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Abstract. Airborne thermal imagery of a large varying-terrain commercial barley field was acquired over a full growing season. The data were analyzed to determine temperature variability within the field and the percentage of area within various size instantaneous fields of view (ifov's) that would be within 1°, 2°, 3°, and 5° C of the mean. There appears to be no great advantage in utilizing a small ifov instead of a large one for remote sensing of crop temperatures.

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1. Introduction

The measurement of crop canopy temperature is increasingly being suggested as a tool to be used in agricultural crop management and assessment; for example, Jackson et al. (1977), Idso et al. (1977), and Hatfield (1979). However, the accuracy with which crop temperatures must be measured and the acceptable temperature variations within a given field have not been determined. Knowledge of the required accuracy and variability would make it possible to determine appropriate instantaneous fields of view (ifov's) for remote sensors.

The Dunnigan Agro-Meteorological Experiment (DAME) airborne thermal scanner results provide insight into the temperature variability question. DAME was a combined airborne and ground field measurement program which was conducted over an entire barley growing season in support of a Heat Capacity Mapping Mission spacecraft experiment. It was performed by Ames Research Center, USDA/SEA, and the University of California at Davis. Measurements of crop temperature, soil moisture, and meteorological parameters were acquired over the growing season.

This paper is concerned with using the airborne thermal scanner results of the experiment and the analysis of data to define (1) the temperature variability (coefficient of variation) that may occur within various instantaneous fields of view, and (2) the percentage of the area within various size ifov's that would be within 1°, 2°, 3°, and 5° C of the mean. Because of the extreme variability in slope of the DAME site, the results may represent a worse-case condition and thus a very conservative estimate on which to base future calculations.

2. DAME site airborne experiment

The DAME site was located on 1 section of land (1 × 1 mile)(1.6 × 1.6 km) located near Dunnigan, California, about 40 km (25 miles) NW of Sacramento. The terrain of this site varied from flat to slopes of about 30 percent; thus, almost any barley-growing terrain in the world was duplicated. Barley, variety Briggs, was planted in December 1977 and harvested in late May 1978. The field was not irrigated, but 65 cm (26 in.) of rainfall, almost twice normal, was received.

Figure 1 is a topographic map of the site, on which is superimposed (1) 16-ha (40-acre) cells; (2) mean slope, m, in percent; (3) standard deviation, σ, of the slope within each cell; and (4) coefficient of variation, V_S, of the slope in each cell. The NE cells are the most rugged, and the southern cells are the flattest.

Airborne thermal imagery of the site was acquired throughout the growing season, from planting to harvest, except in April when the aircraft was down for maintenance. Data were acquired both prior to sunup and about 1 hour after solar noon; these represent minimum and maximum surface temperatures, respectively. Thermal imagery was acquired with a Texas Instruments Model RS-25 infrared scanner operating in the 10.5- to 12.5-μm bandpass region. This instrument has an ifov of 2 m (6.6 ft) at the flight altitude of 1.2 km (4000 ft) and a temperature accuracy of about 0.2° C. It contains two blackbody calibration sources with platinum resistance thermometers for continuous inflight calibration. All thermal data were digitally processed on an HP 3000 computer. In addition to thermal data, natural and color-IR photography were acquired on alternate flight days with a 70-mm Hasselblad camera. At the completion of each flight, atmospheric temperature and humidity were measured at various levels down to near ground level. These were used to correct the thermal-IR data for water vapor absorption.

3. Results

Airborne photographs acquired throughout the growing season (figures 2a-2e) showed that a truly uniform-appearing field never existed. This nonuniformity was caused by variable slope, soil color, gullies, and drainage-induced crop growth patterns. Figure 2a is a natural-color photograph obtained in August prior to planting and when the soil was dry. The nonuniformity of the soil is the result of past leaching and the presence of alluvial soil in the gullies. Figure 2b is a natural color photograph obtained on the 49th day after planting (DAP), after the plants had emerged. Much soil background is still apparent. Nonuniformities in appearance were caused by farm equipment tracks, varying growth patterns, and double-seeded areas. Figure 2c is a color-IR photograph obtained on DAP 94. Except for gullies, the scene was rather uniform in appearance. Figure 2d is a natural-color photograph obtained on DAP 98. Although only 4 days after DAP 94, the nonuniform scene appearance is quite striking. Much bare soil and many gullies are apparent. The reason for this sudden change between DAPS 94 and 98 is unknown, although it may be wind-induced. Finally, figure 2e pertains to DAP 154, very close to harvest. This shows the effect of crop maturity differences, caused by differing soil moisture-holding capacities. The crops on the upper slopes and the tops of the ridges matured earlier than those in the gully areas. Thus, there are many causes of scene nonuniformities throughout the season.

The coefficient-of-variation of afternoon temperatures, pixel by pixel, within the DAME site is shown in figure 3. Maximum values of about 0.22 were obtained near planting time for bare soil and no winds. Throughout the remainder of the growing season values were less than 0.11, and minimum values of about 0.02 were reached under wet soil conditions. As an aid to interpreting these effects, soil moisture, wind conditions, and agronomic values are presented in figure 3.

Figures 4-8 demonstrate the percentage of area, A_i, within various size fields of view that would be within 1°, 2°, 3°, and 5° C of the mean. These were computed from the airborne scanner data, which consisted of equivalent blackbody temperatures for every 2 m (6.6 ft) of the DAME site. Figure 4 pertains to 4 ha (10 acre) ifov's. Since there are 64 such 4-ha (10-acre) cells in the DAME site, we decided to present only values for very rugged terrains [the four 4-ha (10-acre) cells in the upper NE cell of figure 1] and for gently rolling terrains [the four 4-ha (10-acre) cells in the SE cell of figure 2]. These are adequate to bracket the results.

Figure 4 shows a large difference in A_i (percentage of area within 1°, 2°, 3°, and 5° C of the mean) values between level and rough terrain, and even between adjacent 4-ha (10-acre) cells. The explanation for these differences is that many 4-ha (10-acre) cells vary in terms of slope, gullies, and areas of nonuniform appearing vegetation. Where such conditions occur, a wide range of temperatures may exist, resulting in low A_i values. Where the scene is uniform and homogeneous, the spread in temperature is small and high A_i values result. Figure 4 shows that most temperature inhomogeneity occurs for bare soil conditions. As the canopy cover increases, so does temperature homogeneity, especially for rough terrain, thus indicating a smoothing effect of the canopy. For near-level terrain, about 95 percent of the data points are within 3° C of the mean cell temperature during full-canopy conditions; for very rough terrain, about 80 percent are within 3° C.

The percentage of 16-ha (40-acre) cells within various temperatures of the mean is plotted in figures 5 and 6. Two rather distinct families of covers resulted: one for level and intermediate-slope terrains (figure 5) and one for high-slope terrain (figure 6). A small amount of crossover, or inconsistent data did exist; the reason for this is not known. In general, however, the temperature uniformity of the level and intermediate terrain cells increased rapidly with crop growth and then remained level or dropped slightly throughout the remainder of the season. The cells with high slope (figure 6) showed A_i values that increased steadily with crop growth and reached maximum values later in the season. Over 80 percent of the data points are within 3° C of the mean cell temperature over most of the growing season. Comparing the 4-ha (10-acre) cell size results of figure 4 with the 16-ha (40-acre) results of figures 5 and 6, we find identical trends and nearly the same values of A_i, but note that individual A_i values for 4-ha (10-acre) cells can be much more variable, thus reflecting the uniformity or nonuniformity of the scene.

Finally, figures 7 and 8 pertain to cell sizes of 65 ha (160 acres) and 259 ha (640 acres), respectively. Basically, the same magnitudes and trends noted for the previous cell sizes are observed. Approximately 80 percent of the data points are within 3° C of the mean over most of the growing season; for level terrain, the value is 90 percent.

4. Conclusions

The reasons for temperature variability within an agricultural field are many. Variability is caused not only by varying topography, but also by water-carved gullies, varying soil color, moisture state of the soil and crop, nonuniform phenology, and bare spots. Although these various effects were not separated, the combined effect was measured for commercially grown barley planted on varying terrain. For all but the most rugged terrain, over 80 percent of the area within 4-, 16-, 65-, and 259-ha cells (10-, 40-, 160-, and 640-acre cells) was at temperatures within 3° C of the mean cell temperature. The result of using relatively small, 4-ha (10-acre) ifov's for remote sensing applications is that either the worst or the best of conditions is often observed. For example, the observed temperature uniformity of a homogeneous field containing a stream will vary considerably depending on whether the ifov contains the stream. If only the homogeneous field is observed, great temperature uniformity might be observed, but if the stream is within the ifov, then great nonuniformity may be observed.

There appears to be no great advantage in utilizing a small ifov [e.g., 4 ha (10 acres)] instead of a large one [e.g., 65 ha (160 acres) or 259 ha (640 acres)] for remote sensing of crop canopy temperatures. The percentage of the area within any of these ifov's that contributes temperatures that are within 1°, 2°, 3°, and 5° C of the mean is nominally the same. The two alternatives for design purposes are then either (1) a very high spatial resolution, of the order of a meter or so, where the field is very accurately temperature mapped, or (2) a low resolution, where the actual size seems to make little difference.

Acknowledgments

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IDSO, S. B., JACKSON, R. D., and REGINATO, R. J., 1977, *Science* **196**, 19-25.

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Figure captions

Figure 1. Topographic map of DAME site including mean slope M, standard deviation σ, and coefficient of variance (σ/M), V_s.

Figure 2. Aerial photograph of DAME site: (a) Dec. 9, 1977 (DAP 3), natural color film; (b) Jan. 24, 1978 (DAP 49), natural color film; (c) Mar. 10, 1978 (DAP 94), color-IR film; (d) Mar. 14, 1978 (DAP 98), natural color film; and (e) May 9, 1978 (DAP 154), color-IR film.

Figure 3. Coefficient of variation of temperatures within the DAME site.

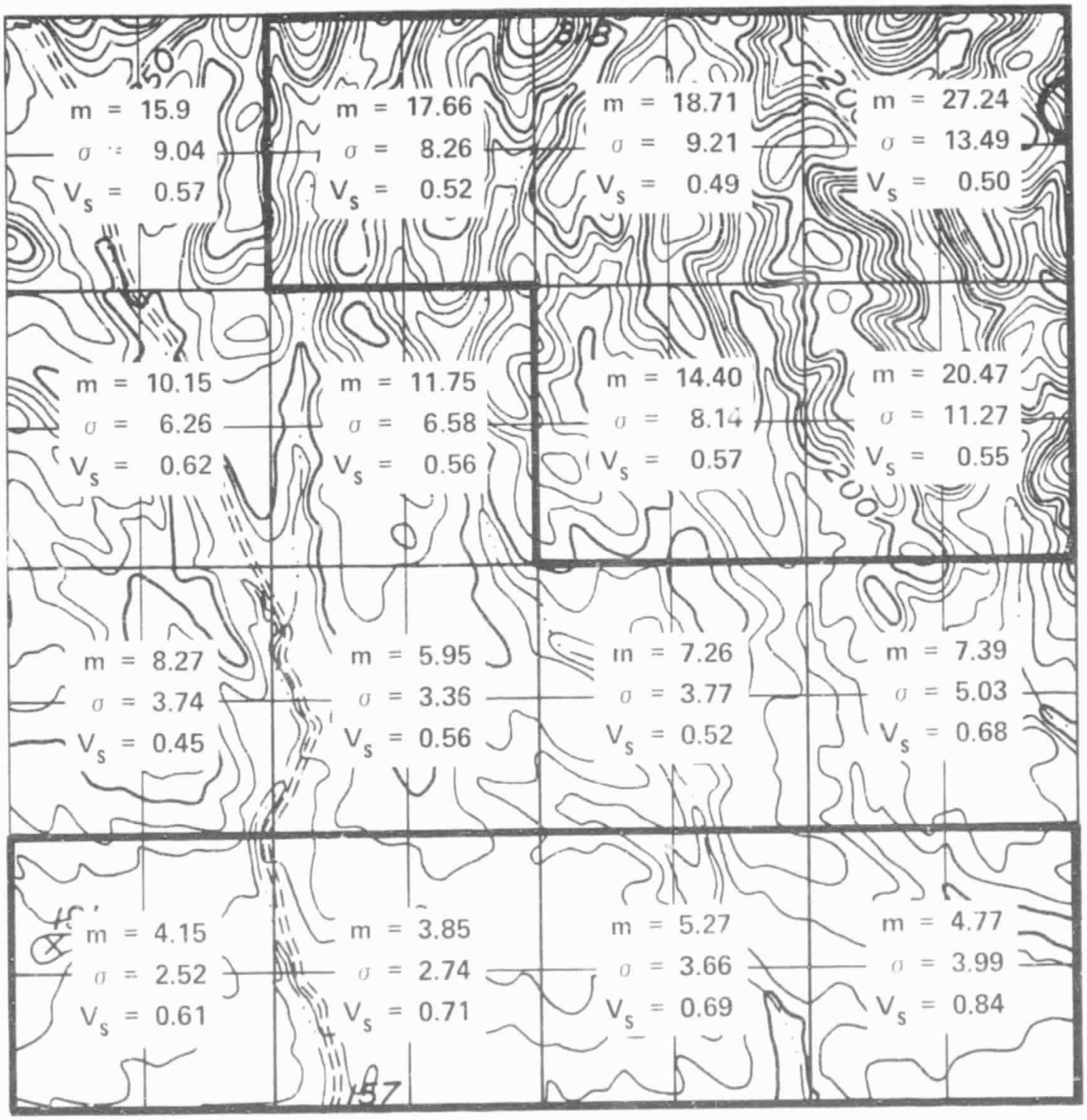
Figure 4. Percentage of 4-ha (10-acre) cells (1/64 DAME site) that is within designated temperature limits of the mean — for the four 4-ha (10-acre) cells in the upper NE cell of figure 2, and the four 4-ha (10-acre) cells in the SE cell of figure 1: (a) within 1° C of the mean; (b) within 2° C of the mean; (c) within 3° C of the mean; and (d) within 5° C of the mean.

Figure 5. Percentage of 16-ha (40-acre) cells (1/16 DAME site) that is within designated temperature limits of the mean — for level and intermediate slope terrains; those cells in the central and lower part of figure 1: (a) within 1° C of the mean; (b) within 2° C of the mean; (c) within 3° C of the mean; and (d) within 5° C of the mean.

Figure 6. Percentage of 16-ha (40-acre) cells (1/16 DAME site) that is within designated temperature limits of the mean — for high-slope terrains; those cells in the upper-right corner of figure 1: (a) within 1° C of the mean; (b) within 2° C of the mean; (c) within 3° C of the mean; and (d) within 5° C of the mean.

Figure 7. Percentage of 65-ha (160-acre) cells (1/4 DAME site) that is within designated temperature limits of the mean: (a) within 1° C of the mean; (b) within 2° C of the mean; (c) within 3° C of the mean; and (d) within 5° C of the mean.

Figure 8. Percentage of 259-ha (640-acre) cells (full DAME site) that is within 1°, 2°, 3°, and 5° C of the mean temperature.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σ = 9.04
V_s = 0.57
m = 17.66
σ = 8.26
V_s = 0.52
m = 18.71
σ = 9.21
V_s = 0.49
m = 27.24
σ = 13.49
V_s = 0.50
m = 10.15
σ = 6.26
V_s = 0.62
m = 11.75
σ = 6.58
V_s = 0.56
m = 14.40
σ = 8.14
V_s = 0.57
m = 20.47
σ = 11.27
V_s = 0.55
m = 8.27
σ = 3.74
V_s = 0.45
m = 5.95
σ = 3.36
V_s = 0.56
m = 7.26
σ = 3.77
V_s = 0.52
m = 7.39
σ = 5.03
V_s = 0.68
m = 4.15
σ = 2.52
V_s = 0.61
m = 3.85
σ = 2.74
V_s = 0.71
m = 5.27
σ = 3.66
V_s = 0.69
m = 4.77
σ = 3.99
V_s = 0.84

Fig. 1

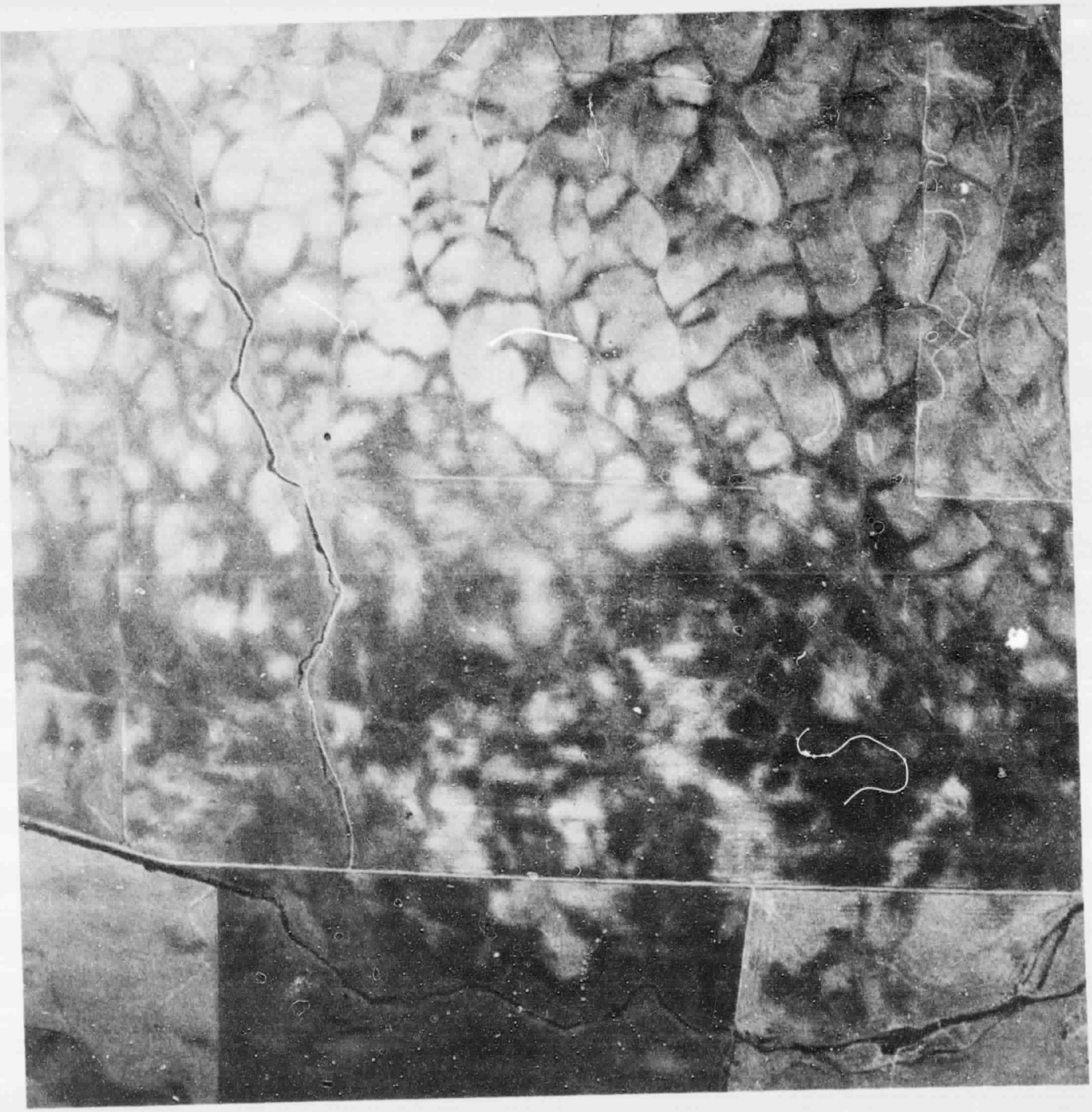


Fig. 2a

Fig. 2b

Fig. 2c

Fig. 2d

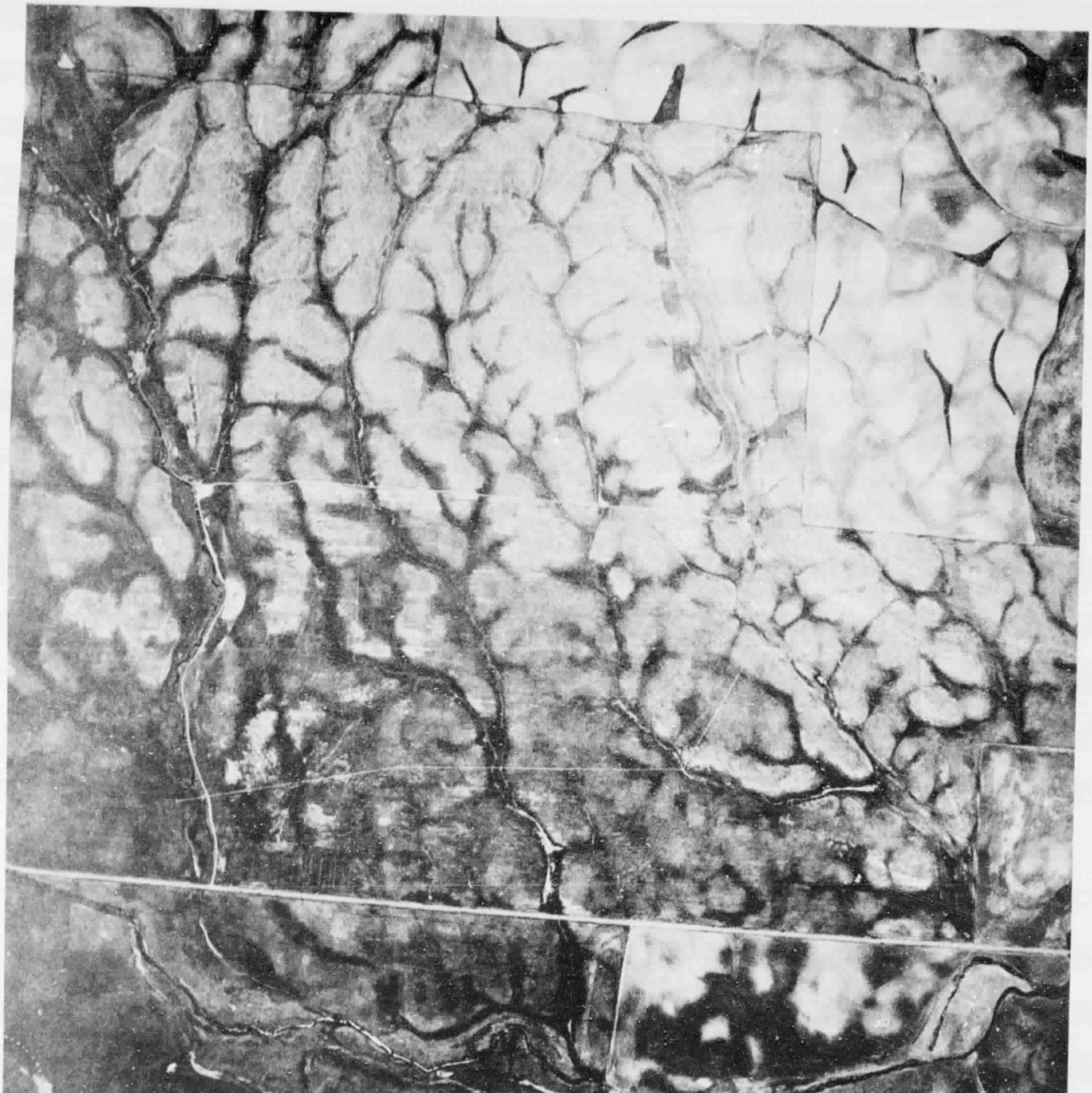
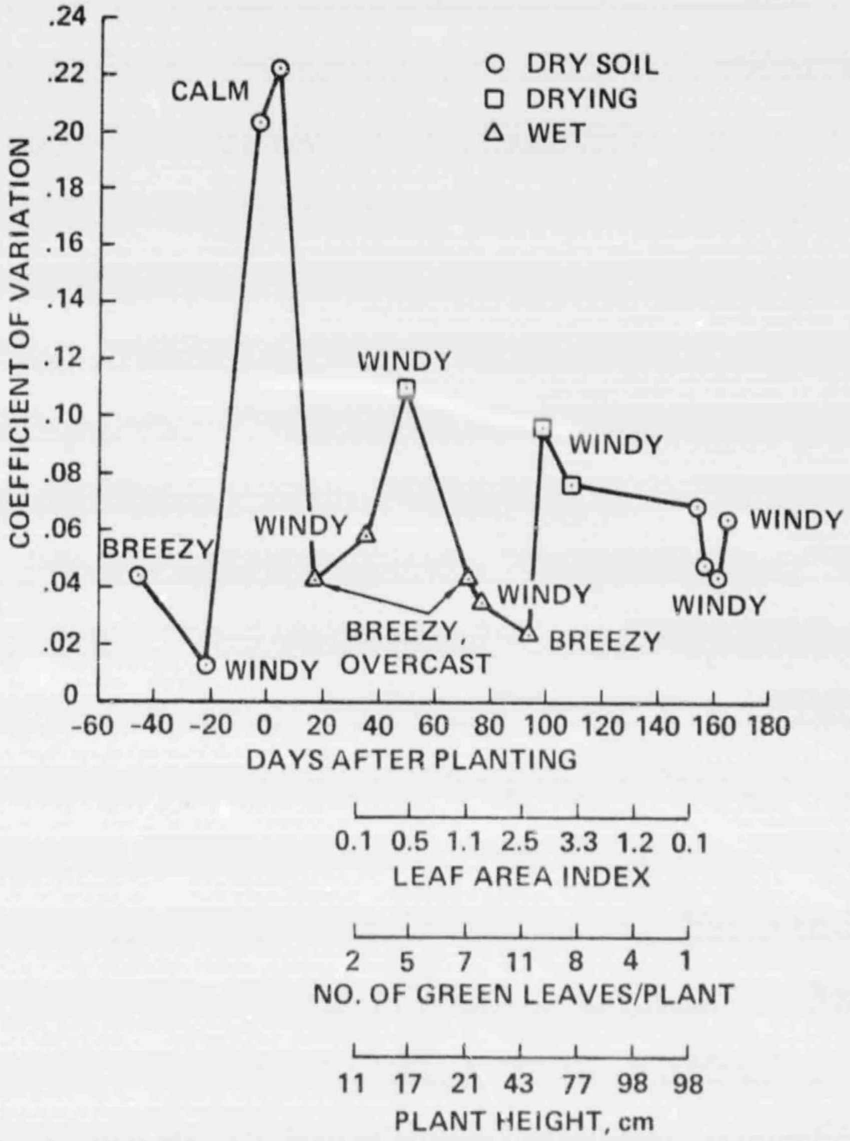


Fig. 2e



.24
.22
.20
.18
.16
.14
.12
.10
.08
.06
.04
.02
0
COEFFICIENT OF VARIATION
○ DRY SOIL
□ DRYING
△ WET
CALM
BREEZY
WINDY
WINDY
WINDY
WINDY
WINDY
WINDY
WINDY
BREEZY, OVERCAST
BREEZY
-60 -40 -20 0 20 40 60 80 100 120 140 160 180
DAYS AFTER PLANTING
0.1 0.5 1.1 2.5 3.3 1.2 0.1
LEAF AREA INDEX
2 5 7 11 8 4 1
NO. OF GREEN LEAVES/PLANT
11 17 21 43 77 98 98
PLANT HEIGHT, cm

Fig. 3

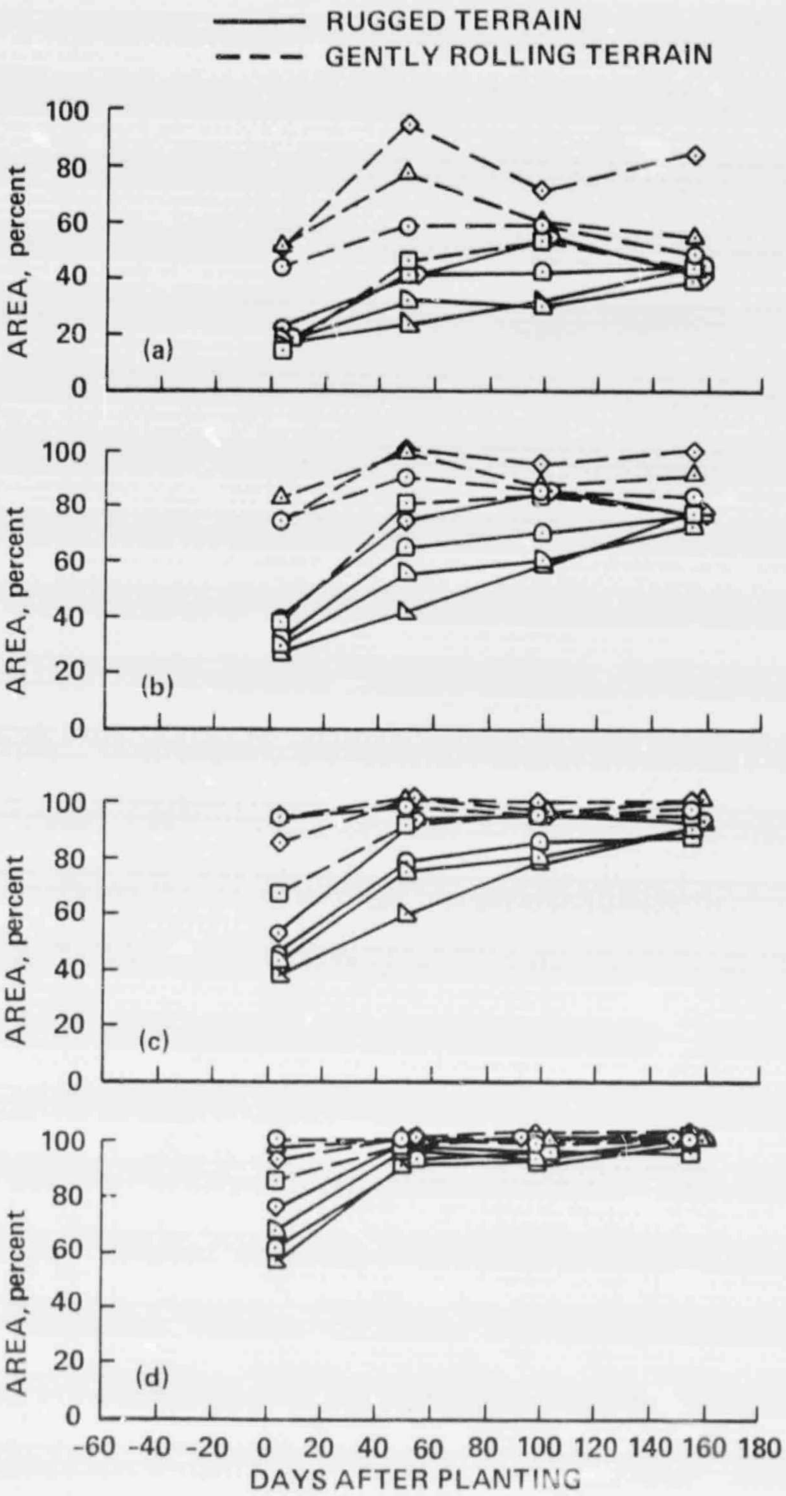

RUGGED TERRAIN
GENTLY ROLLING TERRAIN
AREA, percent
(a)
(b)
(c)
(d)
0
20
40
60
80
100
-60
-40
-20
0
20
40
60
80
100
120
140
160
180
DAYS AFTER PLANTING

Fig. 4

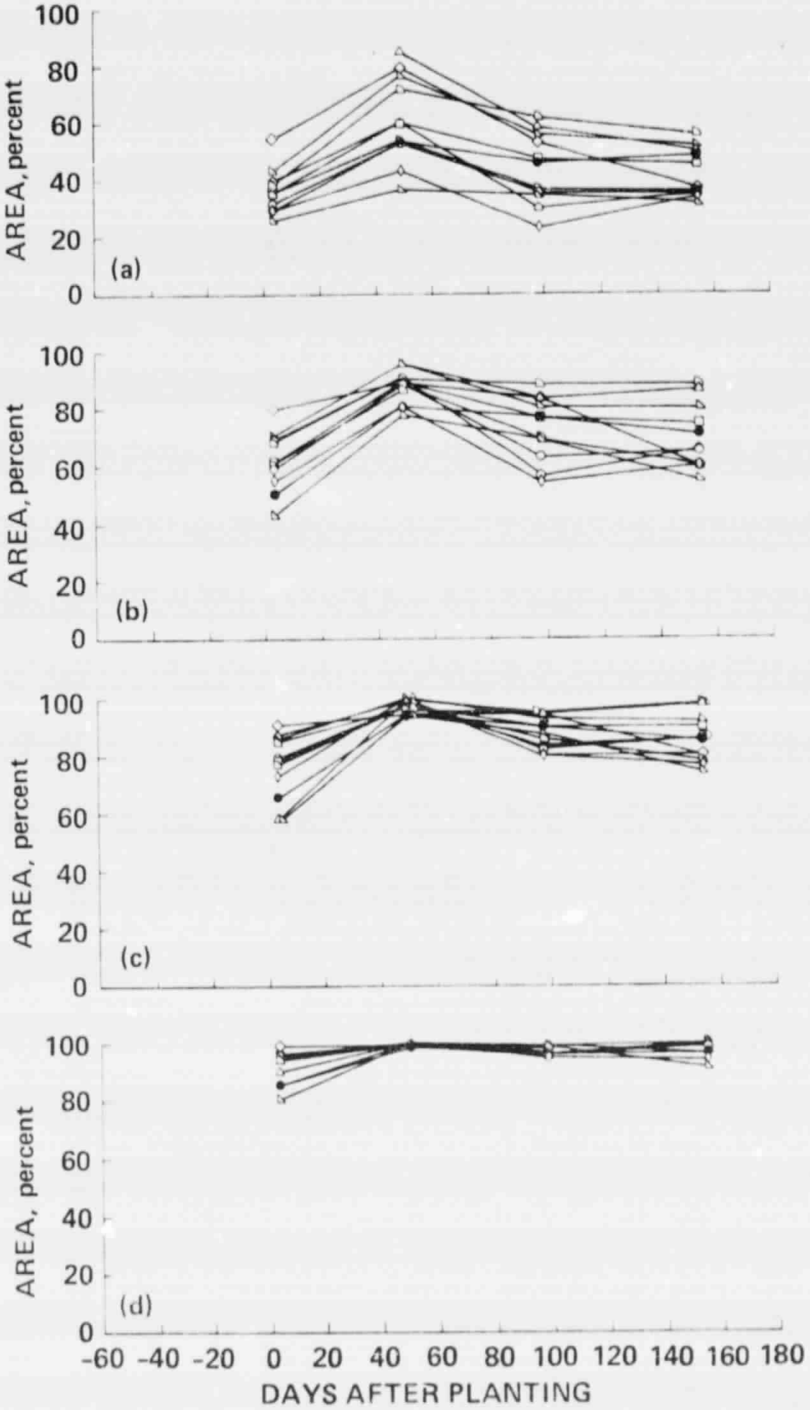

100
80
60
40
20
0
AREA, percent
(a)
(b)
(c)
(d)
-60 -40 -20 0 20 40 60 80 100 120 140 160 180
DAYS AFTER PLANTING

Fig. 5

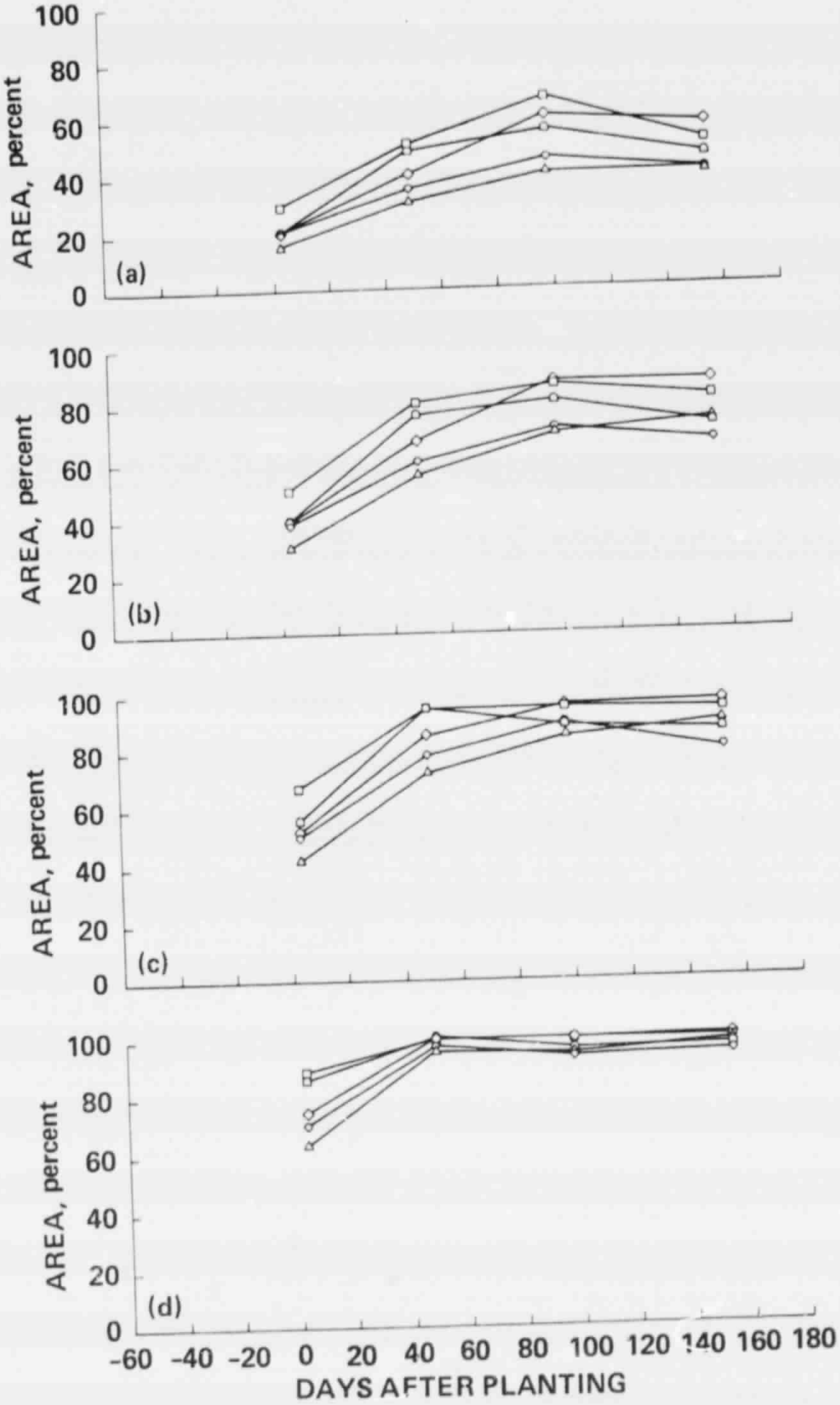
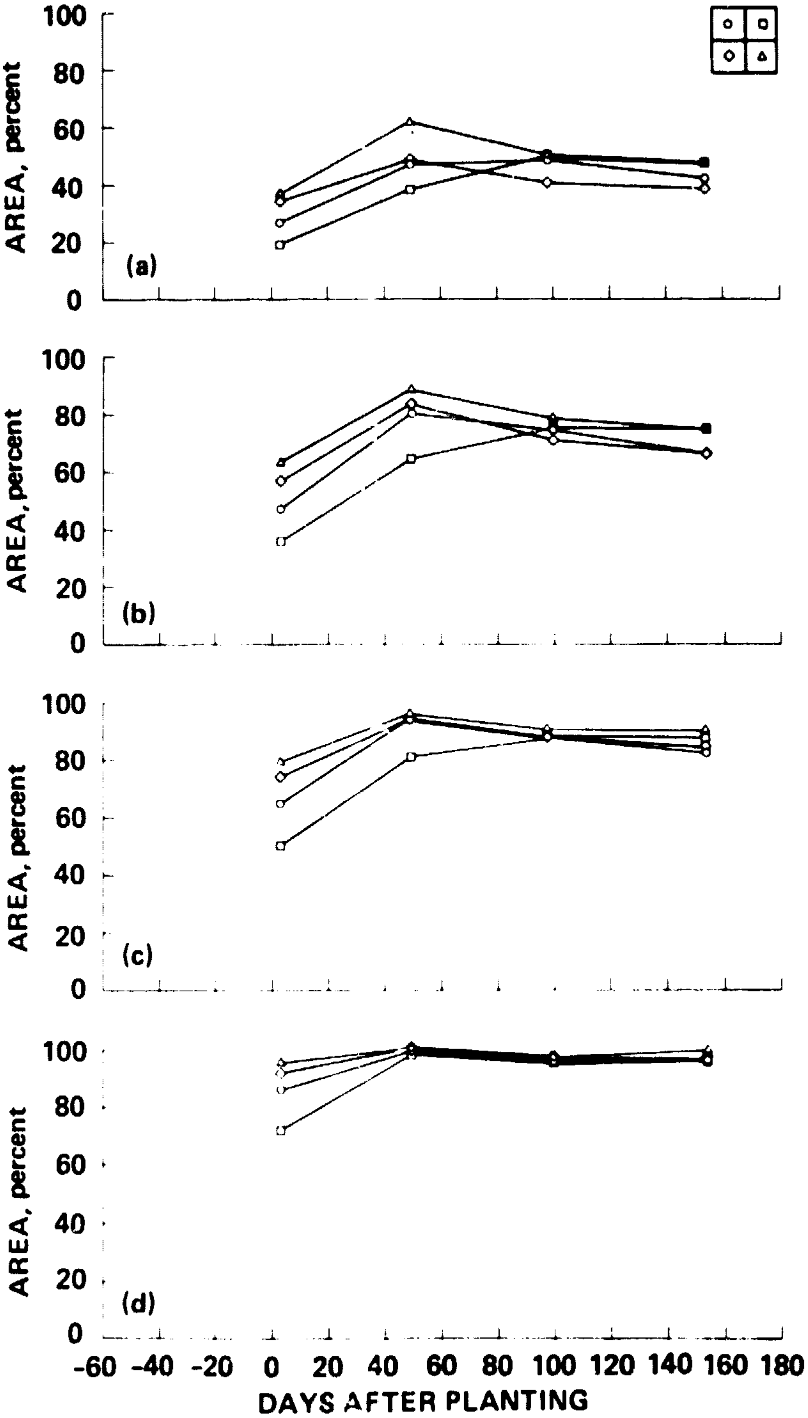

AREA, percent
0
20
40
60
80
100
(a)
(b)
(c)
(d)
-60
-40
-20
0
20
40
60
80
100
120
140
160
180
DAYS AFTER PLANTING

Fig. 6



100
80
60
40
20
0
AREA, percent
(a)
(b)
(c)
(d)
○
□
◇
△
-60
-40
-20
0
20
40
60
80
100
120
140
160
180
DAYS AFTER PLANTING

Fig. 7

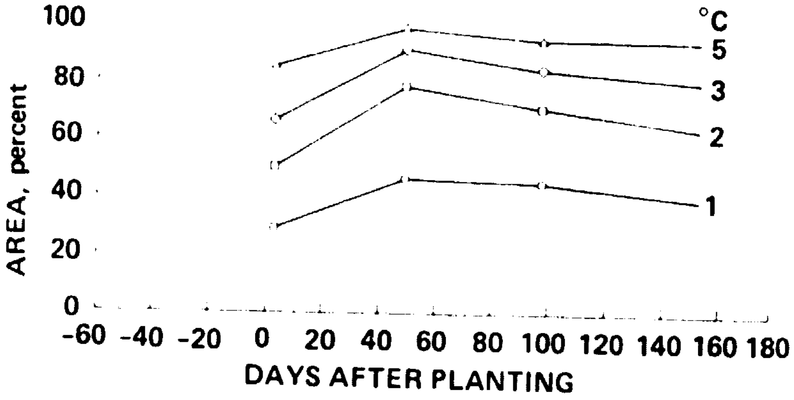

100
80
60
40
20
0
AREA, percent
-60
-40
-20
0
20
40
60
80
100
120
140
160
180
DAYS AFTER PLANTING
°C
5
3
2
1

Fig. 8