# Drought-Stress Detection of Buffelgrass with Color-Infrared Aerial Photography and Computer-Aided Image Processing

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ABSTRACT: Color-infrared (CIR) aerial photography with computer-aided image processing was evaluated for distinguishing among buffelgrass (*Cenchrus ciliaris* L.) plots subjected to low, medium, and high irrigation treatments. Photographic imagery of the plots was obtained during a period of hot, dry weather conditions in mid-summer on three dates: 30 July, 2 August, and 5 August 1985. Canopy reflectance measurements were made on plants and soil within the plots to relate to digital film data and CIR image response. Some plots with low and medium irrigation levels could be distinguished from the high irrigation level plots within the 30 July image. The effects of irrigation levels were more apparent within the 2 August image whereby the high could be distinguished from the medium and low irrigation plots. The three irrigation treatments could be differentiated within the 5 August image. Near-infrared/red black-and-white composite images produced on the image processor from the 30 July and 2 August CIR films showed that the high irrigation treatment plots could be easily distinguished from the medium and low irrigation plots. The ability to separate the high irrigation plots in the near-infrared/red composite image for 30 July indicates that this technique may be more useful than typical CIR film for detecting early drought stress of grasses. Canopy reflectance data indicated that differences among the image tonal responses of the irrigation treatments was probably caused by differences in their red light reflectance values, and to some extent by differences in their near-infrared reflectance values. Digital film data obtained from the near-infrared/red composite images for 30 July and 2 August was highly correlated with near-infrared/red reflectance measurements. The results indicate the CIR aerial photography with computer-aided image processing may be a useful technique to detect drought stress of grasses.

## INTRODUCTION

THERE ARE MANY REPORTS on using reflectance measurements and remote sensors for detecting drought or moisture stress in crop plants (Wiegand *et al.*, 1972; Idso *et al.*, 1977; Jackson *et al.*, 1981; Jackson, 1982; Gardner, 1983; Wiegand *et al.*, 1983; Jackson and Ezra, 1985). Relative to rangelands, Everitt and Nixon (1986) used reflectance measurements to detect drought stress of two shrub species found on Texas rangelands. However, grasses are generally considered to be more important plants than shrubs on rangelands because of their higher forage value to domestic and wild herbivores. Unfortunately, little information is available on using remote sensing techniques to detect drought stress of range grasses.

Our objective was to evaluate the use of color-infrared (CIR) aerial photography with computer-aided image processing to detect drought stress of buffelgrass (*Cenchrus ciliaris* L.). Buffelgrass is the most important forage species found on south Texas rangelands. This information should be useful to range researchers.

## METHODS AND MATERIALS

This study was conducted from mid-June to early August 1985 in south Texas. The study site was a 0.2-ha fenced-buffelgrass-pasture located on the Texas A&M University Hoblitzelle Ranch near Mercedes. The site was previously established with a stand of buffelgrass. The soil was a Comitas loamy fine sand (Loamy, mixed, Hyperthermic Arenic Aridic Paleustalfs). The experimental plots of buffelgrass were arranged within a randomized complete block design with four replications of three irrigation levels (treatments): low, medium, and high. Each plot was 3.7 by 2.4 m in size. Grass on all plots was mowed to a height of 20 cm on 17 June 1985 and then allowed to regrow. The area received about 7.0 cm of rain over a one-week period in late June and early July that caused rapid growth of the grass. By mid-July, however, the grass growth was greatly decreased by high temperatures (daily high of 36 to 38°C) and drought stress was evident. All plots received a 1.90-cm irrigation on 19 July. The high and medium irrigation plots received a 2.5- and 1.25-cm irrigation, respectively, on 23 July. By 29 July, plants in most of the low irrigated plots and some plants of the medium irrigation plots exhibited drought stress. The high irrigation plots were given an additional 2.5 cm of water on 29 July. None of the plots were irrigated after 29 July. Irrigation treatments were applied by either sprinkler or hose, and the amounts given are approximations. The weather was hot and dry throughout the study period with no measurable rainfall except that mentioned above.

Aerial photographs of the plots were taken at an altitude of 460 m (1:3,000 scale) with Kodak* Aerochrome CIR (0.50 to 0.90 μm) type 2443 film, using a Hasselblad camera (150-mm lens, 5.7 by 5.7-cm format) mounted vertically in the floor of a fixed-wing Cessna airplane. The camera lens was filtered with Hasselblad 4 × 0-2 and 3.5 × CB 12-1.5 filters, and the camera's aperture was set at *f*8 with a shutter speed of 1/500 sec. Photos were taken on 30 July, 2 August, and 5 August 1985 between 1300 and 1430 hours under sunny conditions.

Color-infrared transparencies for 30 July and 2 August 1985 were digitized using an I²S image processor, interfaced to a computer. Red (0.62 to 0.70 μm), green (0.51 to 0.58 μm), and blue (0.42 to 0.50 μm) filters were used to separate images of the near-infrared, red, and green sensitive film layers, respectively, to produce a digitized image of each layer. A divide function was used with the near-infrared and red film layers to produce a composite ratio of near-infrared to red images. The image processor's Train and Prepare functions were used with the image of each sensitive film layer and the near-infrared/red

* Trade names are included for the benefit of the reader and do not imply an endorsement of or a preference for the product listed by the U.S. Department of Agriculture.

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composite image to acquire digital data from each whole plot. Composite images shown here were photographed from a monitor.

Ground data were taken on the plots to help to interpret the aerial photos. Spectroradiometric plant canopy reflectance measurements were made on 2 August 1985 with an Exotech-Model 20 spectroradiometer (Leamer *et al.*, 1973). Measurements were made at 0.05-μm increments over the 0.50- to 0.90-μm spectral region with a sensor with a 15-degree field-of-view that was placed 3.0 m above each plant canopy (0.5 $m^2$ ground area). Two measurements were made on each plot between 1100 and 1300 hours. The resulting reflectance data were studied at three wavelengths: 0.55, 0.65, and 0.85 μm, representing the green light reflectance peak, red light chlorophyll absorption band, and a point on the near-infrared (0.75 to 0.90 μm) plateau, respectively.

Herbaceous samples for phytomass measurements were made within three 50 by 50-cm quadrants within each plot by clipping vegetation at ground level. The samples were oven-dried for 72 hours at 68°C and then weighed.

Leaf water content and chlorophyll concentration were determined from plants in each plot on 2 August 1985. For these measurements, two leaf sample composites (five leaves per composite) were collected from each plot for both water content and chlorophyll determination. Water content was determined on an oven dry-weight basis (68°C for 72 hours). Total chlorophyll was determined by a routine method (Horwitz, 1965). Data for each of the two reflectance, two water content, two chlorophyll, and three phytomass samples per plot were averaged.

Digital film count, reflectance, phytomass, water content, and chlorophyll data were analyzed for variance, and treatment means for each category were compared with the least significant difference (LSD). Regression analysis was used to relate reflectance and digital count data to phytomass, chlorophyll, and water content measurements. Linear correlation and regression analysis was calculated between digital count data and reflectance measurements (Steel and Torrie, 1980).

## RESULTS AND DISCUSSION

Figures 1A, B, and C show the CIR photos obtained on 30 July, 2 August, and 5 August 1985, respectively, and Figure 1D shows the plot diagram of the buffelgrass plots for the three dates. Within the image taken on 30 July (Figure 1A), some of the low and medium irrigation plots had a dull red-pink color that could be distinguished from the bright red-pink color of the high irrigation plots. Generally, more soil was detectable within the low and medium irrigation plots than in the high irrigation plots. This was attributed to leaf rolling in response to drought stress which reflected more radiation in the canopy with a corresponding reduction in the amount reflected vertically (Jackson and Ezra, 1985; Jackson and Pinter, 1986). On 2 August (Figure 1B), the effect of drought stress was very evident among the plots. The high irrigation plots could be easily distinguished from the medium and low irrigation plots, and within most of the replications the three treatments could be differentiated. By 5 August (Figure 1C), each of the three irrigation treatments could be easily identified. Healthy appearing grass within the high irrigation plots had a uniform bright red-pink color with few gaps within its canopy, while grass in the medium irrigation plots had more red-pink image flecks and less gaps within its canopy than did the low irrigation plots.

A qualitative comparison of the digitized CIR film layers (not shown) for 30 July and 2 August 1985 showed that the near-infrared and red image bands were responsible for most differences among treatments, whereas the green band showed few differences among treatments on either date. Although differences among treatments could be seen in the single band images, ratioing the near-infrared and red images improved results. Figures 1E and F show the near-infrared/red ratio images for 30 July and 2 August 1985, respectively. A comparison of the near-infrared/red image (Figure 1E) for 30 July with that of the CIR photo for the same date (Figure 1A) showed that the ratio image gave a better separation among treatments than did the CIR photo. This was particularly evident for discriminating the high from the medium and low irrigation treatments. For 2 August, the near-infrared/red image (Figure 1F) provided little improvement over the CIR photo (Figure 1B) to distinguish among the three irrigation treatments. The near-infrared/red image results for 30 July suggest that this technique may be more useful than typical CIR film to detect early drought stress in buffelgrass.

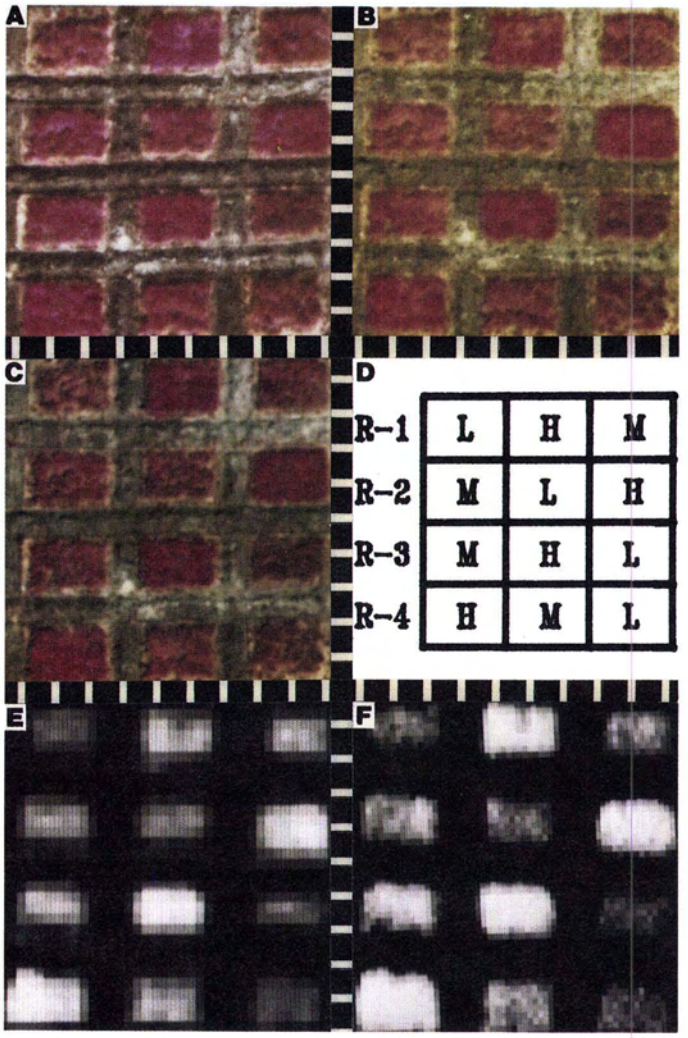


FIG. 1. Color-infrared aerial photos obtained 30 July (A), 2 August (B), and 5 August (C) 1985, and plot diagram (D) of buffelgrass plots with three levels (treatments) of irrigation: H-high, M-medium, and L-low. Prints E and F are near-infrared/red ratio composite images obtained from the color-infrared photos of the plots on 30 July and 2 August 1985, respectively.

Although visual differences could be detected in the individual digitized CIR film layers for both 30 July and 2 August 1985, digital film count data did not differ among treatments in the green, red, or near-infrared images for either date (Table 1). However, digital data obtained from the near-infrared/red composite images for both dates showed that the three irrigation treatments could be separated. These results agreed with image results in Figures 1E and F. Apparently, ratioing the near-infrared/red images normalized the effect of soil background reflectance variations and enhanced differences among the treatments. These results concur with those from other studies using the near-infrared/red ratio to evaluate reflectance data and Landsat and video image analysis of phytomass (Colwell, 1974; Deering *et al.*, 1975; Maxwell, 1976; Tucker, 1979; Richardson *et al.*, 1983; Everitt *et al.*, 1986).

TABLE 1. MEAN DIGITAL COUNTS MADE ON DIGITIZED IMAGES OF THE GREEN, RED, NEAR-INFRARED, AND NEAR-INFRARED/RED COLOR-INFRARED FILM LAYERS OF BUFFELGRASS SUBJECTED TO THREE IRRIGATION TREATMENTS FOR 30 JULY AND 2 AUGUST 1985.

| Treatment and Date | Digital Counts | | | |
|---|---|---|---|---|
| | green* | red | near-infrared | near-infrared/red |
| *30 July* | | | | |
| High | 49 a | 79 a | 91 a | 254 a |
| Medium | 47 a | 82 a | 85 a | 238 b |
| Low | 46 a | 82 a | 79 a | 218 c |
| *2 August* | | | | |
| High | 80 a | 102 a | 131 a | 254 a |
| Medium | 79 a | 109 a | 128 a | 239 b |
| Low | 79 a | 112 a | 124 a | 226 c |

*Means within a column followed by the same letter do not differ significantly at the 0.05% probability level based on the Least Significant Difference.

TABLE 2. MEAN CANOPY REFLECTANCE VALUES OF BUFFELGRASS SUBJECTED TO THREE IRRIGATION TREATMENTS. REFLECTANCE DATA WERE TAKEN ON 2 AUGUST 1985.

| Treatment | Reflectance, μm | | | |
|---|---|---|---|---|
| | 0.55* | 0.65 | 0.85 | 0.85/0.65 |
| | | | % | |
| High | 10.2 a | 5.2 c | 43.5 a | 8.4 a |
| Medium | 9.6 a | 6.3 b | 38.2 a | 6.1 b |
| Low | 8.1 a | 7.5 a | 28.7 b | 3.8 c |

*Means within a column followed by the same letter do not differ significantly at the 0.05% probability level based on the Least Significant Difference.

TABLE 3. MEAN LEAF WATER CONTENT, LEAF CHLOROPHYLL CONCENTRATION, AND PHYTOMASS LEVELS OF BUFFELGRASS SUBJECTED TO THREE IRRIGATION TREATMENTS.

| Treatment | Water* | Chlorophyll | Phytomass |
|---|---|---|---|
| | % | mg/g | kg/ha |
| High | 67.6 a | 1.84 a | 8,839 a |
| Medium | 64.1 a | 1.21 b | 8,072 a |
| Low | 58.7 b | 1.06 b | 6,488 b |

*Means within a column followed by the same letter do not differ significantly at the 0.05% probability level based on the Least Significant Difference.

Canopy reflectance measurements generally concurred better with imagery than did digital data (Table 2). Mean reflectance values at the 0.55-μm green wavelength did not differ statistically among the three treatments. Spectral results at the 0.65-μm visible wavelength, however, did differ significantly among the treatments; whereas, at the 0.85-μm near-infrared wavelength, the medium and high irrigation treatments had significantly higher reflectances than the low treatments. Relative to the CIR photos for 30 July (Figure 1A) and 2 August (Figure 1B) and their digitized red and near-infrared film layers, these data suggest that differences among the treatments were attributed to differences in leaf chlorophyll concentrations and phytomass levels (Table 3). Chlorophyll and phytomass primarily affect the 0.65- and 0.85-μm wavelengths, respectively, which correspond to the film's red and near-infrared sensitive layers, respectively (Myers *et al.*, 1983; Richardson *et al.*, 1983). Differences among treatments were probably also contributed to by differences in amounts of exposed soil background (Satterwhite and Henley, 1982; Huete *et al.*, 1985). The three treatments could also be separated by ratioing the 0.85-μm/0.65-μm reflectance data which coincided with the ratioed near-infrared/red composite images (Figures 1E and F) and near-infrared/red digital data (Table 1). The correlation coefficients for the linear correlations of near-infrared/red reflectance measurements with digital count data from the near-infrared/red composite images for both 30 July and 2 August were highly significant ($r$ = 0.92** and 0.96**, respectively).

The regression equations and coefficients of determination ($r^2$) obtained by regressing the digital film data and reflectance measurements on phytomass, chlorophyll, and water are given in Tables 4 and 5, respectively. For the 30 July digital film data, only the $r^2$ coefficient obtained by regressing near-infrared/red digital data on chlorophyll was significant statistically; whereas, for 2 August, only the $r^2$ coefficients obtained by regressing near-infrared/red digital data on chlorophyll and water were significant. For the reflectance measurements, statistically sig-

TABLE 4. REGRESSION EQUATIONS AND COEFFICIENTS OF DETERMINATION ($r^2$) OF RED, NEAR-INFRARED, AND NEAR-INFRARED/RED DIGITAL FILM (COUNT) DATA FOR 30 JULY AND 2 AUGUST, 1985, ON PHYTOMASS (KG/HA), CHLOROPHYLL (MG/G), AND WATER CONTENT (%) OF BUFFELGRASS SUBJECTED TO THREE IRRIGATION TREATMENTS.

| Dependent Variable | Independent Variable | Equation | $r^2$ |
|---|---|---|---|
| | *30 July* | | |
| Phytomass | red digital | $\hat{y} = 2300.8 + 443430/X$ | 0.12 N.S. |
| Phytomass | near-infrared digital | $\hat{y} = 5982.9 + 21.40\ X$ | 0.03 N.S. |
| Phytomass | near-infrared/red digital | $\hat{y} = -4465.5 + 51.8\ X$ | 0.46 N.S. |
| Chlorophyll | red digital | $\hat{y} = 0.1242 + 100.6/X$ | 0.07 N.S. |
| Chlorophyll | near-infrared digital | $\hat{y} = 0.7186 + 0.0153\ X$ | 0.18 N.S. |
| Chlorophyll | near-infrared/red digital | $\hat{y} = -2.92 + 0.0181\ X$ | 0.68* |
| Water | red digital | $\hat{y} = 53.54 + 799.4/X$ | 0.04 N.S. |
| Water | near-infrared digital | $\hat{y} = 49.26 + 0.1671\ X$ | 0.17 N.S. |
| Water | near-infrared/red digital | $\hat{y} = 18.9 + 0.1881\ X$ | 0.58 N.S. |
| | *2 August* | | |
| Phytomass | red digital | $\hat{y} = -5630.5 + 1439900/X$ | 0.54 N.S. |
| Phytomass | near-infrared digital | $\hat{y} = 10410.0 + 20.41\ X$ | 0.02 N.S. |
| Phytomass | near-infrared/red digital | $\hat{y} = 10601.0 + 76.77\ X$ | 0.53 N.S. |
| Chlorophyll | red digital | $\hat{y} = -2.028 + 364.5/X$ | 0.41 N.S. |
| Chlorophyll | near-infrared digital | $\hat{y} = 0.4651 + 0.0070\ X$ | 0.02 N.S. |
| Chlorophyll | near-infrared/red digital | $\hat{y} = -5.212 + 0.0274\ X$ | 0.81** |
| Water | red digital | $\hat{y} = 36.87 + 2849.9/X$ | 0.20 N.S. |
| Water | near-infrared digital | $\hat{y} = 48.249 + 0.1189\ X$ | 0.06 N.S. |
| Water | near-infrared/red digital | $\hat{y} = -4.595 + 0.2839\ X$ | 0.69* |

*Significant at 0.05 probability level.
**Significant at 0.01 probability level.
N.S. = not significant.

TABLE 5. REGRESSION EQUATIONS AND COEFFICIENTS OF DETERMINATION ($r^2$) OF RED, NEAR-INFRARED, AND NEAR-INFRARED/RED REFLECTANCE (%) ON PHYTOMASS (KG/HA), CHLOROPHYLL (MG/G), AND WATER CONTENT (%) OF BUFFELGRASS SUBJECTED TO THREE IRRIGATION TREATMENTS.

| Dependent Variable | Independent Variable | Equation | $r^2$ |
|---|---|---|---|
| Phytomass | red reflectance | $\hat{y} = 1161.3 + 41046/X$ | 0.69* |
| Phytomass | near-infrared reflectance | $\hat{y} = 3981.8 + 103.8\ X$ | 0.34 N.S. |
| Phytomass | near-infrared/red reflectance | $\hat{y} = 4788.9 + 494.3\ X$ | 0.57 N.S. |
| Chlorophyll | red reflectance | $\hat{y} = -0.6954 + 12.78/X$ | 0.80** |
| Chlorophyll | near-infrared reflectance | $\hat{y} = 0.0383 + 0.0362\ X$ | 0.47 N.S. |
| Chlorophyll | near-infrared/red reflectance | $\hat{y} = 0.3626 + 0.1656\ X$ | 0.76** |
| Water | red reflectance | $\hat{y} = 42.0 + 126.6/X$ | 0.64 N.S. |
| Water | near-infrared reflectance | $\hat{y} = 44.4 + 0.5185\ X$ | 0.81** |
| Water | near-infrared/red reflectance | $\hat{y} = 51.6 + 1.953\ X$ | 0.85** |

*Significant at 0.05 probability level.
**Significant at 0.01 probability level.
N.S. = not significant.

nificant $r^2$ coefficients were obtained by regressing near-infrared and near-infrared/red reflectance on water content, red and near-infrared/red reflectance on chlorophyll, and red reflectance on phytomass. Red reflectance was inversely related to phytomass and chlorophyll. Conversely, near-infrared reflectance was directly related to water and near-infrared/red reflectance and near-infrared/red digital data were directly related to water and chlorophyll. The significant relationships obtained here are in general agreement with the results of other studies (Tucker, 1979; Everitt *et al.*, 1986). Our results showed that reflectance measurements were better related to plant parameters than were digital film data. This was attributed to each reflectance measurement encompassing a small area (0.5 $m^2$ ground area) in the plot, whereas digital film data represented the entire plot (8.9 $m^2$ ground area). Consequently, the digital data integrated all the soil background effects and in-canopy shadowing within the plot, giving it greater variability than the reflectance measurements which were influenced by these factors within a relatively small area.

## CONCLUSIONS

We have shown that CIR aerial photography can be a useful tool to detect drought stress of buffelgrass. Moreover, our results showed that, when the CIR film layers were separated on an image processor and the near-infrared and red bands were combined to give a ratioed near-infrared/red black-and-white composite, buffelgrass under drought stress could be more clearly distinguished from nonstressed grass in the near-infrared/red composite than in the conventional CIR photo. These findings should be useful to range resource managers interested in using remote sensing techniques to monitor vigor or possibly irrigation needs of grasslands.

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