratio threshold. These few included irrigated fields, parks and golf courses, and small scattered areas in the low mountains surrounding Avra Valley. Comparison of the masks for these two seasons provides compelling evidence of the usefulness of the ratioing technique for studying changes in vegetation cover.

In attempting to define the foliar coverage value that is equivalent to the 1.25:1.00 ratio threshold used, we found that the threshold as defined by the ESIAC is exceeded over a range of measured values. The lowest coverage value to exceed the ratio threshold was 10 percent; the highest coverage value not exceeding the threshold was 25 percent. It appears from these incomplete data that the ratio threshold lies within a range of coverage values from approximately 10 to 25 percent. A range of values, rather than a single value, was anticipated from the relationship shown in figure 4. From these curves, it was shown that the albedo of background soil would have a substantial effect on the ratio—darker soils would require lower amounts of plant foliage to exceed a given threshold ratio than would lighter soils. Significantly, the lowest coverage value found to exceed the threshold was on relatively dark soil at Milewide 3.

VI. NEW TECHNOLOGY

1. The technique described in this report can be used to estimate foliar cover and, indirectly, ET in regional hydrologic surveys. The lack of a systematic method of evaluating actual evapotranspiration (ET) is a serious deficiency in studies of the hydrologic cycle in arid and semi-arid regions. In his effort to develop or control water resources, man may change the time, the place, or the quantity of ET. The time is changed by constructing storage reservoirs which retain water from wet seasons for use in dry seasons; the place is changed by the diversion of streamflow or by ground-water pumpage for irrigation, industry, or domestic supplies; the amount of ET is altered by many watershed management practices (ET may be increased or decreased), by practices seeking to retain precipitation in the soil for better crop production (increasing ET), and by urbanization (ET increased or decreased). The basic problem of the hydrologist engaged in water-resources management and planning is to obtain an accurate inventory of an ever-changing resource and to predict the effect of man's efforts at control and development. ET has first priority demand on the water resource in the hydrologic cycle. Thus, the evaluation of ET is essential for a comprehensive understanding of hydrology. Except for bodies of water, for which methods are already available for estimating water loss, the most important variable in the hydrologic cycle is water loss from terrestrial habitats. Plant foliar cover, a readily observable earth surface phenomenon, is closely correlated with water availability.

2. The technique described in this report is well suited to acquiring data essential to the management of many rangelands where forage production is unpredictable. Over vast areas in the West, grazing is a marginal enterprise dependent upon the production of forage during brief unpredictable periods of favorable climate. The grazing ranges are often isolated and poorly served by roads making range condition surveys impractical. Management of these ranges would be greatly aided by a method for synoptic evaluation of range readiness so that the grazing animals could be deployed to the areas of heavy production or withheld from those with poor forage.

3. Human food production in many areas of the world is directly dependent upon rainfall. The widespread hardship that rainfall shortage creates is often alleviated by food contributions from countries with a grain surplus. Anticipation of food needs early enough to arrange for shipment of the surplus is a recurring problem. Surveys by satellites early in the growing season could reveal regions where grain crop failure is imminent, thereby providing sufficient lead time to organize the shipping logistics. Appraisals of plant productivity, made possible by the technique described herein, could contribute significantly to the alleviation of human suffering in such areas as Africa and India.

VII. REFERENCES CITED

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VIII. APPENDIX

Progress Reports

Dynamics of distribution and density of phreatophytes and other arid-land plant communities. Type I reports: by Raymond M. Turner

1 July-31 Aug 1972 - 2 p.
1 Sept-31 Oct 1972 - 2 p.
1 Jan-28 Feb 1973 - 2 p.
1 Mar-30 Apr 1973 - 3 p.
1 July-31 Aug 1973 - 2 p.
1 Sept-30 Oct 1973 - 2 p.

Dynamics of distribution and density of phreatophytes and other arid-land plant communities. Type II reports: by Raymond M. Turner

1 July - 31 Dec. 1972 - 5 p.
1 Jan - 30 June 1973 - 7 p.

Turner, R. M., 1973, Use of the SRI electronic satellite image analysis console for mapping southern Arizona plant communities from ERTS-1 imagery: Symposium on significant results obtained from the Earth Resources Technology Satellite-I, v. 1, Tech. Presentations, Section 4, National Aeronautics and Space Admin. Spec. Rpt. 327, p. 761-768.

Turner, R. M., 1974, Use of ERTS imagery to detect seasonal changes in foliation within arid land plant communities: Abstract prepared for presentation at Amer. Soc. Civil Eng./Amer. Soc. Photogramm. Convention, Los Angeles, Calif.