

USEFULNESS OF LANDSAT DATA FOR MONITORING PLANT DEVELOPMENT AND RANGE
CONDITIONS IN CALIFORNIA'S ANNUAL GRASSLAND

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ABSTRACT

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The California annual grasslands are economically important rangelands. They do, however, present some problems to livestock producers due to the shortlived nature of the forage. Livestock production can be maximized on these lands if the ranchers can receive a better idea of when, how much, and how long forage will be available.

The investigators established a network of sampling sites throughout the annual grassland region to correlate plant growth stages and forage production to climatic and other environmental factors. Plant growth and range conditions were further related to geographic location and seasonal variations.

A sequence of LANDSAT data was obtained covering critical periods in the growth cycle. This data was then analyzed by both photointerpretation and computer aided techniques. Image characteristics and spectral reflectance data were then related to forage production, range condition, range site and changing growth conditions.

As a result of this study, it was determined that repeat sequences with LANDSAT color composite images do provide a means for monitoring changes in range condition. LANDSAT spectral radiance data obtained from magnetic tape can be used to determine quantitatively the critical stages in the forage growth cycle. In addition, a computer ratioing technique provided a sensitive indicator of changes in growth stages and an indication of the relative differences in forage production between range sites.

The anticipated benefits from LANDSAT monitoring of annual range vegetation include: (1) more accurate determination of germination and drying periods for planning movement of grazing animals to or from annual grassland ranges; (2) predictions of the remaining length of the green feed period made early enough to plan more efficiently for alternative sources of livestock feed; (3) comparison of conditions and relative forage production between grazing areas within a season; and comparison of condition and productivity for a given area between seasons; (4) determination of time when dry forage creates a fire hazard in order to better allocate men and equipment for fire suppression; and (5) assess extent and location of grazing areas influenced by abnormal climatic conditions, be it drought or abundance of forage.

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INTRODUCTION

NASA's Earth Resources Technology Satellite (LANDSAT-1) launched July 23, 1972, provided an unique capability for regional monitoring of forage plant development within rangeland environments. The repetitive coverage, the synoptic view and the opportunity for acquiring real time imagery combine to make LANDSAT data a valuable input for determining seasonal range conditions, and forage production. A LANDSAT investigation for the Bureau of Land Management (United States Department of Interior) conducted at the University of California, Berkeley, examined the feasibility of using LANDSAT data to: (a) monitor growth and development of forage plants in the Annual Grassland in California; (b) determine the relative amount of forage produced within and between growth seasons for a given area; (c) map grasslands with different forage production, and (d) predict forage condition and production using models which incorporate ground forage samples, spectroradiometric and climatic data. The study was conducted primarily during the 1972-73 growth cycle, with subsequent comparison of LANDSAT data during the 1974-75 growth cycle. The study area includes the annual grassland range seen within the LANDSAT images of San Francisco Bay; however, observations and measurements of plant growth and spectral data were made at two test sites; Pinole, located within a 50cm rainfall zone, 10 miles northeast of Berkeley, and San Luis Reservoir, located within a 25cm rainfall zone along the shore north of San Luis Reservoir located about 10 miles west of Los Banos, California.

California Annual Grassland

The annual rangeland in California is located primarily in the foothills of the Coast Range and Sierra Nevada Mountains. They are economically important by virtue of the area they occupy (8 to 10 million hectares) and the amount of forage they produce. These ranges are characterized by a complete cover of grasses, clovers, and forbs, which germinate in the autumn following a sufficient amount of rainfall to adequately wet the soil. Foliage growth is generally slow through the winter, followed by accelerated growth during the late winter and early spring. Plants mature, flower and subsequently dry during the spring in response to depletion of soil moisture.

Within the annual grassland range there are various grazing regions which differ in physiography, geomorphology and climatic regime. As a result they also differ in species composition, rate and timing of plant development, season of use by grazing animals, plant density, structure and productivity. (Talbot, Biswell, Hormay, 1939; Biswell, 1956; Heady, 1958). Because of seasonal variations in weather patterns within and between the different grazing regions, the condition and production of forage are also variable (Heady, 1958). The lowest forage producing areas are in the low rainfall zones (13-15 cm) in the southern portion of the annual grassland range, whereas the highest producing areas are in central California (50-75cm rainfall zone). Forage production in the northern portion of the annual grassland range is generally 30% less than the central portion due to lower temperatures despite the higher amounts of rainfall it receives (100-125cm) (Janes, 1969).

Within any given grazing region forage production and the length of the green growth period vary from year to year depending upon the climate pattern. Production also varies from site to site depending upon elevation, slope, aspect, the climatic regime, and various physical, chemical, and biological characteristics of the soil. Generally, sites with northeast exposure remain green longer and have higher forage production compared to sites on a southwest exposure. Similarly, sites with deep, fine textured soils, having high water holding capacities, remain green longer and have higher forage production than sites with

shallow, coarse textured soils. Plant species which occur more frequently on the productive sites include: wild oats (Avena fatua, A. barbata); soft chess (Bromus mollis); riggut (Bromus rigidus); wild barley (Hordeum); Italian ryegrass (Lolium multiflorum); bur clover (Medicago hispida). Forage species commonly associated with less productive range sites include: foxtail fescue (Festuca megalura); red brome (Bromus rubens); filaree (Erodium botrys, E. cicutarium); clovers (e.g. Trifolium microcephalum); wild barley (Hordeum), annual foris; bur clover (Medicago hispida).

Cattle and sheep are the primary grazers of annual rangeland. Approximately 50 to 80 percent of the 5.2 million cattle and 1.1 million sheep in the state spend a portion of their lives on the annual range. Grazing occurs primarily during the winter and spring months, but some livestock operators retain their animals on the dry annual rangelands throughout the summer. Generally, however, once the forage has been depleted or dried, resulting in lower nutritive quality, (Hart, Guilbert, and Goss, 1932) the animals are moved from the range to green pastures in the Central Valley, to feedlots or to perennial summer ranges.

Range Conditions During the 1972-73 Growth Period

The first rains of the 1972-73 season fell in late September causing germination of the annual forage throughout the northern half of the state. The second rains occurred in mid-October causing further germination to the south over approximately half of the remaining range where germination had not occurred. Finally, rains during the first and second weeks of November caused germination throughout the remaining annual grassland areas. This southward progression of germination was monitored by the LANDSAT passes in October and November. By April, the forage in the lower rainfall belts had reached maturity and had begun to dry. Drying occurred first along the east side of the Coast Range and gradually progressed northward and to higher elevations during May. By the end of May most of the annual forage in the state was dry. LANDSAT imagery obtained during this time period made it possible to monitor the location and progression of drying throughout many sites in the California annual rangeland. (Carnegie & DeGloria, 1973.)

METHODS

Collection of Ground Data

A network of sampling sites was established throughout the state from regions representing different climatic regimes. Two of the sites were the Pinole and San Luis Reservoir Test Site seen with the LANDSAT image of San Francisco Bay. Measurements and observations of the annual plants were collected between October 1972 and June 1973. At each site observations of phenological stage, for example, the time periods when germination, maturity and drying occurred, were recorded. Ground photographs were taken periodically at each sample site to provide a permanent record of the phenological stage of plant growth, and the relative condition (greenness or dryness) of the plants.

At each test site two or three replicate samples of plant weight, height, and spectral reflectance were obtained periodically from grazed and ungrazed plots located on several different sites. Plant weight estimates were obtained by clipping the forage to ground level within a one square-foot quadrat. The dry residual material from the previous season was removed and the current growth was oven dried and weighed. Plant height measurements were the average length of the forage or inflorescences within the sample plots. Graphs of forage production at grazed and ungrazed plots at Pinole and San Luis Reservoir appear in Figure 1. These graphs show the differences between sites located in different rainfall zones in terms of date of germination, amount of forage produced under moderate grazing

and without grazing, and the time when production ceased, which generally coincided with the drying period.

Ground spectral reflectance measurements were obtained at the Pinole Test Site throughout the growing period; however, spectral readings were made only during the rapid growth period at other sites. Spectral readings were corrected for sensitivity throughout the spectrum from 400nm to 1200nm. Corrections were not made for sun angle, season of the year or time of day because the primary use of the data was to form spectral reflectance ratios which were compared for the different dates of measurement. Generally the spectral reflectance readings were made just prior to the removal of a forage sample and close to highest sun zenith. The reflectance ratios were formed by dividing reflectance readings in the near infrared (800nm) by the reflectance readings in the red (675nm). This ratio has been shown to be highly correlated with green biomass (oven dried) in the short grass prairie region (Tucker, Miller, and Pearson, 1973); thus, similar studies were performed in the California annual grassland to test its applicability. Roberts and Gialdini (1973) have shown that infrared reflectance decreased while reflectance in the red band increases as annual forage matures and dries, corresponding to a declining amount of green biomass. Ratios formed by reflectance in the infrared and red bands would decrease with declining amounts of green biomass. Other LANDSAT investigators have also shown correlations between green plant biomass and LANDSAT reflectance data in bands 7 and 5 (Rouse, J. W. et.al, 1973; Maxwell and Johnson, 1974). Figure 2 shows the ground spectral reflectance ratio curves, green forage production curves (oven dried), and phenological data at the Pinole Range Test Site.

LANDSAT Imagery Analysis

Cloud-free LANDSAT-1 imagery of the San Francisco Bay Area was available on October 6, October 24, 1972, and January 4, January 22, April 4, April 22, May 10, May 28, and June 15, 1973. This imagery provided the opportunity to observe the initiation of germination, the peak of the growth period, and the progression of maturity and drying. LANDSAT-2 imagery taken over the same area in January 1975, provided an opportunity to compare seasonal development between growing seasons.

Nearly all of the cloud-free LANDSAT imagery which provided coverage of the ground sampling sites was processed to color composites simulating color-infrared images. Color Plate I shows a sequence of LANDSAT color composites of the test site located in Pinole Valley, east of Berkeley. The accompanying ground photographs (Color Plate II) were taken at approximately the same time as the LANDSAT images and document the changes in appearance and condition of the forage during the 1972-73 growth period. Hand held vertical ground photographs were also taken over each sample site to provide a pictorial record of the stage of plant development corresponding to the various dates of LANDSAT overpasses. The ground photographs along with the written record of phenological stage provided the ground references used to evaluate the changing appearance of the annuals as viewed on the LANDSAT color composites. The LANDSAT images provide a reference base for recording and interpreting range condition throughout a large region, and for making comparisons of range conditions in previous or subsequent years. The opportunity provided by LANDSAT imagery to accurately and unbiasedly compare range conditions between grazing regions in any given year, and to compare conditions for a given site between years, is fundamental to the development of an operational range monitoring system.

LANDSAT Data Tape Analysis

LANDSAT tapes for all cloud-free passes over the San Francisco Bay Area, which contain the Pinole and San Luis Reservoir Test Sites, were acquired in order to analyze the spectral data in each of the four spectral bands (4, green; 5, red; 6, near-infrared; 7, near infrared). The objectives for analyses were (1) to determine if LANDSAT spectral data provide

a reliable means for assessing forage conditions, and (2) to examine the relationship between LANDSAT spectral data, ground spectral data, phenology and forage production curves. The LANDSAT tapes analyzed included: July 26, 1972, August 13, 1972; October 6, 1972; January 4, 1973; April 4, 1973; April 22, 1973; May 10, 1973, and May 28, 1973. On each of the magnetic tapes, the spectral radiance values associated with two areas measuring 6 x 6 picture elements in size, (which corresponded with the Pinole and the San Luis Reservoir Test Sites) respectively, were analyzed. No corrections were made for atmospheric variables; however, each date of imagery analyzed was a relatively clear day without any apparent clouds. The average and standard deviation were computed for both areas for each date, and for each MSS band. Figures 3 and 4 show the graphs of LANDSAT spectral radiance plotted over time for the Pinole and San Luis Reservoir Areas. Figure 5 shows the plot of the spectral reflectance ratio of band 7 and band 5 for Pinole and San Luis Reservoir Test Sites.

RESULTS

Manual Analysis of LANDSAT Imagery for Monitoring Plant Growth and Range Condition

Color Plates I and II show LANDSAT images (color composites) and ground photographs taken at eight dates during the 1972-73 growth period of the annual rangelands in Central California. This photo sequence shows the foothills at the Pinole Test Site in a dry condition on October 6, 1972, prior to complete germination. Sufficient rainfall had fallen on September 26, 27, 1972, to cause partial germination of annuals on the bottomland sites. However, evidence of this partial germination is not present in either the ground photo or the LANDSAT image. New plants were obscured by dry residual material from the previous season as seen on the LANDSAT image, where the foothills appear a tan color characteristic of dry vegetation. A second storm occurring between October 7 and 13, 1972, produced more than sufficient rainfall to cause complete germination of the annuals in this region, so that by October 24, 1972, the foothills appeared green with the new growth of the annual plants. This initial transformation in the appearance of the annual rangeland is dramatically illustrated by the LANDSAT image taken October 24, 1972, where the foothills around the Pinole Test Site appear reddish, corresponding to the presence of a new cover of green plants. Initially, growth was rapid, but the cold winter temperatures eventually suppress the growth rate. The January 4 photographs (LANDSAT and ground) show a subtle change from those of October 24, corresponding to a relatively small increase in cover and volume of annual plants. Cattle were introduced to this rangeland during the last week of November; thus, the appearance of the range in January is affected by the winter conditions affecting growth, by moderate grazing pressure, increased soil moisture and low sun angle.

In the grazing region containing Pinole Test Site, warming temperatures caused increased growth beginning in February. Growth remained rapid reaching peak foliage development in mid April. In grazing regions to the south the rapid growth period started earlier and was much shorter relative to the Pinole area.

The LANDSAT and ground photograph taken April 4, 1973, shows the foothills appearing at near their maximum green stage, considering the different stages of development on the different sites (bottomland, midslope and upland) which characterize this grazing region. The intensity of red coloration seen on the LANDSAT image (April 4) indicates the annual range is near its peak green condition. It should be recognized that at this time, plants on the upland sites had already formed inflorescence, while plants on the midslope and bottomland sites had inflorescence which had only recently emerged or were just emerging, respectively.

By April 22, forage plants on the upland sites had begun to dry, while plants on midslope and bottomland sites had developed inflorescence. This change is noted on the LANDSAT image by a subtle shift in color from red to red-orange for the Pinole Test Site. The first indication of widespread drying of the annuals can be noted in the grazing region south and east of the Pinole Site. Here the foothills appear a yellow-orange color characteristic of widespread drying of annual vegetation.

By May 10, all vegetation on upland sites in the Pinole Test Site had dried. Many of the plants on the midslope sites had also dried, and plants on bottomland sites had well developed inflorescence with foliage remaining green. On the corresponding LANDSAT image, the Pinole Range Site appears an orange color. Along the East side of the Coast range the annuals associated with the low rainfall--foothill areas (including the annuals at San Luis Reservoir), had completely dried as evidenced by the yellow color of these areas on the imagery. By May 28, most of the annuals associated with upland and midslope sites had dried, and drying had begun on bottomland sites. The LANDSAT image shows the foothill area around Pinole as a yellow orange color. Note that on this LANDSAT image most of the annual vegetation on the foothills to the east and south had already dried. By June 15, all of the annual plants associated with the foothills in the Pinole Test Site had dried. The LANDSAT image accurately depicts this condition, as evidenced by the yellow or straw colored appearance of the foothills throughout the grazing region. The colors of the dry rangeland are much brighter than those seen on the October 6, LANDSAT image because there is much more residual dry material. Throughout the summer, continued grazing use and/or natural deteriorating would cause the rangeland to return to an appearance very similar to that seen on October 6, 1972.

The sequence of LANDSAT images with the corresponding ground photographs that show range conditions in more detail, demonstrate that if LANDSAT images are cloud free during critical periods of the growth cycle of the annual range, one can monitor the timing of these growth stages and accurately assess the condition of the range plants. The growth stages which are critical are: the period of germination, the time of peak foliage development which coincides with the time that most of the plants have inflorescence in the dough or green stage, and the period of drying. To the extent that these stages can be documented, managers can determine the length of the green feed period, the time when the foliage is near its peak nutritional quality, the time when drying occurs, which reduces the quality of the forage, fuel hazard, and the availability of green forages. The time when these phenological events occur in relation to the expected or average time of occurrence can signal whether the current forage crop is below average or above average; hence, forage production can be inferred from a prior knowledge of the average timing of growth stages. Moreover, the large area coverage of LANDSAT provides a means for determining the progression of growth in the different grazing regions of the California Annual grassland. Thus, in any given year, drought affected areas or areas receiving below normal amounts of rainfall, (hence lower forage production) can be located, and the areal extent of these areas determined. Similarly, LANDSAT images can also show rangelands where above normal rainfall distributed throughout the growth cycle has resulted in a prolonged green feed period resulting in greater forage production and livestock weight gains.

Thus, manual interpretation of LANDSAT color composites can accurately determine the timing of three critical growth stages. However, cloud coverage during any of these periods substantially reduces the advantage of LANDSAT for acquiring this information in comparison to conventional methods. To reduce the possibility of acquiring unsuitable coverage during the critical stages, additional satellites or more frequent coverage would be required. As an alternative, light aircraft could be used for reconnaissance purposes during critical observation periods if cloud coverage was known to obscure the rangeland at the time of LANDSAT overpasses. In spite of the problem presented by cloud

coverage, cloud-free images permit one to estimate the portion of rangeland which has already dried, rangeland which is drying, and rangeland which is still green. Such an assessment can be used to predict the amount of animal movement from the range, and determine where the movement originates. Moreover, one can determine which areas are still green and make predictions regarding the amount of time that the forage would remain green, given particular weather conditions. Finally, maps showing different seasonal conditions could be produced each year for comparison with known conditions on previous and subsequent years, and statements regarding present conditions (greenness or dryness; or productivity) in relation to past conditions could be made. The value of these interpretations can be realized through better planning, predictions, and wiser decisions regarding rate and location of animal movement, need for supplemental feed, amount and location of residual dry material which causes critical fire hazard, and amount and quality of green feed in relation to (a) previous years or (b) an established normal.

Color Plate III shows a LANDSAT-2 color composite of rangelands adjacent to the San Francisco Bay Area, taken on January 24, 1975. When compared with the LANDSAT-1 image dated January 4, 1973 in Color Plate I, one can readily detect differences in the colors associated with the rangeland vegetation. The dull pink colors in the LANDSAT-2 image (January 24, 1975), correctly signify that forage growth had not progressed as rapidly for the 1974-75 growth season compared with the 1972-73 growth season. In fact, rainfall during the 1974-75 season was 50-60% below normal at the time the LANDSAT-2 image was taken. Not only was plant development slow, but forage production was also below normal. Ranchers were obliged to reduce number of livestock and/or provide feed supplements for a longer period of time. The important value of the LANDSAT data is in providing a permanent, unbiased record for comparing range conditions at approximately the same time period in two different growing years.

Monitoring Plant Growth and Range Conditions: Quantitative Analysis of LANDSAT Tapes and Ground Spectral Reflectance Data

Ground spectral reflectance data.- Throughout the 1972-73 growth season ground spectral reflectance (reflected radiant energy) measurements were made at frequent intervals at the Pinole Test Site. For the most part, reflectance measurements were made at randomly selected locations on both grazed and ungrazed bottomland, upland and midslope sites. Once a spectral reflectance measurement had been obtained, the plot was clipped, and the weight of the forage recorded. The spectral reflectance values corresponding to 675 and 800 nanometers were formed into a ratio and this ratio plotted over time for the growth season. Figure 2 permits a comparison of the spectral reflectance ratio curves for three sites in the Pinole Test Site with the corresponding green forage production data (oven dried) associated with the same range sites.

The similarity between the spectral reflectance ratio curve and the green forage production curve can be seen in Figure 2. The spectral reflectance ratios increase dramatically at the outset of the growth season corresponding to the period when germination has occurred. That the ratio for the upland site was so high can be explained in part by the complete cover of new vegetation and partly by the reflectance characteristics of the species occupying these sites. The ratios decrease markedly at the end of the growth season corresponding to the drying period prior to complete senescence of the forage crop.

The time when the spectral reflectance ratios peak is of particular importance. For each site, both grazed and ungrazed, the peak of the ratio curve occurs at the growth stage corresponding to early inflorescence development. This growth stage occurs just prior to the time when foliage production is at its peak and the nutritive quality of the

forage is also near maximum. It should be noted that the ratio curve peaks first for the upland site, followed by the intermediate and then the bottomland site. The time of these peaks and the order of their occurrence are consistent with the documented phenological ground conditions at these sites which are diagramed in Figure 2.

Finally, the relative difference in magnitude of the peaks of the ratio curves correspond with the relative difference in the forage production curve peaks associated with the three respective sites. These data indicate that the spectral reflectance ratio (800/675) is a sensitive indicator of the relative difference in green forage when different sites are compared. In addition it appears that the peak of the ratio curve coincides with the period when the forage is at its peak green stage, just prior to maximum foliage production.

LANDSAT spectral reflectance data.- LANDSAT spectral radiance data for the Pinole and the San Luis Reservoir Test Sites was extracted from LANDSAT computer compatible tapes. The average radiance value and the standard deviation of this mean for the two 6 x 6 picture element areas were determined from LANDSAT tapes acquired on August 13, and October 6, 1972, and January 4, April 4, April 22, May 10, and May 28, 1973. The average radiance for each of the four MSS bands is plotted against the date of acquisition in Figures 3 and 4 for the Pinole Test Site and San Luis Reservoir Test Site, respectively. These two Test Sites were selected for comparison because they occur within the same LANDSAT frame, and because they are in two different rainfall zones. The Pinole Test Site is in a 50 cm. rainfall zone having a green feed period of about 7½ months; whereas, San Luis Reservoir Site is in a 25 cm. rainfall zone having a green feed period of about 6 months.

An examination of the LANDSAT radiance curves for Pinole and San Luis Reservoir Test Sites reveals that the radiance values for all spectral bands decreases from the dry summer stage to the period of first rainfall or germination. Once the annual plants have germinated the infrared bands 6 and 7 increase in reflected radiance in response to increasing cover and density of forage. The visible bands 4 (green) and 5 (red) decrease in reflected radiance due to absorption of these wavelengths by the plants, and remain fairly constant through the slow growth period during the winter months. When growth begins to accelerate in late winter and early spring, reflected radiance in the infrared wavelengths increases rapidly while the visible wavelengths increase very slowly. Both infrared radiance curves (bands 6 and 7) peak when inflorescence are developing. This is also when the forage is at its peak green stage, just prior to maximum green forage production. The radiance curves for the infrared bands decrease in response to the drying of the annual vegetation. LANDSAT radiance for bands 4 and 5 increases rapidly during the time period coinciding with inflorescence maturity and the onset of drying on the shallow sites. Approximately 1 month after radiance in the infrared bands has reached a peak, radiance values from bands 4 and 5 cross over, due to the more rapid increase in radiance of band 5 compared to band 4 during this period. This rapid increase in band 5 radiance is correlated with the period of rapid drying of the annual forage. Moreover, this cross-over period occurs when forage on approximately half of the range sites is dry, while the other half is green and maturing. Once all the annual vegetation has dried, the radiance curves return to approximately the same level as those for the summer stage in the previous year. The late spring (1973) radiance levels are slightly above the radiance levels for the previous summer, (1972) because a greater amount of dry residual material remains on the sites at the outset of the summer of 1973.

The shape of the LANDSAT radiance curves is similar for the Pinole and San Luis Reservoir Test Sites (Figure 3 and 4, respectively) despite differences in the amount of forage produced and the length of the green feed period. For example, at both Test Sites the outset of germination was indicated when radiances from all four bands are very nearly

the same, and from which point the infrared bands increase while the visible bands decrease in radiance value. Notice this separation point occurs in mid-October for the Pinole Site, but does not occur until early November for the San Luis Reservoir Site. (This is consistent with the ground observations.) The radiance curves for the infrared bands peak in mid-April at Pinole and prior to early April at San Luis Reservoir Site. These peaks coincide with the time when the annuals were at their peak green stage and when green forage production was near maximum. Radiance values from bands 4 and 5 cross over in mid-May at Pinole and mid-April at San Luis Reservoir Site. These crossovers coincide with the period when half of the forage was dry at each site, respectively.

The conclusion to be drawn from these curves is that LANDSAT radiance data appears to provide a quantitative measure of the time of germination, the time of peak greenness or near maximum forage production, time when half of the forage is dry, and the time when drying is complete. This information permits determination of the length of various growth stages throughout the life cycle of the annual forage plants. The LANDSAT spectral data correctly revealed that annual plants germinated later, and matured and dried earlier at San Luis Reservoir compared to similar plants at Pinole.

LANDSAT radiance data from band 7 and 5 were formed into a ratio (7 over 5), and plotted over time (the dates of acquired cloud free LANDSAT Data). The radiance ratio curves for both Pinole and San Luis Reservoir are plotted in Figure 5. The curves reach a low point at or before germination. The ratio curves peak during the spring coinciding with the occurrence of peak foliage production. Thereafter, the curves fall signaling the period of drying following the maximum green period. Once the curves level off, one can conclude that all annual vegetation has dried.

The LANDSAT radiance ratio curve for Pinole is an integration of reflected radiance from bottomland, midslope and upland sites which are contained within the 36 picture element study area. This curve compares favorably in shape with the ground reflectance ratio curves for each range site seen in Figure 2, if one disregards the high reflectance ratios measured on the ground early in the growth season.

When the LANDSAT radiance ratio curve for Pinole is compared with the one for San Luis Reservoir (Figure 5), one can observe the difference in timing of critical growth stages. Moreover, the difference in magnitude for these two curves corresponds to the relative difference in forage production at the two range sites. Thus, the LANDSAT radiance ratios appear to provide a valid quantitative method for comparing relative differences in forage production for different grazing regions throughout the annual grassland, as well as assessing the timing of growth stages, and determining range condition (greenness or dryness).

DISCUSSION

Monitoring Growth Stages and Condition of Annual Forage

Although a complete sequence of cloud free LANDSAT images was not obtained, coverage at the critical growth periods was available for the San Francisco Bay Area frame to demonstrate that the time of growth events, the stage of plant development, and the condition of the annual forage can be determined from manual interpretation of LANDSAT imagery. The critical stages which must be monitored, in order to assess the relative length of the green feed period, to assess relative productivity and forage quality, and to determine the availability of green forage, are the period of germination, the peak of

the green foliage production stage, and the period of drying. If LANDSAT coverage is not available or of unusable quality due to cloud coverage, then supplemental data would be required. This could be in the form of ground reconnaissance or aerial reconnaissance from a light aircraft. If, however, supplemental data is required for more than one of the three critical growth stages, the efficiency gained from interpreting LANDSAT imagery decreases.

Whereas manual interpretation of LANDSAT imagery appears to be sufficient for identifying forage growth stage and condition, the element of interpreter subjectivity is inherent in the analysis of the images. Interpreter subjectivity by itself is not sufficient reason to discount the potential beneficial applications for using repetitive satellites to monitor changes in the condition of the California annual grassland, but an operational system which proposes to not only determine range conditions but provide predictions of forage production and extended length of the green feed period, of necessity requires more quantitative methods. Consistent with this need, the results from analysis of ground reflectance measurements coupled with analysis of LANDSAT spectral radiance data, indicate that changes in spectral reflectance characteristics of the annual grassland provide the quantitative indicators of plant growth stage and range condition. Specifically, the spectral radiance data from the LANDSAT MSS bands, and ratios of selected bands appear to provide accurate indicators of germination, peak of green foliage development, and the drying period. Moreover, the shape and magnitude of these reflectance data curves plotted over time provide a measure of the relative difference in condition and production and a measure of the differences in timing of growth stages between sites or grazing regions. To the extent that LANDSAT data is available at similar dates in different growing seasons, one can determine differences in time of growth stage and productivity between years. This may be as important an application of LANDSAT data as monitoring differences in development of the different grazing regions within a single season.

The criteria required for an operational monitoring system would include: (1) cloud free LANDSAT tapes (corrected for atmospheric differences) from representative Test Sites or analogous alternative sites during critical growth periods which will occur at different and unpredictable times at the different grazing regions within the state; (2) less than one week turn-around time for receipt of tapes during the peak of foliage development and the drying period; (3) backlog of phenology and production data upon which to make predictions of remaining length of green feed period, and regression equations for relating LANDSAT spectral reflectance (radiance) values to estimates of forage production; and (4) a medium for disseminating data to potential users. The LANDSAT system is vital in acquiring the data base required for the surveillance of the annual grassland for the following reasons: The annual grassland encompasses a large area (approximately 8-10 million hectares); the range of annual grasslands in the state encompasses many different environments from the 12 cm. rainfall zone to the 100 cm. rainfall zone, from sealevel to 1000 meters, and a wide temperature range throughout approximately 8 degrees of latitude; the repetitive coverage over the same areas, the use of scanner data and transmission equipment shows different range areas under the same lighting making comparisons of sites valid.

Determining Relative Amount of Forage Within and Between Seasons

Estimating or predicting the amount of forage produced within a given grazing region for a given year is a difficult yet important task for managers of forage resources. Conventional methods are generally inadequate or unrepresentative of large areas to provide a valid assessment of the quantity of forage produced within and between seasons. However, the feasibility of using remote sensing data to estimate or predict forage biomass is

demonstrated both in the literature (Tucker, Miller, and Pearson, 1973; Rouse, 1973; Maxwell and Johnson, 1974) and by the relationships discussed in this study. Namely, that relative differences in forage production for different sites in the same area (Pinole) correspond closely to difference in measured ground spectral radiance from the forage at these sites. Moreover, relative differences in forage production at two different grazing regions (viz. Pinole and San Luis Reservoir) are expressed in this study by measured differences in LANDSAT spectral radiance data extracted directly from the LANDSAT tapes. What is common to these methods for assessing forage production is the apparent high correlation between spectral reflectance ratios in specific bands (viz. the red and near infrared bands) and green forage biomass. Deviations from this relationship were noted early in the growth season when high reflectance ratios did not correspond to high biomass values. Unusual reflectance values were explained by active plant metabolism and by morphological characteristics of the plants during an early stage of growth. Although atmospheric haze was not a problem in this study, it is not known to what extent atmospheric conditions could invalidate the close relationship between biomass and reflectance characteristics.

Although the feasibility of assessing relative differences in forage production within and between sites is encouraging, range managers still seek reliable data regarding the estimated amount of standing biomass. Such estimates can be obtained using regression equations which regress LANDSAT spectral radiance data with ground sampled forage production data. Further study is needed in the area of ground sampling required to provide valid forage production data to be compared with the LANDSAT spectral data. The problem is that a single LANDSAT picture element or a group of LANDSAT picture elements may integrate many range sites with varying amounts of forage production. Thus, it is important to obtain ground samples in such a manner as to determine average forage production associated with a single or group of picture elements.

A second approach to estimating forage production using direct inputs from LANDSAT imagery is based upon prior knowledge of the average forage produced (in a given area) associated with an average growth cycle. Here, departures from the normal growth cycle as expressed by the length of the green growth period and by the condition of the forage, combined with measured departures of LANDSAT spectral reflectance data provide the indicators of below or above normal forage production. Whereas, assessment of below or above normal conditions favorable for below or above normal forage production is still qualitative, the use of regression models (simple or multiple regression) which incorporate LANDSAT spectral reflectance data, ground data and climatic data where appropriate, enables more quantitative predictions of forage production to be made. Within a growth season, some grazing regions may experience above normal conditions for growth, while others experience normal or below normal conditions for growth. Provided that the normal conditions are known for each of these grazing regions, one can determine relative differences in production between grazing regions for a given season. Similarly, when the average conditions are known for a given grazing region, departures from this average can be monitored using LANDSAT data and differences in forage production between seasons determined quantitatively. The extent to which assessment of length of green growth cycle and forage production can be made efficiently for large grazing areas depends upon the availability of LANDSAT data obtained at critical periods during the growth cycle. To determine the length of the growth cycle which is one variable closely associated with the amount of forage produced, one must acquire cloud free coverage during the germination period and the maturation and drying period at the end of the cycle. In order to assess differences in amount of forage through analysis of LANDSAT spectral data, the LANDSAT data must be acquired at the peak of the green forage production stage. Differential drying of plants after this period, causes radiance ratio values to decline although there may continue to be a small increase in total forage produced.

LANDSAT Imagery as a Means for Locating Available Forage

In Color Plate I the greenness or dryness of the forage can be determined visually upon inspection of the LANDSAT images. Moreover, the location of the areas possessing green forage during the latter portions of the growth cycle can be readily determined. Since this may vary from year to year, the LANDSAT monitoring system provides a potentially valuable tool for determining areas which either have abundant green forage due to favorable amount and distribution of rainfall, or areas which have dry forage relatively early in the growth cycle due to unseasonably low rainfall.

Because the LANDSAT spectral radiance response curves (Figures 3 and 4) indicate changes in the condition (greenness or dryness) and phenology of the forage, a quantitative approach to determination of forage condition and location is made possible. Furthermore, because of the distinctive spectral radiance differences between green and dry forage, automatic classification is a feasible and accurate method for determining the location and the area of range land which contains green healthy forage.

SUMMARY AND CONCLUSIONS

In this feasibility study LANDSAT imagery and magnetic tapes were analyzed to determine their utility for monitoring and assessing range condition within the annual grassland in California. LANDSAT data, forage samples at selected range sites, and ground spectral reflectance data were all examined in order to verify the usefulness of LANDSAT imagery for determining range condition, growth stage and assessing relative forage production. The results of ground spectral reflectance data compared with green forage production data show a close correspondence between spectral reflectance ratios and green biomass. Changes in ground spectral reflectance data also correspond with observed changes in growth stage and condition of the forage species. Moreover, LANDSAT spectral reflectance data provides quantitative signals of significant growth stages in the development of annual forage species. Relative differences in forage production are also indicated by the LANDSAT spectral radiance data.

It has been illustrated that LANDSAT color composite images provide a visual picture of the condition of the rangeland. Repetitive sequences of these images provide the means for monitoring change in condition and comparison of condition of different range areas. When LANDSAT spectral radiance data is extracted from specific range sites, one can determine quantitatively the occurrence of germination, the peak of foliage production, and the period of drying from spectral curves constructed from a sequence of LANDSAT images. In addition, ratios of spectral bands, namely 7 over 5, provide a sensitive indicator of changes in growth stages and an indication of the relative differences in forage production when two or more range areas are compared.

Provided that cloud free LANDSAT coverage is available during critical growth stages of the annual plants, namely, germination, peak of foliage production and period of maturation and drying, LANDSAT data can be used to: (a) assess differences in range condition on a regional basis; (b) compare differences in production between grazing regions for a given year; and (c) compare differences in condition and production for a given site between years. Moreover, the length of the green feed period can be determined and this information along with ground samples of forage production and climatic data can provide the inputs to simple models for estimating forage production or determining the remaining length of the green feed period beyond a definable threshold date late in the growth cycle of the annuals.

The anticipated benefits from LANDSAT monitoring of annual range vegetation include: (1) more accurate determination of germination and drying periods for planning movement of grazing animals to or from annual grassland ranges; (2) predictions of the remaining length of the green feed period made early enough to plan more efficiently for alternative sources of livestock feed; (3) comparison of conditions and relative forage production between grazing areas within a season, and comparison of condition and productivity for a given area between seasons; (4) determination of time when dry forage creates a fire hazard in order to better allocate men and equipment for fire suppression; and (5) assess extent and location of grazing areas influenced by abnormal climatic conditions, be it drought or abundance of forage.

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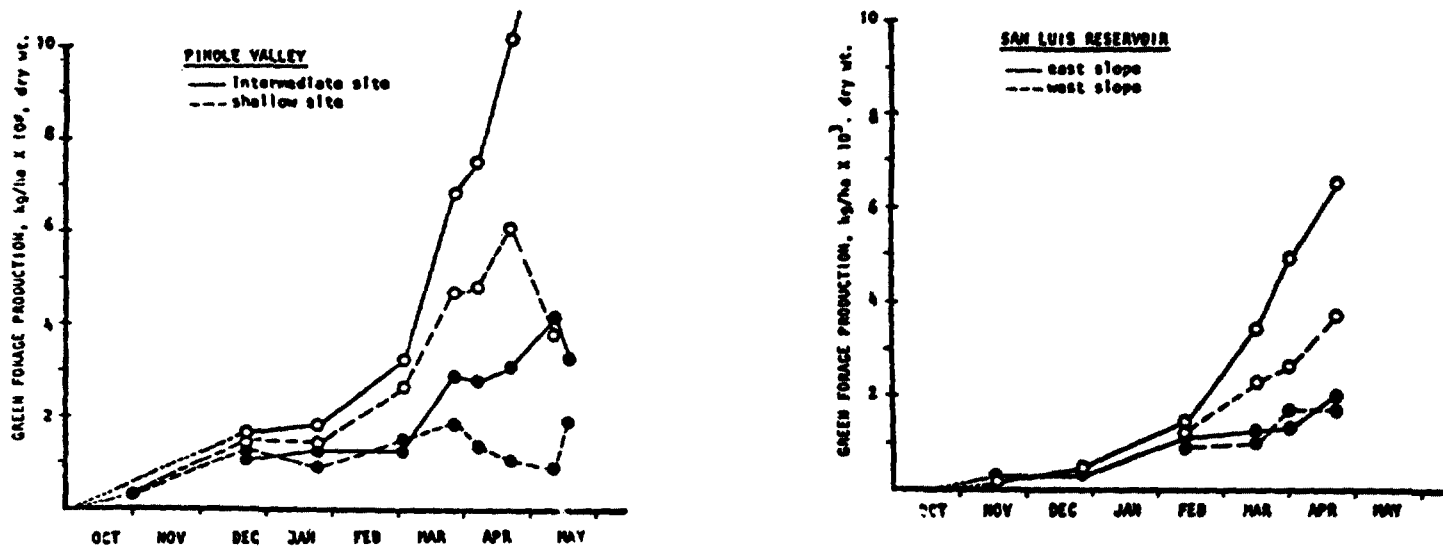


FIGURE 1. Total forage production, exclusive of residual material (over dry weight) at two of three sample sites at Pinole and at two sample sites near San Luis Reservoir. Samples were collected during the 1972-73 grazing season. Those made from ungrazed plots are indicated by an open circle. Note that forage production at Pinole is nearly double the production at San Luis Reservoir Test Site.

PINOLE VALLEY RANGELAND TEST SITE

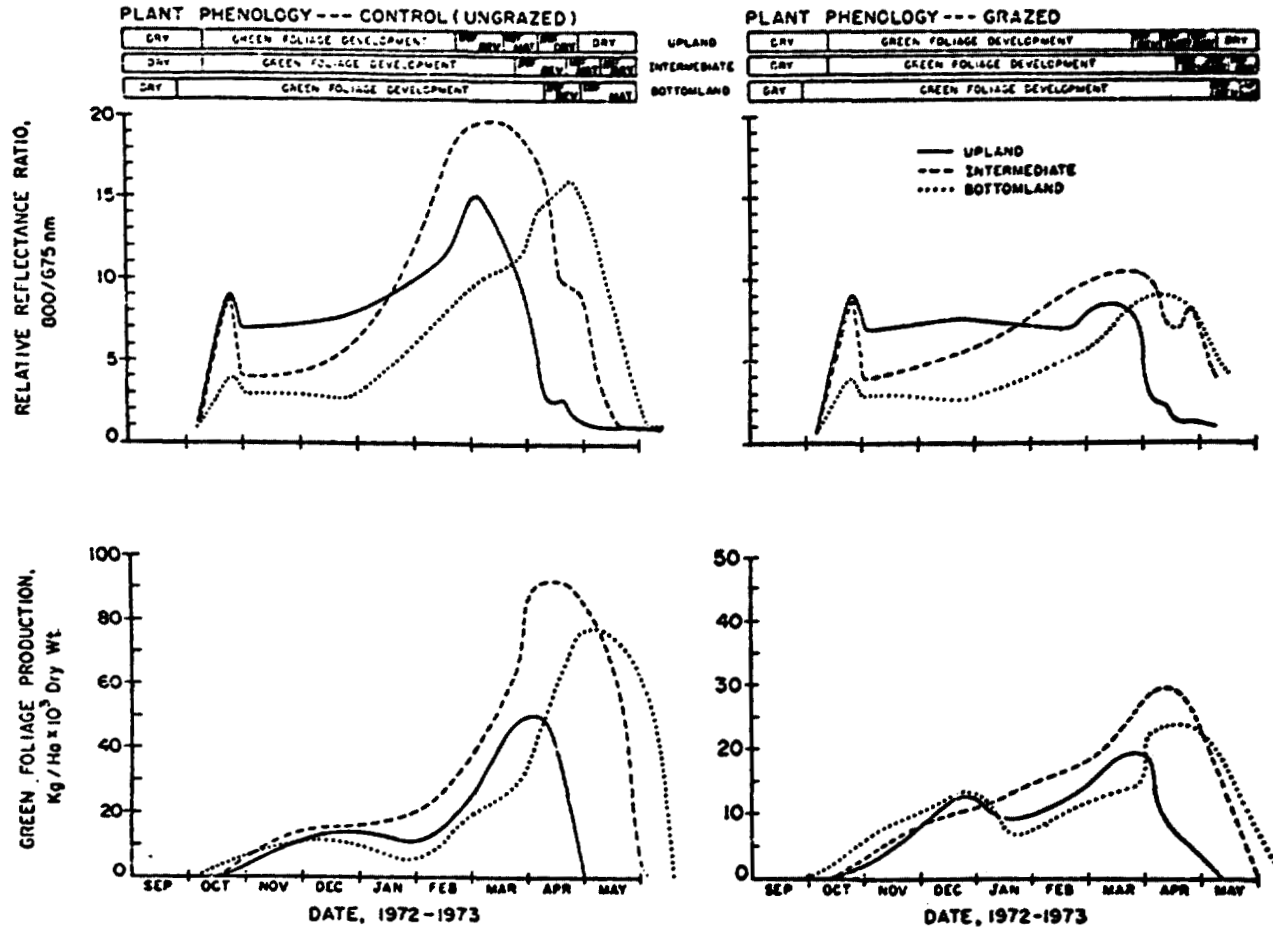


FIGURE 2 Green forage production and spectral reflectance ratio curves are plotted, and plant phenology is documented over time for three range sites at the Pinole Test Site. Note the correspondence of the shape of the curves (both production and reflectance) to changes in plant phenology as the annual grassland progresses toward maturity and subsequent drying. This correspondence is evident in both the grazed and ungrazed portions of the range sites. The phenological stages observed and documented include dry, green foliage development, inflorescence development (INF DEV), inflorescence mature (INF MAT), inflorescence dry (INF DRY) and dry.

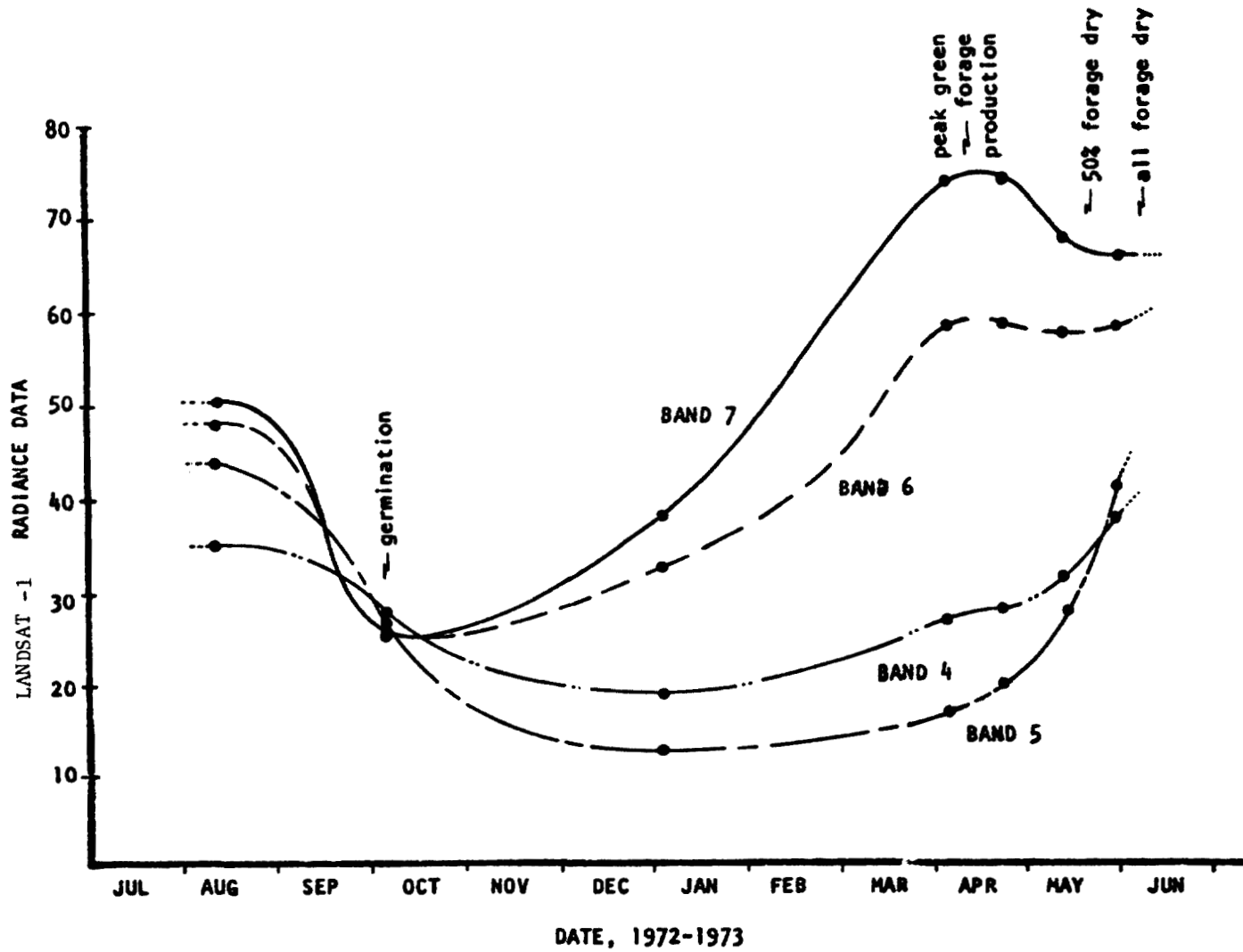


FIGURE 3. LANDSAT spectral reflectance curves for each MSS band (4,5,6,7) plotted over time for the Pinole Test Site. The data used in this graph was extracted from LANDSAT-1 tapes for a 6 x 6 picture element area which includes the study sites where ground data was collected. Note how changes in the curves correspond with phenological stages of plant growth.

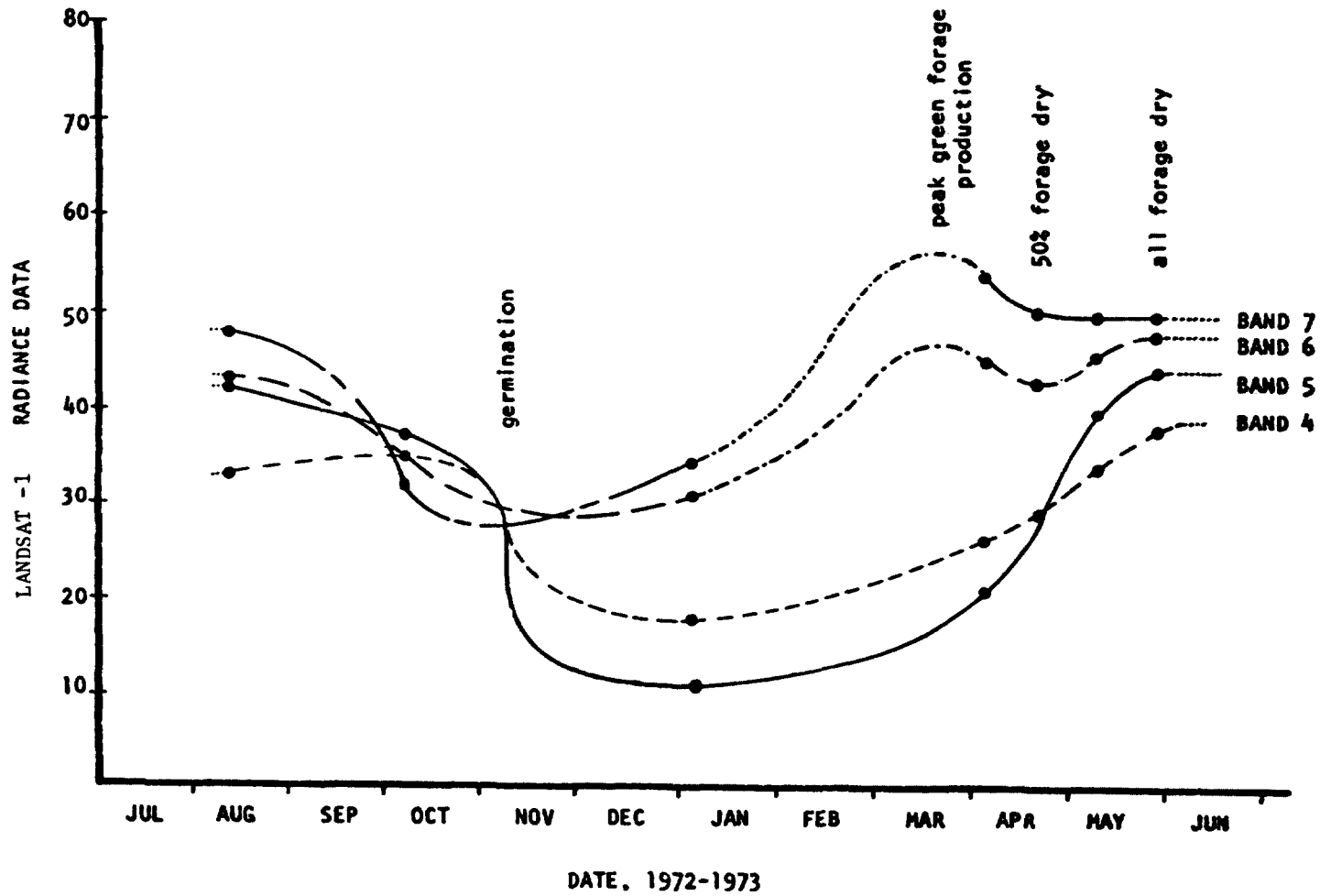


FIGURE 4. LANDSAT Spectral reflectance curves for each MSS band (4,5,6,7) plotted over time for the San Luis Reservoir Test Site. The data used in this graph was extracted from LANDSAT tapes for a 6 x 6 picture element area which includes the test site where ground data was collected. Note how changes in the curves correspond with phenological stages of plant growth.

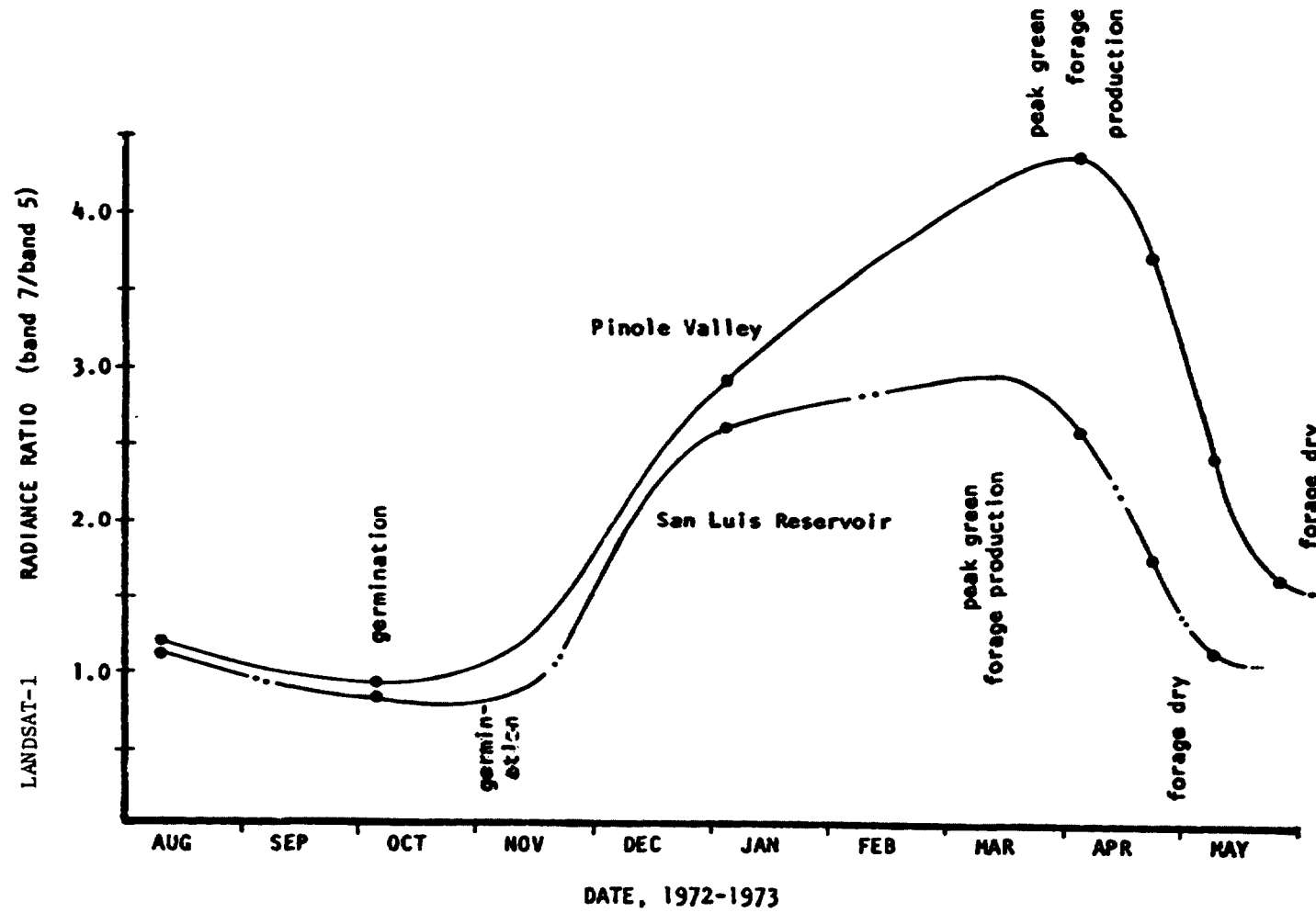
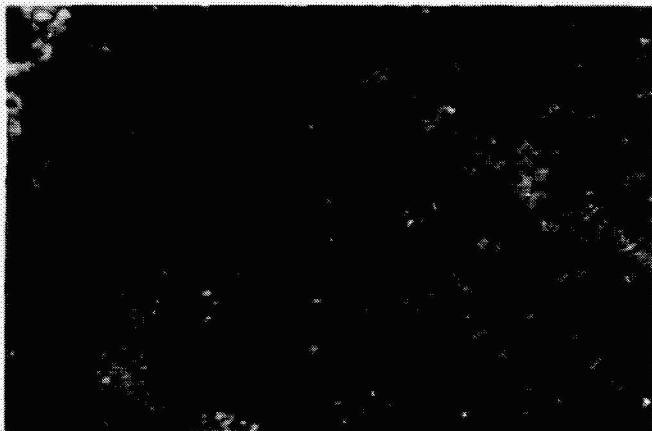
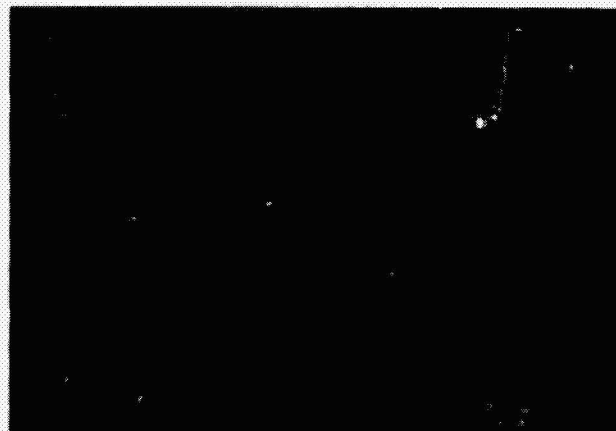


FIGURE 5. LANDSAT spectral reflectance ratio curves for the Pinole and San Luis Reservoir Test Sites. The ratio (band 7/band 5) is plotted over time for the 1972-73 grazing season. Note how changes in the curves correspond to the time of occurrence of phenological stages of plant growth. Difference in magnitude of the curves suggest the relative difference in forage production between the two sites.



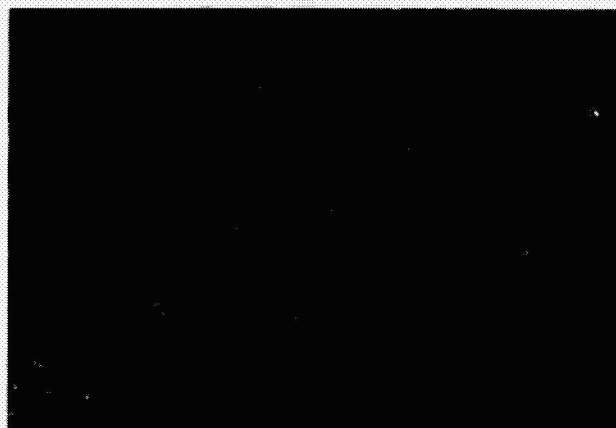
October 6, 1972



October 24, 1972

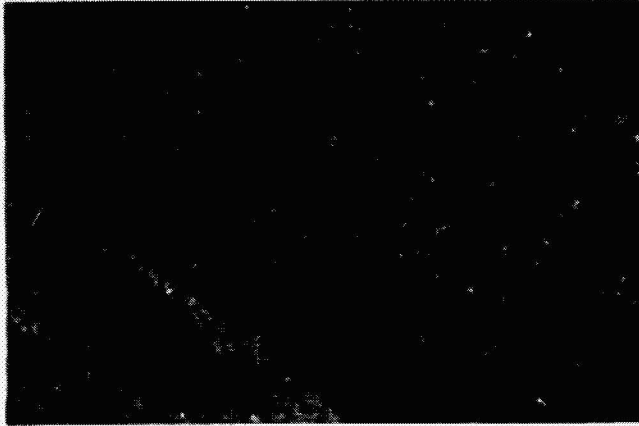


January 4, 1973



April 4, 1973

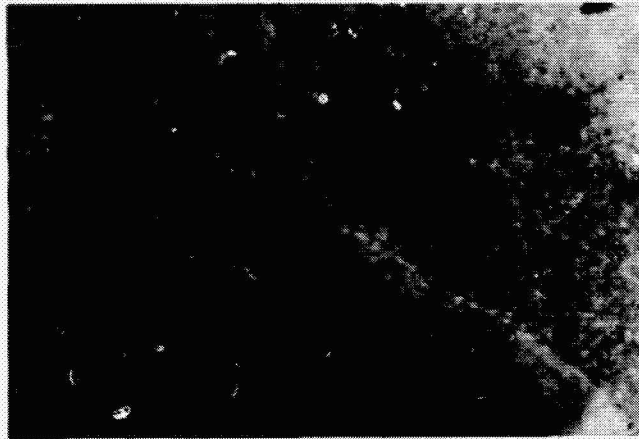
COLOR PLATE I. This sequence of LANDSAT color composites shows the changing appearance of the California annual grassland adjacent to the San Francisco Bay Area. The Pinole Test Site is located northeast of San Francisco, across the Bay and beyond the metropolitan area of the East Bay cities of Oakland, Berkeley and Richmond. The annual grasslands are readily identified on the October 6 color composite by their tan to gray color which indicate that the rangelands are still dry. Note that on subsequent dates germination and progressive plant growth account for the shift from tan to pink colors corresponding to the presence and vigor of the green annual plants. These rangelands reach a stage on April 4, 1973 where foliage production is near maximum, hence the bright red color seen on the LANDSAT color composite. Progressive drying beyond April 4 account for the shift in colors from bright red to orange to yellow. The ground photographs seen in COLOR PLATE II show how the annual rangeland appeared on the dates of the LANDSAT overpasses.



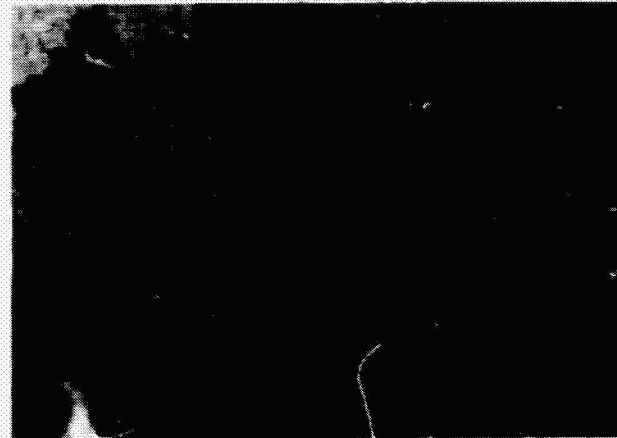
April 22, 1973



May 10, 1973



May 28, 1973



June 15, 1973

COLOR PLATE I. Concluded.

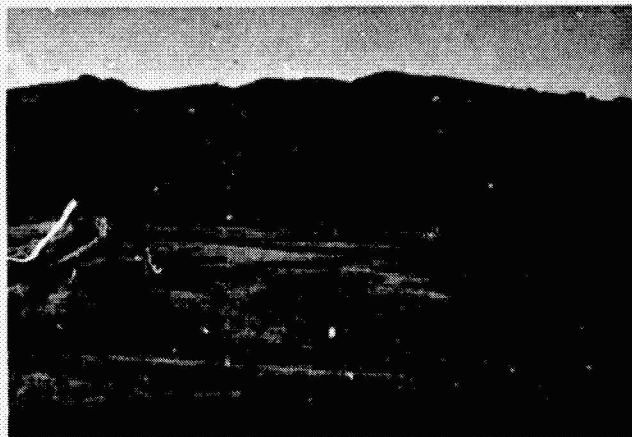
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October 6, 1972



October 24, 1972



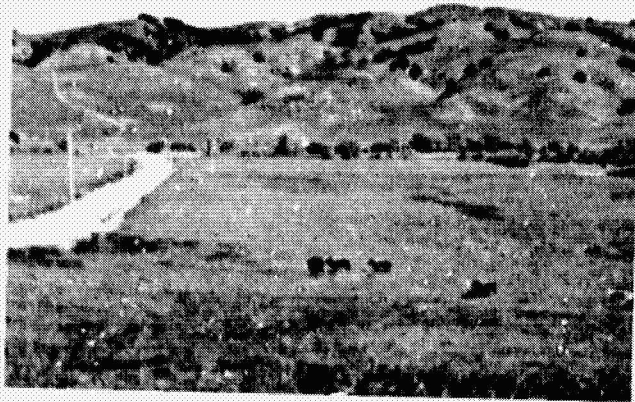
January 4, 1973



April 4, 1973

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COLOR PLATE II. This sequence of eight ground photographs shows the changing appearance of the annual grassland range at the Pincle Test Site during the 1972-73 growing period. The dates of the ground photographs coincide with the dates of LANDSAT overpasses. The LANDSAT color composite images for the corresponding dates are seen in COLOR PLATE I. Note that germination of the annuals has occurred between October 6 and October 24, 1972. Note also that on April 4, 1973, the rangeland still appears green, but progressive drying of the forage plants is evident on subsequent ground photographs. In early April the forage plants had reached their peak for foliage production and were rapidly developing in florescence and maturing.



April 22, 1973



May 10, 1973



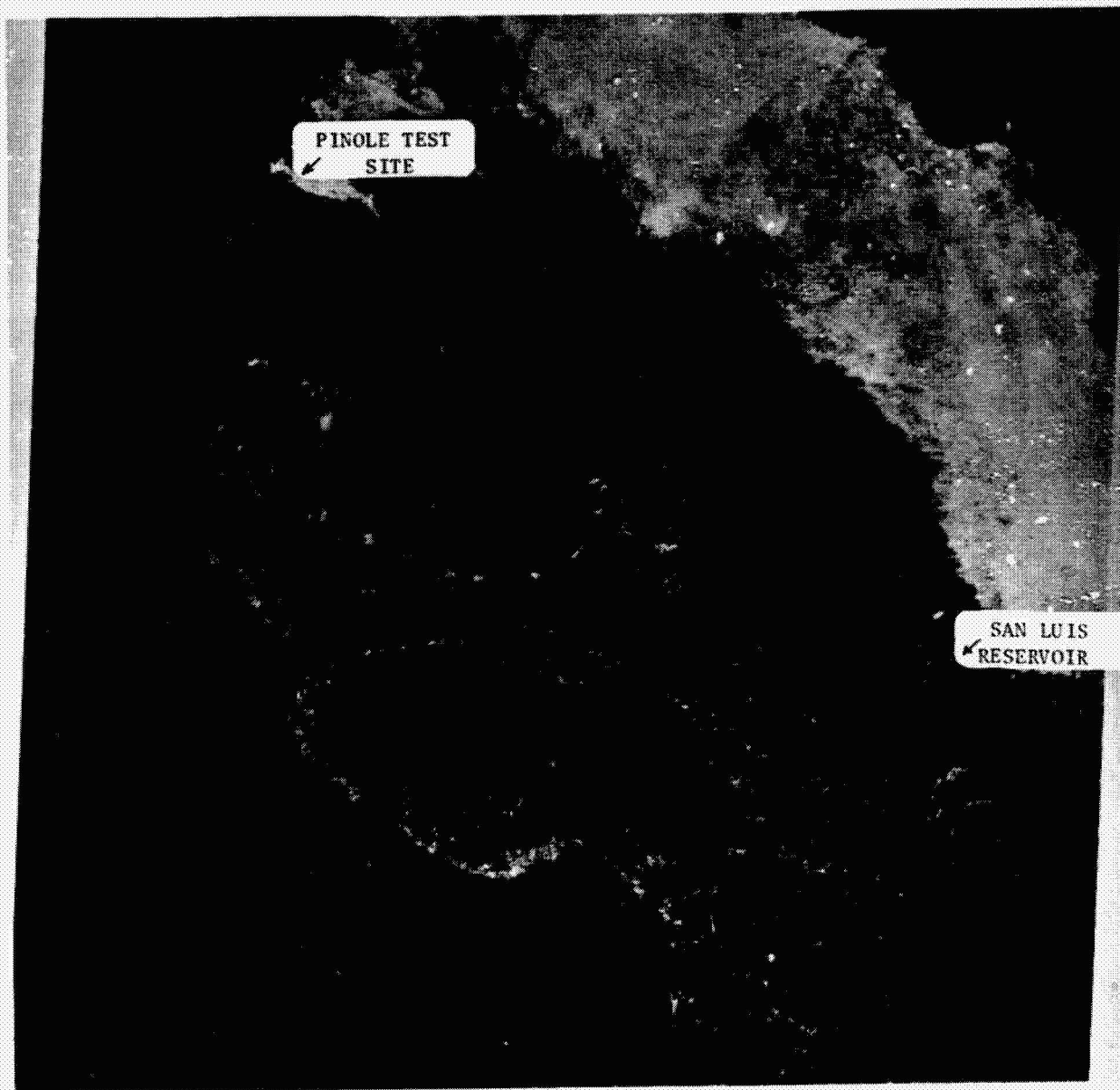
May 28, 1973



June 15, 1973

COLOR PLATE II. Concluded.

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COLOR PLATE III. This LANDSAT-2 color composite of the San Francisco Bay Area shows the location of the Pinole and San Luis Reservoir test sites discussed in this paper. This image was taken on January 24, 1975, and provides an opportunity to compare range conditions in January 1975 with conditions in January 1973 (COLOR PLATE I). The relatively brighter pink color associated with the annual grasslands as seen on the January 4, 1973 LANDSAT-1 image correctly indicates that plant growth and forage production in January 1973 exceeded that in January 1975. Range conditions in January 1973 were normal or slightly in excess of normal, whereas in January 1975 range conditions were considerably below normal causing ranchers to reduce stocking rates and provide feed supplements to sustain their grazing animals.