# THE EFFECTS OF SLOPE ASPECT ON THE EARLY GROWTH OF SUGARCANE IN HAWAII UNDER MID-WINTER CONDITIONS

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## ABSTRACT

The variation in slope and aspect which occurs in any area with undulating terrains will result in relatively large differences in the climate of a specified area. Mountain slopes are characterized as having low soil temperatures especially in winter months in Hawaii. However, south-facing slopes theoretically have higher soil temperatures than slopes of other aspect because they receive more net radiant energy. This study was conducted to examine the water and energy balance variations between north- and south-facing slopes and their subsequent effects on the early growth of sugarcane.

Lysimeters having initial slopes of 20% ($11^{o}09'$) with north- and south-facing aspects were used in the study. The study was conducted in Manoa Valley (Makua Campus, University of Hawaii) under mid-winter conditions (December-March).

The results showed that soil temperature and net radiation were, respectively, 0.7 C and 21 langleys$\cdot$day$^{-1}$ greater on the south-facing slopes throughout the three-month experimental period. The effect of slope-aspect on the water balance was small. As a result of the temperature and radiation differences, cane fresh weight and leaf area at the end of the three month period were approximately 40% greater on the south-facing slopes than on the north-facing ones. Leaf and tiller number of the cane plants on the south-facing slopes were about seven days ahead of plants grown on the north-facing ones. Germination of setts and first secondary tiller were at several days earlier on the south-facing slopes.

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|---|---|---|---|
| A | Aspect of slope ( $0^o$ for south-facing slope and $90^o$ for north-facing one) | Degree | 25, 26, 74 |
| AA | Sensible heat in the air | $\text{Langleys}\cdot\text{days}^{-1}$ | 18 |
| $\Delta$AA | Difference of sensible heat in the air between above the north- and south-facing slopes | $\text{Langleys}\cdot\text{days}^{-1}$ | 62 |
| Ao | The proportion of radiation absorbed by ozone in the atmosphere | 7% | 28 |
| Aw | The proportion of radiation absorbed by water vapor in the atmosphere | 2% | 28 |
| B | Steepness of slope | Degree | 25, 26, 27, 28, 74 |
| C | Calibration factor for direct radiation attenuation by clouds | - | 88 |
| CF | Reduction of direct radiation by clouds | $\text{Langleys}\cdot\text{day}^{-1}$ | 19, 20 |
| Ch | Heat capacity | $\text{Cal}\cdot\text{gm}^{-1}\cdot\text{C}^{-1}$ | 63 |
| D | Declination of sun (positive for northern latitude and negative for southern latitude) | Degree | 25, 26, 74 |
| d | The day of the year in $r_s$ | - | 26 |
| DR | Direct radiation on horizontal plane | $\text{Langleys}\cdot\text{day}^{-1}$ | 18, 19, 20, 26 |
| DR' | Direct radiation on sloping surfaces | $\text{Langleys}\cdot\text{day}^{-1}$ | 19, 20, 26 |

LIST OF SYMBOLS AND CUSTOMARY UNITS (Continued)

| Symbol | Definition | Units and Constants | Page |
|---|---|---|---|
| dT | Time interval in integration | 5 min.= 0.021816 | 26 |
| $\frac{dTs}{dz}$ | Temperature gradient with depth | $C \cdot cm^{-1}$ | 106 |
| $\frac{\Delta Ts}{\Delta T}$ | Temperature gradient with time | $C \cdot min^{-1}$ | 106 |
| E | Noon-shift, i.e., departure from solar noon on the slope relative to a horizontal surface | Degree | 25, 74 |
| $\int ET$ | Water use or evapotranspiration | Cm, in | 17, 19, 21, 22, 49, 108 |
| $\Delta \int ET$ | Difference of water use between north- and south-facing slopes | Cm, in | 62 |
| F | Latitude (positive in northern hemisphere but negative in the southern hemisphere) | Degree | 25, 26, 74 |
| F' | Corresponding latitude of slope | Degree | 25, 26, 74 |
| F(T) | Direct radiation intensity | $Langleys \cdot min^{-1}$ | 26, 75 |
| f(T) | Function of time angle | - | 26 |
| H | Diffuse radiation on horizontal plane | $Langleys \cdot day^{-1}$ | 18, 19, 20, 27 28, 80 |
| $\Delta H$ | Relative relief | M, ft | 86 |
| Hs | Diffuse radiation on sloping surface | $Langleys \cdot day^{-1}$ | 19, 20, 27, 28, 80 |

LIST OF SYMBOLS AND CUSTOMARY UNITS (Continued)

| Symbol | Definition | Units and Constants | Page |
|---|---|---|---|
| I | Irrigation | Cm, in | 17, 18, 22, 26, 34, 49, 108 |
| Io | Solar constant | 1.94 langleys$\cdot$min$^{-1}$ | 26, 28 |
| It | The extraterrestrial radiation or Angot's value | Langleys$\cdot$min$^{-1}$ | 28 |
| Ih | Direct radiation intensity on a horizontal plane | Langleys$\cdot$min$^{-1}$ | 28 |
| KK | Cloudiness | - | 88, 93 |
| Kw | Budyko's constants | - | 92, 93 |
| L | The projected horizontal distance | M, ft | 86 |
| $L\uparrow$ | Longwave outgoing radiation | Langleys$\cdot$day$^{-1}$ | 18, 19, 20, 30, 92 |
| LAI | Leaf area index | - | 48 |
| LE | Latent heat of vaporization of water and water vapor flux | Langleys$\cdot$day$^{-1}$ | 18 |
| $\Delta$LE | Difference of LE between north- and south-facing slopes | Langleys$\cdot$day$^{-1}$ | 62 |
| M | Heat storage in canopy or soil body | Langleys$\cdot$day$^{-1}$ | 18 |
| $\Delta$M | Difference of M between north- and south-facing slopes | Langleys$\cdot$day$^{-1}$ | 63 |
| m | Air mass (= 1/(Cos F Cos D Cos T + Sin D Sin F)) | – | 26 |

LIST OF SYMBOLS AND CUSTOMARY UNITS (Continued)

| Symbol | Definition | Units and Constants | Page |
|---|---|---|---|
| n | Normal to horizontal surface at point L in Figure 10 | - | 74 |
| n' | Normal to horizontal surface at point L' in Figure 10 | - | 74 |
| $N_E$ | North-facing lysimeter located in east side | - | 24 |
| $N_W$ | North-facing lysimeter located in west side | - | 24 |
| O | Runoff | Cm, in | 17, 19, 22, 49, 108 |
| OA | Obstacle angle | Degree | 86 |
| P | Photosynthetic fixation of energy | Langleys$\cdot$day$^{-1}$ | 18 |
| PP | Percolation | Cm, in | 17, 19, 22, 35, 49, 108 |
| $\Delta P$ | Difference of P between north- and south-facing slopes | Langleys$\cdot$day$^{-1}$ | 62 |
| R | Reflection of shortwave radiation on the horizontal plane | Langleys$\cdot$day$^{-1}$ | 18, 20 |
| R' | Reflection of shortwave radiation on the sloping surface | Langleys$\cdot$day$^{-1}$ | 19, 20 |
| $r_s$ | Ratio of sun-earth distance (= 0.01676 Cos(-0.172615(d-3)) + 1) | - | 26, 28 |
| RN | Net radiation | Langleys$\cdot$day$^{-1}$ | 18, 19, 20 |

LIST OF SYMBOLS AND CUSTOMARY UNITS (Continued)

| Symbol | Definition | Units and Constants | Page |
|---|---|---|---|
| $\Delta$RN | Difference of RN between north- and south-facing slopes | Langleys·day$^{-1}$ | 62 |
| RR | Rainfall | Cm, in | 17, 18, 22, 34, 108 |
| S | Soil heat flux | Langleys·min$^{-1}$ | 18, 22 |
| $\Delta$S | Difference of S between north- and south-facing slopes | Langleys·min$^{-1}$ | 62 |
| S$\downarrow$ | Incoming thermal sky | Langleys·day$^{-1}$ | 18, 19, 20, 30 |
| $S_E$ | South-facing lysimeter located in east side | - | 24 |
| Sa | The actual soil heat flux | Langleys·day$^{-1}$ | 108 |
| Se | The estimated soil heat | Langleys·min$^{-1}$ | 108 |
| $S_W$ | South-facing lysimeter located in west side | - | 24 |
| SE | Reduction in direct radiation due to shading by adjacent obstacle | Langleys·day$^{-1}$ | 19, 20, 88 |
| $\Delta$SS | Soil water storage change and plant tissue moisture increment | Cm, in | 17, 18, 22, 49 |
| SW | Net longwave radiation in cloudy day | Langleys·day$^{-1}$ | 19, 93 |
| T | Time angle of horizontal surface | Degree | 25, 26 |
| T' | Time angle of sloping surface (T + E) | Degree | 25 |
| $T_1$ | Sunrise | - | 26, 28 |

LIST OF SYMBOLS AND CUSTOMARY UNITS (Continued)

| Symbol | Definition | Units and Constants | Page |
|---|---|---|---|
| $T_2$ | Sunset | - | 26, 28 |
| Ta | Temperature of air | C | 30 |
| Ts | Surface temperature of ground | C | 30, 92, 108 |
| $\Delta$Ts | Difference of soil temperature between north- and south-facing slopes | C | 63 |
| TVD | Top visible dewlap | - | 36, 38 |
| V | Volume | $Cm^3$ | 63 |
| $\rho$ | Transmissivity of atmosphere | 0.8 | 26 |
| $\rho_b$ | Bulk density of soil | $gm \cdot cm^{-3}$ | 63 |
| $\lambda$ | Thermal conductivity of soil | $\frac{Langleys \cdot min^{-1}}{C \cdot cm^{-1}}$ | 55, 108 |
| $\Lambda$ | Longitude of point L in Figure 10 | Degree | 74 |
| $\Lambda'$ | Corresponding latitude of slope in Figure 10 (L') | Degree | 74 |
| $\theta$ | Incident angle of sunlight on the slope | Degree | 25 |
| $\theta'$ | Incident angle of sunlight on the horizontal surface | Degree | 25 |
| $\varepsilon$ | Effective emissivity | - | 30, 92 |
| $\delta$ | Stephen-Boltzmann constant | $5.67 \times 10^{-5}$ erg$\cdot$ $cm^{-2} \cdot sec^{-1} \cdot K^{-4}$ | 30, 92 |

# CHAPTER I

# INTRODUCTION

Sugarcane is a very important crop in Hawaii. The sugarcane plantations are located on the four largest islands of the Hawaiian group; namely, Hawaii, Maui, Oahu and Kauai. None are on Molokai and Lanai because the supply of water is not adequate (SCS, 1972). Cane occupies areas ranging in elevation from sea level to nearly 3,000 feet (Ayres, 1955). Soil texture ranges from stony clay to silty loam and fields range in slope from 0 to 35 percent. Cultural practices vary according to the nature of soil and the climatic conditions. Sugarcane soils in Hawaii are grouped on the basis of the similarity of management needs, including irrigation, and the amounts of solar isolation (SCS, 1972 and 1973).

Sugarcane is harvested about every 20 to 24 months though the period of the crop may extend to 36 months on the island of Hawaii. The age at which cane is harvested depends to a large extent on the climate and on the particular clone being grown. Sugarcane yields in Hawaii have been reported to vary from 25 to 150 tons of cane per acre (Clements, et al., 1952). According to Evenson and Kislev (1975), sugarcane yields in Hawaii are the highest in the world and have been so ranked since 1928. For instance, in the period from 1963 to 1967, the average yield in Hawaii was 98.7 tons of cane per acre, while yields were 64.2 tons per acre in second-ranked Indonesia. This accomplishment has been especially attributed to the favorable climate in Hawaii (Chang, 1970; Alexander, 1973).

Despite the high average yields attained in Hawaii, quite large variation in yield does occur from one field or area to another. Various reasons for the yield variation exist and include such factors as soil type and level of management. Climatic factors have also been implicated. Silva (1969) believed that sugarcane yields in windward areas were less than leeward areas because of less sunlight and lower temperature. Oldeman (1971) assessed the effect of elevation on yield in Hawaii. He suggested that the decrease in yield with increasing elevation on the Leilehua soil series might be correlated with increasing cloudiness. He also found a highly significant correlation between yield and rainfall, evaporation, radiation and maximum air temperature although the correlations with all except rainfall were negative.

Yields on the Hamakua Coast of Hawaii and other high elevation areas generally are quite low. The most likely reason for the low yields is indicated by the following statement:

> "Figure 1 shows the drop in soil temperature at the 12-inch depth with increase in elevation. These data were obtained during early March from fields of closed-in cane in a section of the Hamakua Coast. Studies at Makiki have established that optimum soil temperatures are above $72^{\circ}$ F, and that temperatures of $62^{\circ}$ F are extremely

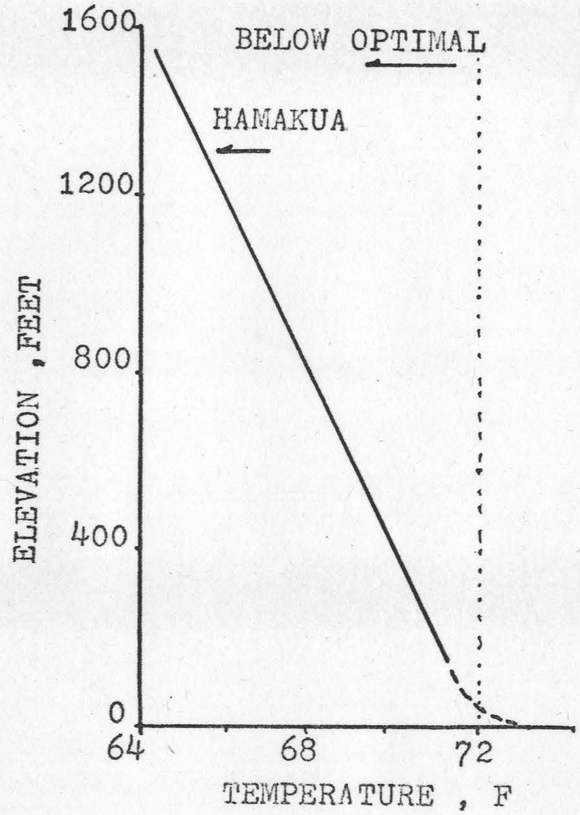


FIGURE 1: EFFECT OF ELEVATION ON SOIL TEMPERATURE AT THE DEPTH OF 12" ON THE HAMAKUA COAST ( After Anon.,1960).

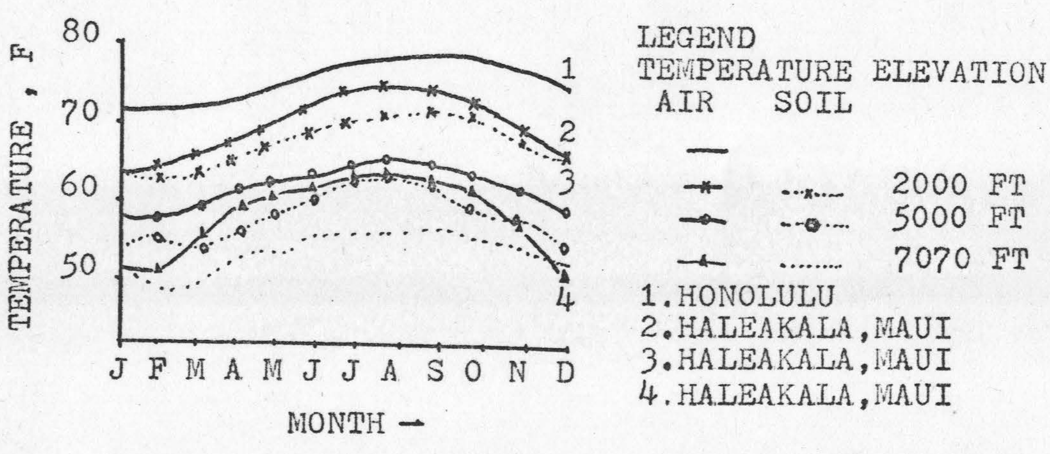


FIGURE 2: VARATION IN THE MONTHLY MEAN OF SOIL TEMPERATURE AND AIR TEMPERATURE (AT 3") WITH ELEVATION IN HAWAII (After Britten,1962).

> limiting to top growth and to nutrient- and water-uptake. Hence, March temperatures along the Hamakua Coast are below optimum near sea level and are strongly limiting at higher elevation." (ANON, 1960)

In most high elevation areas sugarcane growth will be seriously restricted by low soil temperature, especially during the winter months from September to April (Figure 2 from Britten, 1962).

With large changes in elevation existing within most plantation areas, slope is an additional factor which may markedly influence the microclimate of an area. Slope has an unique effect on the soil-climate system (Moormann, 1972). Differences among various slope aspects can include soil texture (Copper, 1960), soil temperature (Nutt, 1973), wind (Wang, 1971), rainfall (Hayes, 1944; Helmers, 1954; Hamilton, 1954; Hovind, 1965), erosion (Lee, 1963), length of growing season (Taylor, 1967), and isolation (Shul'gin, 1957; Lee, 1963; Monteith, 1973). In Hawaii, rainfall is significantly influenced by topography with windward slopes receiving considerably more precipitation than leeward ones, primarily because of uplift of onshore northeasterly trade winds. Temperature, wind, and cloudiness are also markedly different (Blumenstock and Price, 1967) between leeward and windward exposures.

The investigation of crop response to all climatic elements at one time is not feasible. The subject of this study was the effect of slope on the microclimate of a lysimeter and on the early growth of sugarcane. The sugarcane variety H59-3775 was planted in the same soil in lysimeters with south and north exposures having identical slopes. Irrigation and fertilization minimized possible water or nutritional limitations on growth. The soil temperature differences generated by the differences in incident solar radiation on the different slope aspects were measured from 26 December 1975 through 24 March 1976 at Mauka campus, University of Hawaii, in Manoa valley (Figure 9, Appendix I).

# CHAPTER II

# REVIEW OF LITERATURE

## 1. THE CLIMATE OF SLOPES:

Zelitch (1975) defined agriculture as the business of collecting and storing solar energy as food energy in plant and animal products. The solar energy available to the biological ecosystem of the earth is called net radiation which is the sum of net longwave radiation and net shortwave radiation (Monteith, 1965; Idso and Baker, 1967). The longwave radiation components are the downward sky thermal radiation (Idso and Jackson, 1969; Brutsart, 1975) and outgoing longwave radiation from the ground surface (Fuchs and Tanner, 1968) which are temperature dependent. Therefore, slope temperature has a close relation to the radiation balance on the slope. Net radiation in the field can be used to heat soil and plant surfaces, to heat the air by conduction and convection, to evaporate water, and to generate photosynthetic products (Lemon, *et al.*, 1971). The relative importance of radiation, convection, evapotranspiration and storage determine the climate of an area (Idso and Baker, 1967). In areas of varied topography, slope angle and aspect can have a significant influence on the net radiation receipt and thus the microclimate of the sloping field. Some of the effects of slope and aspect on radiation receipt and microclimate are summarized in the following paragraphs.

Sunshine duration governs the quantity of solar radiation received at a given site. A long day will have a higher radiation income, especially of direct radiation. Since north-facing slopes are shaded earlier in the day than south-facing slopes, north-facing slopes can be expected to receive direct radiation for a shorter period of time than south-facing slopes. Sunshine duration and global radiation data for a horizontal surface are given by the Smithsonian Meteorological Tables (List. 1966) and Nautical Almanac Office (1945). Radiation receipt and sunshine duration on sloping surfaces have been predicted using a number of models (Garnett, 1935; Okanoue, 1957; Okanoue and Makiyama, 1958; Lee, 1963; Swift, 1976; Garnier and Ohmura, 1968 and 1970; Williams, et al., 1972; Swift, et al., 1973; Buffo, et al., 1972; Norris, 1966; Gloyne, 1965).

Monteith (1973) believed that the difference in direct irradiation on slopes of different aspect was often responsible for major differences in microclimate and plant response. In the Northern Hemisphere, south-facing slopes tend to be warmer and thus more droughty than north-facing slopes. Cottle (1932) noted that there was a very marked difference in the species and environmental conditions found on north and south slopes. Machattie (1961) showed that evaporation rates paralleled soil temperature fluctuations on both the north and south aspects. Geiger (1965) reported that soil and air temperatures within the plant canopy were cooler on north- than south-facing slopes. Soil water content at the 5 cm depth was greater on the north-facing slope. In a comparison of north- and south-facing slopes in Michigan, Cooper (1960) showed that in April the relative light intensity, the maximum air temperature and the soil temperature at a depth of 20 cm were all higher on a south-facing slope than on a north-facing slope. He also found the percentage of clay was higher on the south-facing slope while depth of the A horizon and solumns were greater on the north-facing slope. Cooper also found that the soil moisture content of the north-facing slope was one-third higher than that of the south-facing slope. Southard and Dirmhirn (1972) concluded that soil and climatic factors combined to provide the necessary environment to sustain different vegetation types on north- and south-facing slopes and that the vegetation in turn influenced both soil and climate. They found that vegetative cover and soil moisture percentage were lower and the soil was more sandy on the south-facing slope while global radiation, pan evaporation and organic carbon content were lower on the north-facing slope. Shul'gin (1957) reported that similar north-south relationships were found in Russia and also that soils on west-facing slopes were warmer than those on east-facing slopes. He attributed this to a greater expenditure of solar radiation for evaporation of dew on east-facing slopes than on west-facing slopes. The west-facing slopes were drier during the afternoon as a result of more direct insolation. Taylor (1967) reported that in England, most of the farms producing early potatoes were located on south-facing slopes, especially those slopes not exposed to winds off the sea, where soil temperatures were higher. Variation in precipitation has been noted on slopes having different aspects (Geiger, 1965). The supporting statements can be found elsewhere (Hayes, 1944; Helmers, 1954; Hamilton, 1954; Hovind, 1965).

Slope also influences the microclimate of adjacent areas. Cold air, because of its greater density, tends to move down slopes during the night and collect in depressions. However, above the cold air layer in the valley, there is usually a thermal belt which is more advantageous for crop growth (Dunbar, 1966). Tuller (1973) had observed that stations near the forest edge had a higher total of global solar radiation than those placed at some distance from the edge. The result was due to the higher surface albedo of the adjacent forest growing along the slopes which outweighed the depletion of diffuse sky radiation due to the presence of tall trees. Robinson (1966), Kondratyev and Manolova (1960), Kondratyev (1965) and Williams, et al. (1972) also noted that cloudiness, reflection, elevation, additional radiation received as a result of reflection from facing objects, and shading from obstacles influenced radiation receipt at a given location.

## 2. CLIMATIC EFFECTS ON THE GERMINATION, TILLERING AND EARLY GROWTH OF SUGARCANE:

Excellent reviews of sugarcane agronomy by Alexander (1973), Humbert (1968), and Barnes (1964), include all stages of sugarcane culture. Reviews which emphasize cane growth in Hawaii are Burret, et.al. (1957) and Clements, et al. (1952).

Since all early development of shoots occurs within the soil, soil moisture, aeration and temperature are the important factors influencing germination and early growth.

Though a number of studies have been made of the relationship between cane growth and soil moisture, few indicated the actual level soil moisture stress. Robinson (1963) reported stalk elongation declined when soil moisture stress exceeded 2 bars as measured with resistance blocks 12" below the furrow. However, the scatter of data at 0.5 bar was too great to be certain about the effect of low stress on shoot elongation. Hudson (1968) demonstrated a 50% reduction in spindle elongation of 6 week old plants grown at an osmetic potential of 2 bars in Barbados soils. Mongelard (1968) found that the top visible dewlap of one month old cane at ½ bar stress was 0.83 that of ¼ bar stress. In the same test a ½ bar stress reduced leaf area by 27% and dry matter by 33%. Therefore, Mongelard (1973) recommended a soil moisture stress of less than 0.2 bar to prevent growth reduction of cane. Buren and Yamasaki (1973) reported that germination can be improved by drip irrigation.

Jain and Agrawal (1970) studied the effect of clod size in the seedbed on development and yield of sugarcane using Yoder's (1937) pulverization indices. They found soil porosity, cane germination, tillering, height, and yield to be highest at pulverization modulus 2 (clod size of 1/8 1/4 inches). Clod sizes of greater or lesser size provided a less favorable environment for growth. Their results were similar to those obtained by Yoder when growing cotton on a Cecil clay. Therefore, Jain and Agrawal concluded that, "the results of this experiment show that preparatory tillage operations for sugarcane should be directed towards preparing a modulus 2 for best crop growth, yield, and quality." Soil compacted to bulk density of 1.44 (dry weight 90 $lb/ft^3$) prevented root penetration of cane in Lahaina soil (Trouse and Humbert, 1961). The pore size of the Hawaiian red oxisols has a bimodal distribution (Tsuji, _et al_., 1975). Compaction eliminates the large inter-aggregate pores essential to air and water movement (Sharma and Uehara, 1968). Mongelard and Mimura (1971 and 1972) reported dry matter production of the variety H59-3775 increased almost linearly as soil temperature was increased from 15.5 C to 30.5 C. Tiller production was reduced by root temperatures below 24.5 C. The mean number and dry weight of tillers increased with increasing temperature above 24.5 C. Whiteman _et al_. (1963) reported that the optimum temperature for germination of the cultivar Pinder was in the vicinity of 30 C, with severe growth depression below 22 C and virtually no growth in the range 10 to 16 C. Van Dillewijn (1952) believed that observed differences in temperature optima for germination of sugarcane could be related to the origin of the variety. Canes of subtropical origin had a temperature optimum between 26 and 33 C, while tropical canes were reported to have an optimum of 34 to 38 C (Verret, 1927).

Warm water irrigation significantly increased cane growth during a three month experiment (Mongelard, 1973). The aerial environment also influenced the growth of sugarcane. Sugarcane possesses the anatomical and metabolic characteristics of $C_4$ plant species (Kortschak, et al., 1965; Hatch and Slack, 1966; Hatch, et al., 1967; Bull, 1969; Berry, 1975). Thus sugarcane photosynthesis is not light saturated at full sunlight and the temperature optimum for photosynthesis and growth is $30^{\circ}$ C or greater.

Lee and Lin (1948) observed that shortening the duration of daily exposure to light resulted in decreased tillering. Hill and Evans (1933) reported a significant negative correlation between growth and relative dryness of the air. The effect of wind may be dual: direct effects are due to mechanical damage; and indirect effects result from changes in transpiration, soil moisture, and air humidity. Verret and Mclennan (1927) exposed cane plants to artificial wind from a fan and when soil moisture was kept optimal, the loss in weight resulting from wind was 14%. However, when water supply was less than optimum (i.e. the normal field practice) reductions of 35% in dry weight and 20% in stalk height were observed, while tiller number was increased.

Das (1935) studied the effect of climate on yield of sugarcane by growing cane in pots at different localities on Oahu. The pots were filled with the same soil and the same varieties were used. Care was taken to keep other factors such as fertilization, irrigation, etc. identical at all sites. The two climates involved were the lowland climate at Makiki station, 40 feet above sea level, and the upland climate at Manoa station, at 650 feet above sea level. The climate at the former station was characterized by bright sunny weather with relatively few rainy days, while at the latter there were many rainy days and the sunlight received was less than 50% of that at Makiki. Maximum temperatures at Makiki were about 4 F higher than at Manoa, but there was little difference in minimum temperature at the two locations (Borden, 1941). Three times as much cane was grown at Makiki than at Manoa. Borden (1936 and 1941) grew cane in pots filled with two types of soil, Makiki soil and Manoa soil, at both stations. This offered the possibility of separating the soil effect from the climate effect. Under the conditions of the climate of Makiki, cane yield (69 pounds) was almost three times that obtained at Manoa (24 pounds) while the sugar yield was more than 3 times as high

(7.8 pounds against 2.1 pounds) at Makiki.

Clements (1940) grew cane in two localities only a few miles apart, i.e., at Waipio with very bright days, and at Kailua with many cloudy days. Light intensities were significantly different between the two localities. Despite comparable fertilization and moisture conditions, the Waipio crop was more than twice that obtained at Kailua, due mainly to differences in light intensity.

Clements and his colleagues in Hawaii (1952) developed a number of growth formulae for sugarcane which incorporated interrelating features of cane morphology, physiology, and ecology. For example, the growth equation incorporated such factors as crop age, sheath moisture, daily relative humidity, wind velocity, maximum and minimum temperature and daily solar radiation. Sarker (1964) examined the influence of prevailing weather on yield of sugarcane at Poona. He found that the weather factors maximum temperature, minimum temperature, rainfall and sunshine hours during the tillering phase accounted for about 50% of the variation in final yield. Prevailing weather during the tillering phase and the elongation phase accounted for about 80% of the variation in final yield. The weather during tillering appeared to be more important in determining yield than the weather during later stages of growth. Gascho, et al. (1973) also found that inadequate temperature may be a factor in low yield.

## 3. LYSIMETRY:

Lysimeters are valuable research tools because water income and outgo from a given soil volume can be separated into its components. The lysimeter has been defined as a device for measuring the percolation of water through soils and determining the soluble constituents removed in the drainage. An excellent review of literature by Kahnke and coworkers (1940) covered two and a half centuries of research on lysimetry up to 1939. Harrold and Dreibelbis (1958 and 1963) reported information from 1939 to 1962. The first monolithic American lysimeter (soil-block) was constructed by Sturtevant in 1875. The first soil-block lysimeter with self-recording weighing mechanism were built in 1939 by the Soil Conservation Service at Coshocton, Ohio.

From the viewpoint of sensor systems, Ekern (1967) and Tanner (1967) gave a brief review, in which 4 types were defined. (1) Mechanically weighed lysimeters include the Coshocton lysimeters, the 6.1 m diameter lysimeter at Davis, California (Pruitt and Angus, 1960), some small-size lysimeters in North Carolina (England and Lesesne, 1962) and the Tempe, Arizona lysimeter with electrical strain gages (Bavel, 1962) as well as the remote type used by LeDrew and Emerick (1974). (2) Floating lysimeters contained buoyant air chambers supported on water (King, et al., 1956) or heavy liquid (McMillan and Paul, 1961). (3) Hydraulic load-cell lysimeters supported on water field bolsters are especially suited to tropical areas where freezing does not occur (Ekern, 1967). (4) Drainage lysimeters have been used to measure evaporation or evapotranspiration as the difference between irrigation plus rainfall and percolation.

Lysimeters, if classified according to the principles of construction, are of three major types: (1) Ebermayer, (2) Filled-in and (3) Monolith, or undisturbed soil block. In the Ebermayer type (1), the soil is left in situ and a percolate collecting funnel is placed under it, but no side walls separate a definite soil block from the adjoining soil. Recently, tension lysimeters, a modification of the Ebermayer system, have been used (Coles, 1958). The filled-in type (2), consists of a container, which has vertical side walls, an open top, and a bottom that provides for percolation. The lysimeter should be refilled in such a manner that the soil density and structure will approach natural conditions as closely as possible. The monolith or soil-block lysimeter (3) combines the most desirable features of the Ebermayer and the filled-in types. A block of soil as it is found in the field is enclosed, a bottom is attached, and the percolate is conducted to receiving tanks.

Lysimeters should be constructed in such a way that their moisture relationships correspond closely to those of soils under natural condition. The ideal lysimeter should contain an undisturbed, representative soil profile, deep enough for undisturbed rooting (Chang, 1968). The heat storage and transfer in the lysimeter walls should not be different from that in the surrounding soil if best results are to be obtained. The sensitivity of sensor system significantly influences the accuracy, too.

Recently, lysimeters were used to investigate evapotranspiration of crops (Pruitt and Angus, 1960; Visser, 1965; Tanner, 1967; Goddard, 1970; Ekern, 1971 and 1972).

The water components of a lysimeter are related to the water balance equation where

$$RR + I = \Delta SS + \int ET + PP + O \qquad \text{Equation 1}$$

RR is rainfall, $\Delta SS$ is soil storage change and crop tissue moisture increment. $\int ET$ is evapotranspiration, PP is percolation, O is runoff on the surface, and I is irrigation (Kahnke, et al., 1940; Harrold and Dreibelbis, 1958 and 1963).

# CHAPTER III

# MATERIALS AND METHODS

## 1. INTRODUCTION:

Because both climatic and plant processes derive their energy from solar radiation, it is reasonable to treat crops as energy exchange systems. In this study a single soil-filled lysimeter, a sugarcane crop and the aerial environment form such an energy system. When several lysimeters are placed side by side with a short slope (length 152.4 cm), the aerial environment (temperature, humidity, carbon dioxide concentration, wind, and rainfall) are so nearly the same that they can be presumed to be identical.

The major exchange processes in the above specified system can be expressed by 3 equations which describe the radiation balance, the heat balance, and the water balance. These equations are: The radiation balance, where

Net radiation (RN) = net short-wave balance (DR + H - R) + net long-wave balance ($S\downarrow - L\uparrow$)

Equation 2

The heat balance, where

Net radiation (RN) = sensible heat (AA + S) + heat storage (M) + latent heat and water vapor flux (LE) + photosynthetically chemical equivalent (P)

Equation 3

The water balance (Equation 1), where

Rainfall (RR) + irrigation (I) = evapotranspiration

($\int$ ET) + percolation (PP) + runoff (O) + soil moisture storage change and plant tissue moisture increment ($\Delta$SS).

All the above terms and others introduced later are defined in List of Symbol Notation and Customary Units (page iX ).

Sunlight intensity and duration in any plane (air) above the lysimeters can be presumed identical. The radiation balance for an individual lysimeter depends on the nature of surface. Details of the method of calculating the theoretical radiation components received on the north- and south-facing slopes at the experiment site are given in Appendix II and section 3 of Materials and Methods. A summary of the calculated results are presented in Table 1. This theoretical consideration includes direct radiation on a clear day (DR or DR'), the reduction of direct radiation by clouds (-DF) and the shading effect (-SE) of adjacent objects, diffuse radiation (H or $H_S$), reflection loss (-R or -R') from the ground surface, net short-wave radiation under cloudy conditions ((DR + H - CF - SE - R) or (DR' + HS - CF - SE - R')), outgoing longwave radiation (-L$\uparrow$ ), incoming longwave radiation (S$\downarrow$ ) on a clear day, net longwave radiation (SW) under cloudy conditions and net radiaticn under cloudy conditions (RN). That is to say, Equation 2 is derived as Equation 2a or 2b for cloudy conditions for a horizontal surface and a sloping surface, respectively.

TABLE 1. --RADIATION BALANCE (LANGLEYS·DAY$^{-1}$) OF VARIOUS SURFACES WITH 20% (11°9') SLOPE BASED ON THE THEORETICAL CONSIDERATION AT EXPERIMENT SITE UNDER THE CLOUDY CONDITION.

| Radiation Component | December 21 | | | March 21 | | |
|---|---|---|---|---|---|---|
| | Horizontal | North | South | Horizontal | North | South |
| Direct (DR or DR') | 369 | 276 | 448 | 592 | 535 | 626 |
| Cloudiness (-CF) | -148 | -110 | -179 | -284 | -257 | -300 |
| Shading effect (-SE) | -10 | -10 | -10 | -13 | -13 | -13 |
| Diffuse (H or Hs) | 95 | 95 | 95 | 84 | 84 | 84 |
| Reflection (-R or -R') | -79 | -63 | -92 | -115 | -105 | -121 |
| Cloudy net short-wave | 227 | 188 | 262 | 264 | 244 | 276 |
| Outgoing (-L↑) | -775 | -775 | -775 | -797 | -797 | -797 |
| Thermal (S↓) | 551 | 551 | 551 | 578 | 578 | 578 |
| Cloudy net longwave (SW) | -181 | -181 | -181 | -184 | -184 | -184 |
| Net radiation (RN) | 46 | 7 | 81 | 80 | 60 | 92 |

$$RN = (DR + H - CF - SE - R) + S_w \qquad \text{Equation 2a}$$

$$\text{or } RN = (DR' + Hs - CF - SE - R') + S_w \qquad \text{Equation 2b}$$

Because this experiment was performed from December 26 to March 26 this table, therefore, shows the theoretical condition for the experiment period. At the Winter Solstice (December 21) the south-facing slope will have 73 langleys more net radiation per day than the north-facing slope and 35 more than a horizontal surface. At the Vernal Equinox (March 21) the south-facing slope will receive only 32 langleys more than the north-facing slope; 12 more than the horizontal surface. If half of the net radiation at the Winter Solstice is consumed to heat the soil, the soil temperature on the south-facing slope will be 0.75 C higher than the horizontal surface and 1.45 C higher than on the north-facing slope. At the Vernal Equinox the south-facing slope will have a temperature 0.24 C greater than the horizontal, 0.7 C greater than the north-facing slope. The above result would hold only if the soil condition was the same for all surfaces.

In this study, global radiation was measured, net radiation was sampled, and all other terms were estimated.

Under Hawaiian conditions a well-watered, fully vegetated canopy has an evapotranspiration rate ($\int ET$) which is about 1:1 with class A pan evaporation (Chang, 1961; Ekern, 1972). This means that essentially all net radiation is used for ET. In much of the irrigated sugarcane, positive advection of heat occurs particularly in summer, so that $\int$ET often exceeds the local RN. During the period of early growth of sugarcane in this experiment, LE is the energy used for $\int$ET (Equation 1). Convective transfer of heat (AA) was not measured and was assumed to be the same for both north- and south-facing lysimeters because of a small fetch. The energy used by photosynthesis (P) and by canopy storage (M) are small and were ignored (Baumgartner, 1956; Rosenberg, 1974). Soil heat flux (S) in Equation 3 is expressed as $S = \lambda \frac{dTs}{dz}$. The soil temperature change in response to the heat flux depends on the heat capacity of the soil. The heat capacity of Lahaina soil can be estimated from the soil composition and water content (De Vries, 1963). Soil heat flux was not measured directly, but was calculated from soil temperature by the null-alignment method (Kimball and Jackson, 1975)

$\int$ET was estimated from the lysimeter water balance (Equation 1) using measured rainfall (RR), irrigation (I), and percolation (PP). Changes in soil storage ($\Delta$SS) were estimated from soil water content measured by tensiometer. Water in the plant tissue was ignored in this experiment because of the small plant weights. Within the defined system, runoff was not removed but contributed to percolation, thus Equation 1 can be written as

$$RR + I = \Delta SS + \int ET + PP \qquad \text{Equation 1a}$$

Sugarcane sets of the variety H59-3775 were planted on north- and south-facing slopes of the lysimeters. In Hawaii, stalk populations have been shown to increase from planting to about three months (Figure 3). Thus stalk number and relevant parameters could be expected to reflect the climatic conditions without any disturbance by competition, in this three-month experiment.

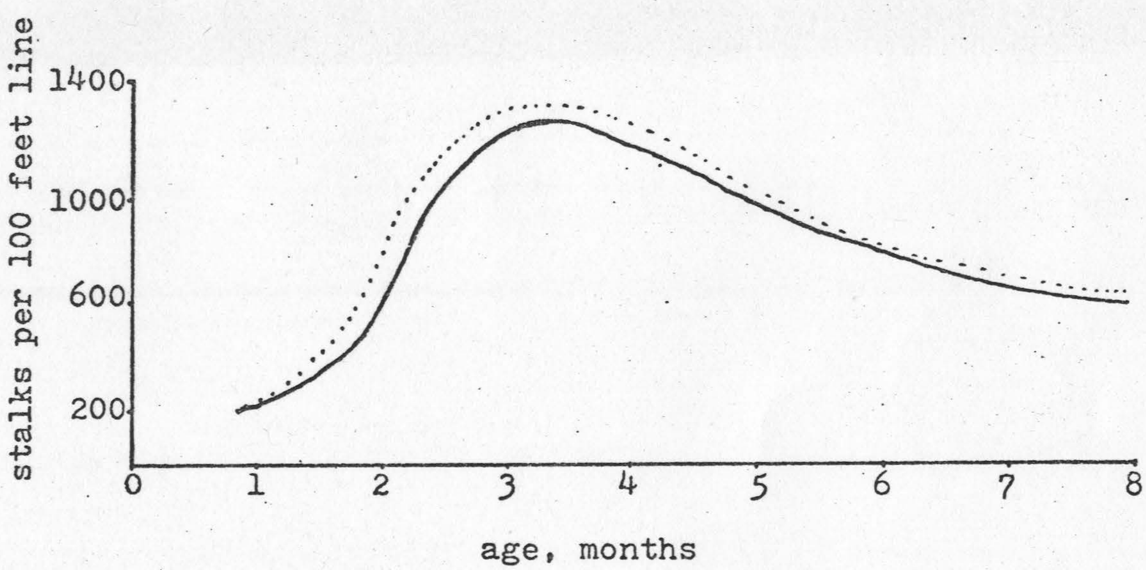


FIGURE 3: STALK POPULATION FROM STANDARD PLANTATION PRACTICE (After Nickell, 1965).

Solid line: Kekaha. Dotted line: Honolulu

## 2. LOCATION AND INSTALLATION OF EXPERIMENT:

The lysimeters were installed on the Mauka campus of the University of Hawaii, in Manoa valley, at about 160 feet elevation. The experiment location in shown in Figure 9, Appendix I. The experiment layout is shown in Figure 4.

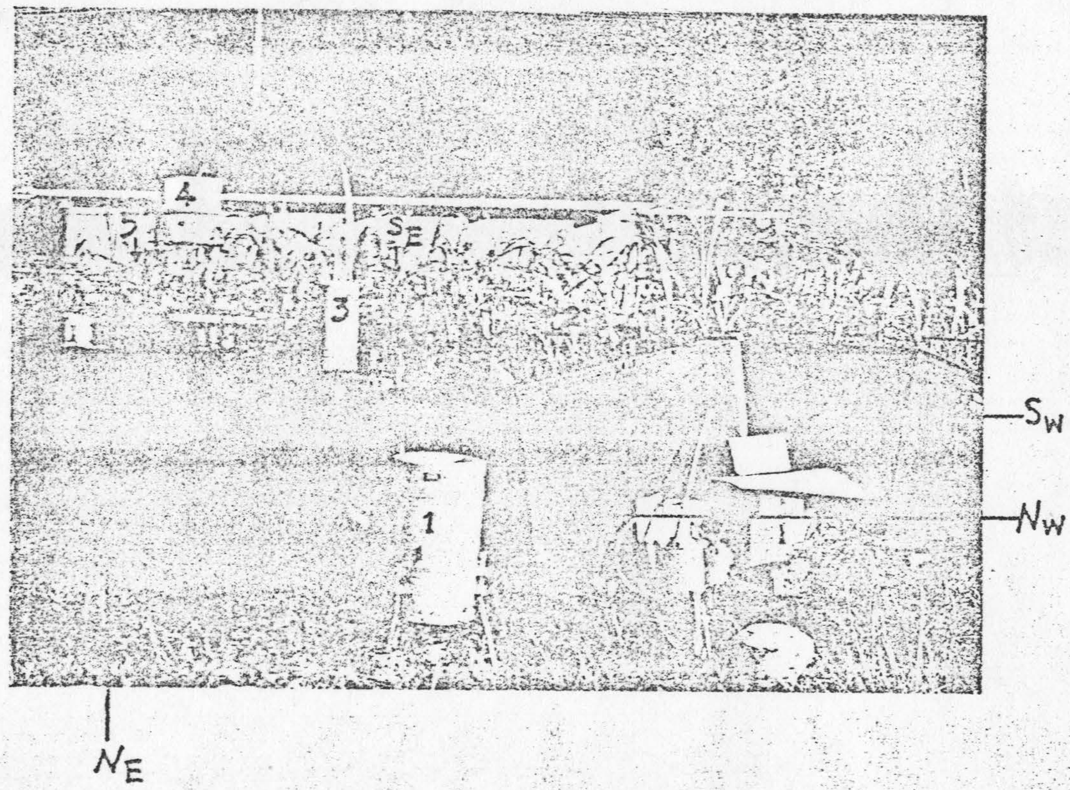


FIGURE 4: PHOTOGRAPH OF THE EXPERIMENTAL INSTALLATION.

$S_E$ = The south-facing lysimeter located on the east side
$S_W$ = The south-facing lysimeter located on the west side
$N_E$ = The north-facing lysimeter located on the east side
$N_W$ = The north-facing lysimeter located on the west side
1 = rain gauge, 2 = drip irrigation lines,
3 = float gauge, 4 = irrigation water tank,
5 = recorders for temperature and radiation

## 3. THEORETICAL EVALUATION OF RADIATION BALANCE FOR THE EXPERIMENT SITE:

### A. SUNSHINE DURATION

Sunshine duration is affected by season, latitude, and slope angle, and aspect so calculation of sunshine duration is complex. Sunshine duration was estimated for the experimental site by Gloynes' method (1965). In this method

$$\text{Sin } F' = \text{Sin } F \text{ Cos } B - \text{Cos } F \text{ Sin } B \text{ Cos } A$$

$$\text{Cos } E = \frac{\text{Cos } B - \text{Sin } F \text{ Sin } F'}{\text{Cos } F \text{ Cos } F'}$$

$$\text{Cos } \theta' = \text{Sin } D \text{ Sin } F' + \text{Cos } D \text{ Cos } F' \text{ Cos } T'$$

Equation 4

All the above terms are defined in List of Symbol Notation and Customary Units (page iX ). When $B = 0^{\circ}$, $F' = F$ and $E = 0^{\circ}$, $\text{Cos } \theta = \text{Sin } D \text{ Sin } F + \text{Cos } D \text{ Cos } F \text{ Cos } T$ is obtained for horizontal surfaces.

Equation 4 is portrayed by the model presented in Figure 10, Appendix II under the assumptions that:

1. The earth is spherical.
2. The difference between solar and sidereal time may be neglected.
3. Refraction by the atmosphere can be ignored.
4. Sun's declination may be regarded as constant on a given date.
5. The mean solar semi-diameter (16') is assumed to be zero.

Setting $\theta$ and $\theta'$ equal to $90^{o}$, which is the moment of sunset or sunrise, T and T' can be calculated by the equations: $T = \mathrm{Cos}^{-1}(-\frac{\mathrm{Sin\ D\ Sin\ F}}{\mathrm{Cos\ D\ Cos\ F}})$ and $T' = \mathrm{Cos}^{-1}(-\frac{\mathrm{Sin\ D\ Sin\ F'}}{\mathrm{Cos\ D\ Cos\ F'}})$. The results are given in Table 17 of Appendix II. The computer program developed for the calculations is given in Appendix III.

B. GLOBAL RADIATION:

Global radiation is the sum of direct radiation (DR for horizontal surface, DR' for slopes) and diffuse radiation (H for a horizontal surface, $H_s$ for slope). Direct radiation was obtained by integrating radiation intensity over 5 minute intervals over sunshine duration. The intensity of direct radiation on a surface is proportional to the angle between the solar beam and the surface. This incident angle depends in turn on the five independent variables latitude, time of day, declination of the sun, surface inclination (slope) and surface orientation (aspect) (Garnier and Ohmura, 1968 and 1970; Williams, et al., 1972; Swift and Knoerr, 1973).

Global radiation (DR') was computed using the equation derived by Garnier and Ohmura (1968). The equation

$$DR' = \frac{I_o}{r_s^2}\int_{T_1}^{T_2} \rho^{m(T)}(-\mathrm{Sin\ F\ Cos\ A\ Sin\ B\ Cos\ D} \cdot \mathrm{Cos\ T} - \mathrm{Sin\ T\ Sin\ A\ Cos\ B\ Cos\ D} + \mathrm{Cos\ F\ Cos\ T\ Cos\ B\ Cos\ D} + \mathrm{Cos\ F\ Cos\ A\ Sin\ B\ Sin\ D} + \mathrm{Sin\ F\ Cos\ B\ Sin\ D})dT = \frac{I_o}{r_s^2}\int_{T_1}^{T_2} \rho^{m(T)} f(T)dT$$

Equation 5

is based on Garnier's model which is shown in Figure 11 of Appendix II. All terms in the equation are defined in the List of Symbol Notation and Customary Units on page iX.

$I_o$ is 1.94 langleys$\cdot$min$^{-1}$ in this study rather than 1.95 langleys$\cdot$min$^{-1}$ used by Garnier and Ohmura.[1] A has the same meaning as in Equation 4, but A is obtained according to the generating model in Appendix II, A of Equation 5 = $180^o$-A of Equation 4. $T_1$, $T_2$ and dT are sunrise, sunset and hour angle intervals respectively during the 5 minute integration intervals. Sample results of calculated direct radiation are listed in Table 18 of Appendix II.

Although diffuse radiation from scatter is generally isotropic, reflected radiation from clouds can be anisotropic and its relationship to solar elevation, azmith, slope degree and aspect is complex (Robinson, 1966, p. 121).

Diffuse radiation (Scatter + reflection) incident on a sloping surface therefore is computed by the equation:

$$Hs = H \, Cos^2 \frac{B}{2} \qquad \text{Equation 6a}$$

The ratios $\frac{Hs}{H}$ shown in Table 19 of Appendix II are approximately identical when topographic variations are small as they would be for a 20% ($11^o9'$) slope. This conclusion was supported by Geiger (1965, p. 375). Estimation of H is given by the following equation (List, 1966, p. 420; attributed to Fritz):

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[1]Since 1971, the Standard solar constant value is accepted 1.94 langley min$^{-1}$. (Tkekaekara and Drumond, 1971; Tkekaekara, 1973).

$$H = 0.5\ ((1 - Aw - Ao)I_t - I_h \qquad \text{Equation } 6b^2$$

The definitions and units of the terms are given in the Table of Symbols (page iX ). Aw is assumed to be 7% and Ao is assumed to be 2%. It can be expressed by $I_t = \frac{I_o}{s^2}(\text{Cos D Cos F Cos T} + \text{Sin D Sin F})$. $I_h$ is direct radiation (=DR). All terms have the same meaning as was given previously. Therefore, diffuse radiation on a sloping surface is calculated by the equation:

$$H_s = 0.5(0.91 \frac{I_o}{rs^2} \int_{T_1}^{T_2} (I_t - I_h))\text{Cos}^2\frac{B}{2}$$

Equation 6c

Angot's value ($I_t$) and the calculated diffuse radiation for the experiment site are given respectively in Tables 20 and 21 of Appendix II. The global radiation, for clear sky condition is given in Table 22 of Appendix II.

C. THE REFLECTED RADIATION (-R or-R')

Reflectance of global radiation from the red Hawaiian soils is very low (0.10) because of the high iron oxide content. As the cane canopy increases, the reflectance increases until it reaches about 0.20 for a full canopy (Ekern, 1965). Therefore, 0.17 is adapted for this evaluation in consulting with Table 23, Appendix II. R is obtained from 0.17x(H + DR) for a horizontal surface and R' is obtained

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[2]Williams, et al. (1972) mistook this expression in their Equation 4 because

(1) Eliminate 0.5, half downward only counted, and
(2) Cos $Z_s$ should not be same between horizontal plane and slope surface.

from $0.17x(Hs + DR')$. A sloping surface may receive an additional amount of solar radiation due to reflection from surfaces adjacent to the sloping surface. However this component is ignored here.

D. REDUCTION IN RADIATION RECEIPT DUE TO ADJACENT OBSTACLES

An isolated and infinitely elongated slope is rarely found under natural conditions. However, when such features do influence the radiation regime, as was the case for this experiment, it may then be necessary to consider such features in radiation calculations. For this experiment site, the shading effect (SE) on radiation receipt was considered as presented in Figure 12 and Equation 8 of Appendix II.

The effect of cloud cover was evaluated by estimating the reduction in hours of sunshine due to the presence of clouds. Where cloud cover is complete with zero hours of sunshine, the fraction of sunlight received is 0.2 and conversely, the reduction in light is 0.8 (Dr. P. C. Ekern, personal communication). If cloud cover averages 0.5 on a clear day, the reduction in radiation would be 0.5 x 0.8, or 0.4. Cloudiness was estimated from the data given in Table 24 (Ekern, 1965), Appendix II, and the reduction in direct radiation due to clouds was presented in Table 25, Appendix II for December 21 and March 21.

The summation of the factors DR' (or DR), Hs (or H), -R, -SE, and -CF which were considered in sub-sections A through D results in the net shortwave radiation. Another aspect of solar radiation is net longwave radiation.

E. NET LONGWAVE RADIATION

Idso and Jackson (1969) stated that the clear atmospheric thermal radiation, $S\downarrow$ , integrated over all wavelengths, can be specified solely in terms of the screen level air temperature T and the Stefan-Boltzman constant, $\delta$, as

$$S\downarrow = \delta Ta^4(1 - 0.261 \,\mathrm{Exp}(-7.77 \times 10^{-4}(273 - Ta)^2)).$$

The above equation is valid at all latitudes and seasons. Applying this result, thermal longwave radiation ($S\downarrow$ ) from the sky was 551 langleys$\cdot$day$^{-1}$ on December 21, when the measured temperature was 19.5 C and 578 on March 21 when the temperature was 21.5 C.

Outgoing longwave radiation ($-L\uparrow$ ) was computed directly by the Stefan-Boltzman equation, $L\uparrow = \varepsilon\delta Ts^4$, where Ts is the surface temperature of the ground, $\delta$, a constant, and $\varepsilon$, the effective emissivity of the ground surface (Table 26, Appendix II). The estimated values were -775 and -797 langleys$\cdot$day$^{-1}$ for December 21 and March 21 respectively.

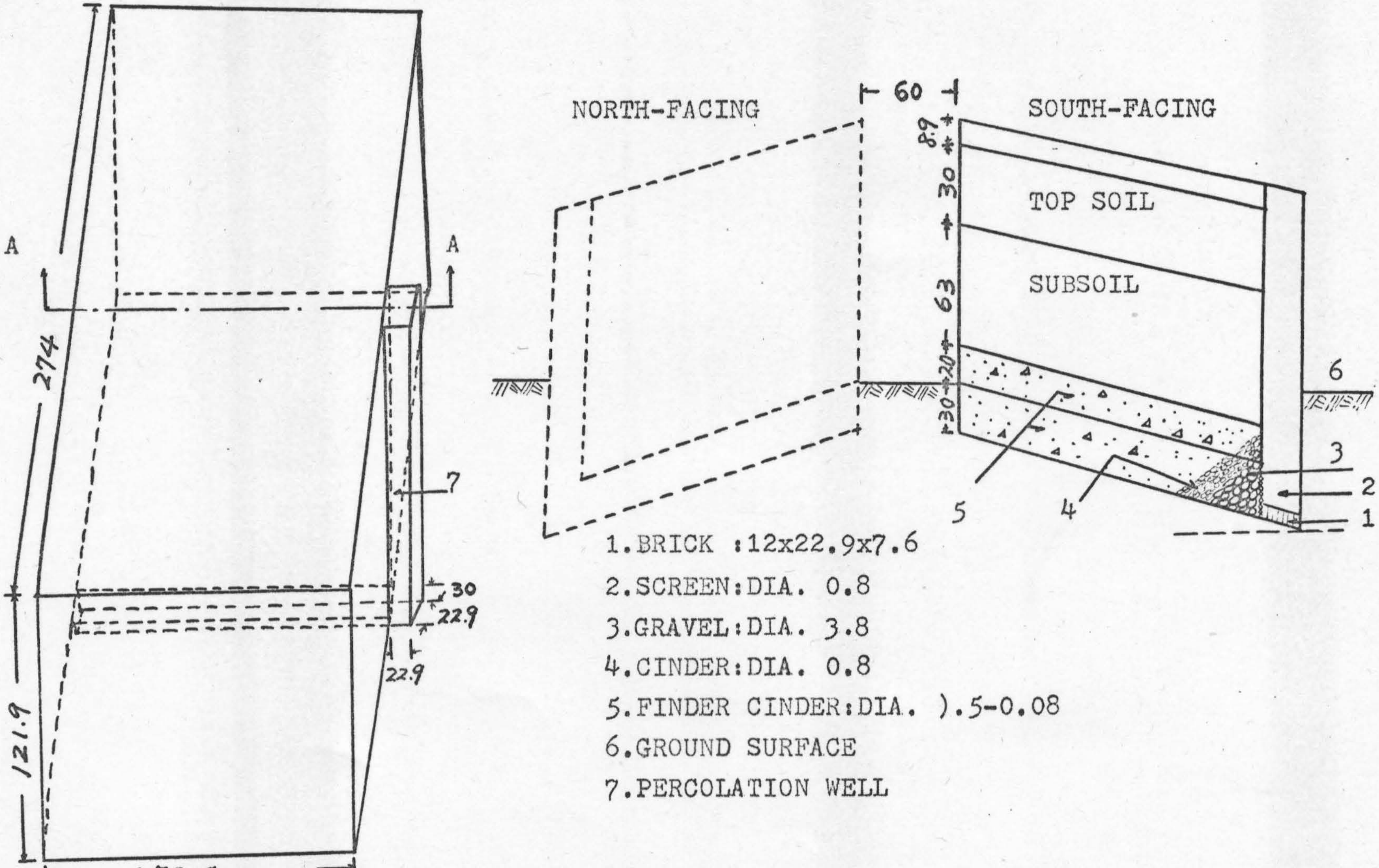
The summation of $S\downarrow$ and $-L\uparrow$ is the net longwave radiation. With a cloudiness factor of 0.5 and the appropriate Kw value for cloud type (Budyko, 1956, Table 27, Appendix II) in the Brunt's equation (Budyko, 1956), the net longwave radiation under cloudy conditions was calculated by Brunt's equation to be -181 and -184 langleys$\cdot$day$^{-1}$ for December 21 and March 21 respectively.

Net radiation was obtained from the summation of net longwave and net shortwave radiation.

4. DESCRIPTION OF THE LYSIMETER DESIGN AND SOIL CHARACTERISTICS

Four lysimeters, 5 feet x 9 feet x 4 feet deep (153.4 cm x 121 cm x 121.9 cm) were installed above ground at the experiment site (Figure 5). North- and south-facing slopes of 20% (11°9') were established by blocking the lysimeters at the proper angle. The lysimeters were the filled-in drainage type. The lysimeters were filled with Lahaina soil (Clayey, Kaolinitic, Isohyperthermic, Typic Torrox) which is predominately used for the culture of sugarcane.

The soil was tamped to simulate field conditions. The soil used for this experiment was moved from an area within the Mililani Sewage Treatment Plant (21°25'49" N--158°1'3" W). The surface layer was dark reddish brown and the apparent field texture was silty clay with a depth of about 35 cm. The available water holding capacity was about 1.3 inches per foot (=0.11 cm/cm of soil) for the subsoil and 1.4 inches per foot (=0.12 cm/cm of soil) for the top soil. The volumetric water holding characteristics of this soil, analyzed by directly sampling from the lysimeters (0-26 cm), are shown in Table 2. Information on the water holding characteristics of the soil is useful for calculating soil heat flux and permits the estimation of soil moisture content




(a) DIMENSION

(b) PROFILE A-A

FIGURE 5: LYSIMETER (CM).

TABLE 2

VOLUMETRIC WATER HOLDING CHARACTERISTICS OF LAHAINA SOIL.

| Lysimeter Aspect | Depth (cm) | Water Content, % by Vol. Saturation (0) | Water Tension 50 cm | 100 cm | 150 cm | 200 cm | 250 cm | Particle** Density $gm \cdot cm^{-3}$ | O.M.*** by Vol. | Mineral, % by Vol. |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 - 3 | 68.1 | 46.9 | 44.5 | 43.4 | 42.5 | 42.3 | 2.90 | 4.97 | 17.95 |
| | 4.5 - 7.5 | 65.3 | 48.0 | 44.6 | 42.4 | 41.5 | 41.2 | 2.91 | 2.86 | 20.98 |
| | 9.0 - 12.0 | 58.6 | 42.8 | 40.3 | 39.4 | 38.0 | 37.6 | 2.90 | 2.01 | 33.30 |
| S | 13.5 - 16.5 | 55.5 | 44.2 | 42.4 | 41.3 | 40.8 | 40.8 | 2.90 | 2.20 | 28.37 |
| | 18.0 - 21.0 | 55.1 | 42.6 | 38.9 | 37.8 | 36.9 | 36.1 | 2.91 | 1.29 | 29.56 |
| | 22.5 - 25.5 | 58.9 | 46.7 | 44.4 | 42.4 | 39.6 | 38.8 | 2.89 | 1.32 | 26.92 |
| | mean | 58.6 | 45.2 | 42.5 | 41.1 | 39.9 | 39.5 | 2.90 | 2.28 | 26.17 |
| | 0 - 3 | 67.0 | 45.2 | 42.6 | 40.1 | 39.0 | 38.3 | 2.90 | 4.5 | 19.17 |
| | 4.5 - 7.5 | 64.6 | 45.0 | 42.8 | 40.3 | 38.2 | 37.8 | 2.91 | 3.7 | 21.65 |
| | 9.0 - 12.0 | 66.0 | 43.6 | 40.9 | 38.5 | 36.0 | 35.3 | 2.90 | 5.0 | 18.35 |
| N | 13.5 - 16.5 | 55.9 | 40.6 | 38.9 | 36.1 | 33.8 | 33.0 | 2.89 | 1.1 | 28.99 |
| | 18.0 - 21.0 | 57.7 | 42.4 | 40.0 | 38.1 | 37.3 | 36.5 | 2.90 | 1.5 | 27.91 |
| | 22.5 - 25.5 | 55.2 | 45.7 | 41.5 | 39.9 | 38.0 | 37.6 | 2.90 | 1.6 | 29.42 |
| | mean | 61.1 | 43.8 | 41.1 | 38.8 | 37.1 | 36.4 | 2.90 | 2.5 | 24.25 |
| | Total mean | 59.9 | 44.5 | 41.8 | 40.0 | 38.5 | 38.0 | 2.90 | 2.39 | 25.21 |

*Determined by Tempe meters, sampling cores have diameter 5.4 cm and height 3 cm (V = 68.7 $cm^3$).
**The volume of organic matter was determined by: Volume of organic matter = core volume - water volume - mineral volume.
***Organic matter (O.M.) of soil was removed by 6% $H_2O_2$.

from tensiometer reading.

5. SUGARCANE VARIETY:

The sugarcane variety H59-3775 grown on the lysimeters is a high-sucrose cane having resistance to smut, red rot, eye spot, leaf scald, and pineapple disease. It is tolerant to the stalk weevil and to herbicides. It has a positive response to chemical ripeners. It grows well in leeward, windward or wet Hilo coast areas (Anon., 1973).

The cane setts were provided by the H.S.P.A., Kunia substation. Average weight per one-eye sett was 123 grams, but weights ranged from 78 to 172 grams. The mean length was 15 cm and ranged from 10.5 cm to 21.5 cm. The diameter ranged from 2.5 cm to 3.0 cm.

The planting of sugarcane setts was done on December 26, 1975 by two individuals to exclude possible experimental bias. The planting depth was maintained at 6 cm. A dense planting on a one foot grid was made, resulting in 45 setts per lysimeter.

6. INSTRUMENTS AND MEASUREMENTS:

A. Rainfall (RR) was measured by a tipping bucket recording rain gauge with a 12" (30.5 cm) opening. Each tip was calibrated as 0.013" of rainfall.

B. Irrigation (I) was supplied by gravity feed through 2 drip lines on each lysimeter with an opening at each cane stool. A water tank with 196.5 liters water, provided 4.71 cm for each lysimter (5.06 cm/100 cm of soil). Lysimeters were irrigated so that tensiometer readings were never greater than 0.25 bars.

C. Percolation water (PP) was pumped out and the amount recorded. The percolating water level was monitored by float gauges to prevent too much water from accumulating in the percolation well.

D. Soil water was measured with a tensiometer set at 15.2 cm depth in each lysimeter and the tensiometer was used as a guide for irrigation management.

E. RADIATION

Global radiation was measured by silicon cells (4 cells) set parallel to the slopes so that the ratio of radiation measured on north- and south-facing slopes could be obtained. Net radiation was sampled on several days from the south-facing slope only using a Thornthwaite net radiometer with a calibration factor of 3.08 $mV/langley \cdot min^{-1}$ (Fritschen, 1965).

F. TEMPERATURE AND SOIL HEAT FLUX

Soil temperature was measured using both a horizontal and vertical grid system. Horizontal measurements were made primarily at the 2.5 and 7.5 cm depth while vertical measurements were made at depths to 27 cm. Glass thermometers, thermocouples, and thermisters were used. In one case soil temperature profiles were measured at intervals of 3 cm up to 27 cm. In another case spacing was 1.5 cm and the data were used for evaluating soil heat flux. In applying this data in soil heat flux calculations, the data were smoothed by the method of Kimball (1974 and 1976a) and the null-alignment method was used because of its simplicity in experimental performance (Kimball, et al., 1975, 1976b and 1976c).

G. PLANT MEASUREMENTS

The following data were collected on the cane plants:

(i) Germination - Date of emergence from the soil of the primary and secondary tiller was recorded.

(ii) Number of tillers was counted weekly for all plants.

(iii) Height of total plant (stalk + leaf) and number of leaves were recorded monthly for all plants.

(iv) Height of top visible dewlap (TVD) of primaries was recorded weekly during March.

(v) Final green weight of the above ground portions of each stool was measured on March 25, 1976 and selected samples were used to evaluate the dry weight.

(vi) Leaf area was measured with a LI-COR (model LI-3000) portable area meter (Lamboa Instruments Corporation, Nebraska).

7. Fertilizer was applied on January 8 (500 lb/A with an N-P-K ratio of 5-10-10), January 22 (Urea, 500 lb/A), and February 25 (1000 lb/A of 5-10-10). The total N-P-K applied was 300-150-150 lb/A.

# CHAPTER IV

## RESULTS

The germination period was from planting date, December 26, 1975 to January 26, 1976. After germination, the tillering and elongation of sugarcane stalks were observed. Data collected on cane growth and development included germination count, first tiller date, tiller count, height of stalk, height of top visible dewlap (TVD) and number of green leaves on primaries. Final observation made on March 25 and 26, 1976 included leaf area (and leaf area index), fresh weight and dry weight of representative samples.

In the first three weeks, soil temperature measurements at 2.5 and 7.5 cm showed less than a 0.5 C difference at positions more than 30 cm from the side wall of all lysimeters. The effect of border heat was significant within 30 cm from side wall of all lysimeters. Accordingly, data collected on sugarcane growing in this position was considered separately from data for the central area of the lysimeter.

The intervals of water use were based on the soil moisture condition and computation convenience rather than the calendar months. This approximately coincided with the growth status described in Section 4 of this chapter.

Sections 1, 2 and 3 describe the early growth parameters of sugarcane. Section 4 treats the water balance. Sections 5 and 6 are concerned with the heat and radiation balance. Section 7 presents the relationship between climatic factors and sugarcane growth. The results in Section 7 were obtained from the second interval (January 25 to February 24). It probably was representative of this experiment.

1. GERMINATION:

Germination was first observed on January 5 (10 days after planting). Germination rates for the whole and the central area of lysimeters are shown in Figures 13a and 13b, respectively. Setts in south-facing lysimeters germinated earlier than those in north-facing lysimeters by 3 days at 50 and 90 percent germination. Each lysimeter had 98 percent germination, i.e., 44 out of 45 setts on January 26. Table 3 shows average germination counts per 5 days and $X^2$ test for slope pair lysimeters. The detailed data for each slope pair and each location pair are given in Table 31, Appendix IV. The difference between north- and south-facing lysimeters was highly significant for the whole lysimeter, but only significant for the central area of the lysimeter.

TABLE 3

GERMINATION COUNT PER 5 DAYS AND $X^2$ TEST.

| Area observed | Slope[a] | Days after planting 10 | 15 | 20 | 25 | 30 | $X^2$ value |
|---|---|---|---|---|---|---|---|
| Whole lysimeter | $\bar{N}$ | 0.5 | 6.5 | 26.5 | 10 | 0.5 | |
| | $\bar{S}$ | 0 | 19 | 21 | 3 | 1 | 11.2002** |
| Edge plants excluded | $\bar{N}$ | | 0 | 13.5 | 6.5 | 0.5 | |
| | $\bar{S}$ | | 6 | 12 | 2 | 0 | 8.9706* |

[a]$\bar{N}$ and $\bar{S}$ are averages for north- and south-facing lysimeters, respectively.

*Significant at 5%.

**Highly significant at 1%.

2. TILLERING:

The first tillering was initially observed on February 14 (50 days after planting) and additional data are presented in Figure 14a and 14b of Appendix IV. Fifty percent emergence of the first tiller occurred 2 weeks earlier on the south- than on the north-facing lysimeters. Rates of emergence of first tiller per 5 days and $X^2$ test are presented in Table 4. The detailed data for each slope pair and each location pair are given in Table 32, Appendix IV. Significant differences were found between the north- and south-facing slopes for the central area, and highly significant differences were found for whole lysimeter.

3. EARLY GROWTH:

Number of leaves, number of tillers, height of top visible dewlap (TVD) and height of stalks for all plants and for central plants only are presented in Figure 6. The effect of slope on the growth parameters was not statistically significant (Table 5, 6, 7, and 8). The detailed data for each pair and each location is given in Table 33, 34, 35 and 36, Appendix lV. Plants in the south-facing slope produced a given number of leaves,(i.e. 5, 6, etc.) 10 days earlier than those on the north-facing slopes (Figure 6a). Tiller counts and stalk heights observed on the south-facing lysimeters were about 7 days ahead of those on the north-facing slopes (Figures 6b and 6c). The difference in height of TVD in the two aspects was linearly time-dependent during the

TABLE 4

THE RATES OF EMERGENCE OF FIRST TILLER PER 5 DAYS AND $X^2$ TEST

| Area observed | Slope | Days after planting | | | | | | | | | $X^2$ value |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 51 | 56 | 61 | 66 | 71 | 76 | 81 | 86 | 91 | |
| Whole lysimeter | $\bar{N}$ | 0 | 0 | 2 | 5 | 5 | 11 | 6.5 | 4 | 5 | |
| | $\bar{S}$ | 0.5 | 3 | 9 | 1.3 | 9.5 | 4 | 1.5 | 0.5 | 2 | 23.3063** |
| Edge plants excluded | $\bar{N}$ | | 0 | 0 | 0 | 1.5 | 6 | 3 | 2 | 4 | |
| | $\bar{S}$ | | 0.5 | 3 | 6.5 | 5.5 | 2 | 1.5 | 0 | 1.5 | 17.9221* |

**Highly significant at 1%.
*Significant at 5%.

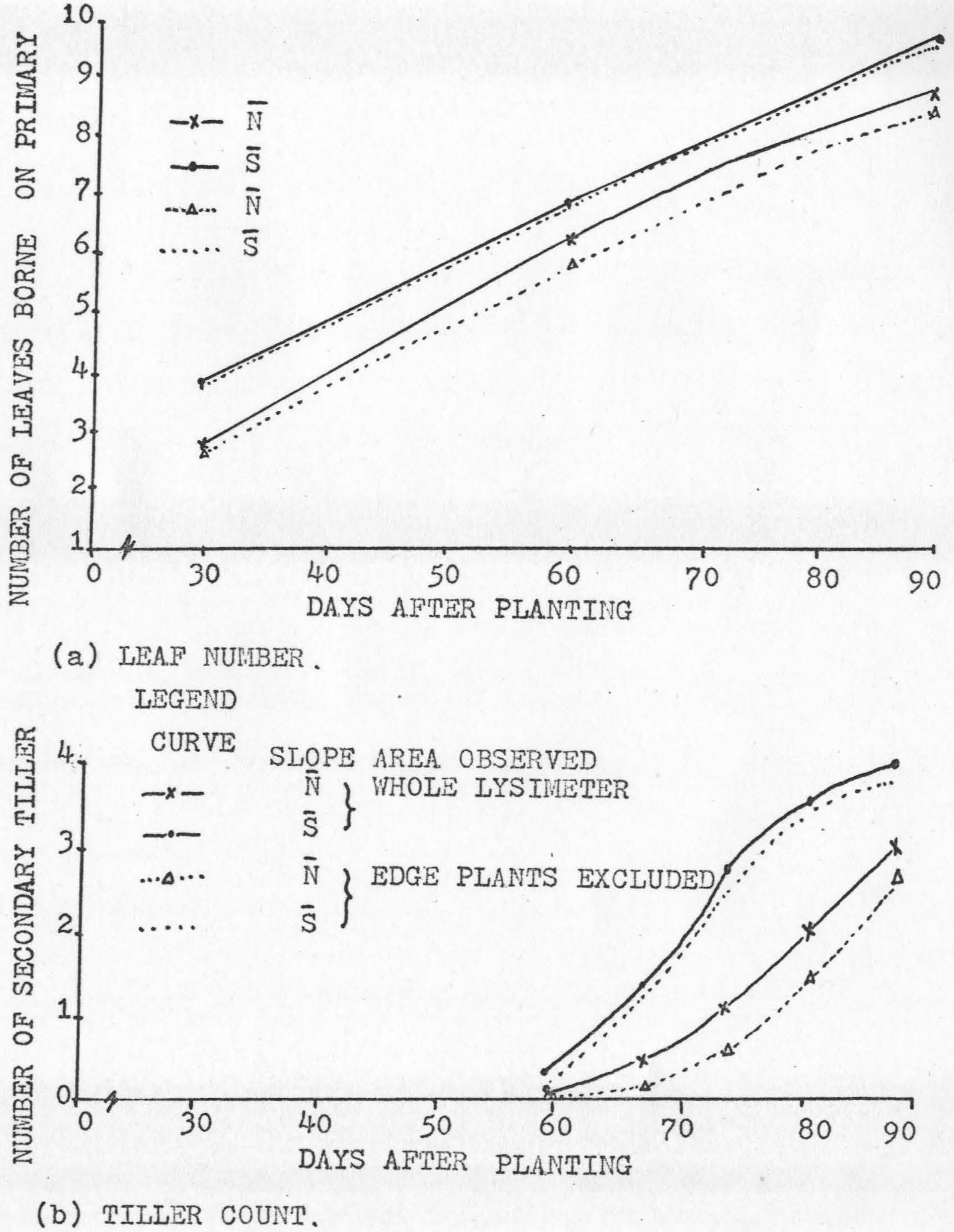
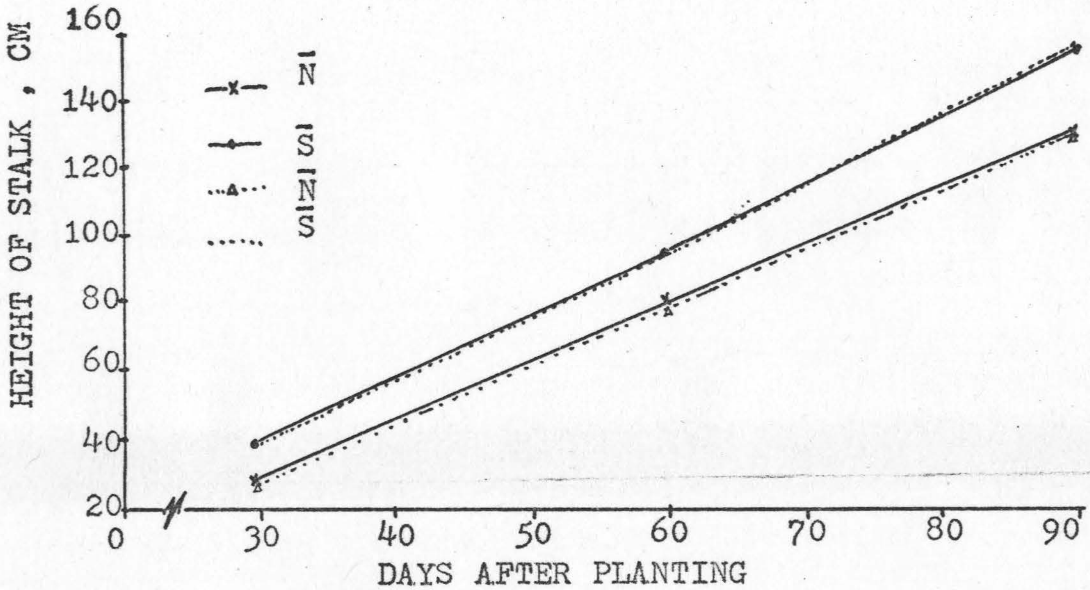
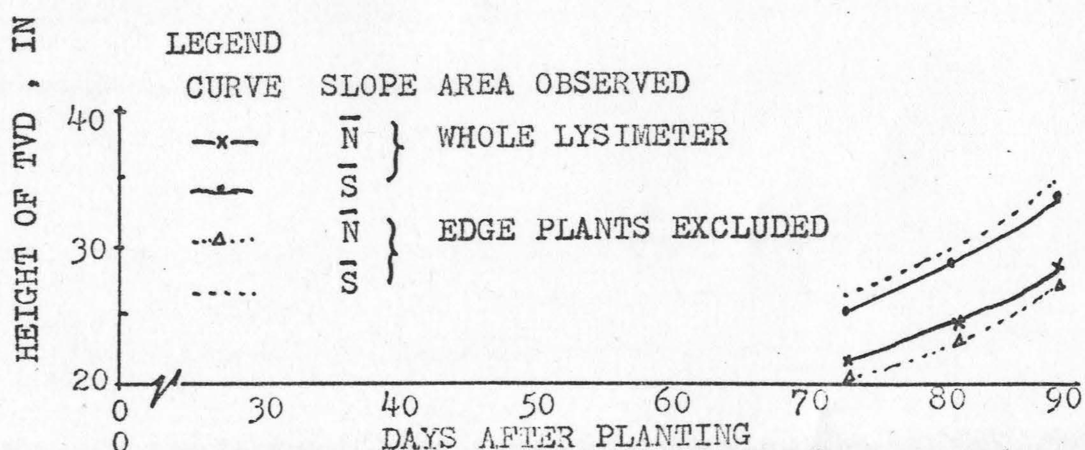



FIGURE 6: COMPARISON OF EARLY GROWTH PARAMETERS BETWEEN NORTH- AND SOUTH-FACING SLOPES.




(c) STALK HEIGHT.




(d) HEIGHT OF TOP VISIBLE DEWLAP (TVD).

FIGURE 6: COMPARISON OF EARLY GROWTH PARAMETERS BETWEEN NORTH- AND SOUTH-FACING SLOPES.

TABLE 5

MONTHLY INCREMENT OF NUMBER OF LEAVES PER PLANT AND $X^2$ TEST.

| Area observed | Slope | Days after planting 30 | 60 | 88 | $X^2$ value |
|---|---|---|---|---|---|
| Whole lysimeter | $\bar{N}$ | 2.85 | 3.3 | 2.3 | |
| | $\bar{S}$ | 3.75 | 3.1 | 2.7 | $0.0672^{NS}$ |
| Edge plants excluded | $\bar{N}$ | 2.75 | 3.05 | 2.45 | |
| | $\bar{S}$ | 3.7 | 3.05 | 2.6 | $0.0688^{NS}$ |

NS: Non-significant.

TABLE 6

WEEKLY TILLERING RATE PER PLANT AND $X^2$ TEST.

| Area observed | Slope | Days after planting 60 | 67 | 74 | 81 | 88 | $X^2$ value |
|---|---|---|---|---|---|---|---|
| Whole lysimeter | $\bar{N}$ | 0.0 | 0.2 | 0.8 | 0.7 | 1.0 | $0.1360^{NS}$ |
| | $\bar{S}$ | 0.3 | 1.05 | 1.4 | 0.6 | 0.6 | |
| Edge of plants excluded | $\bar{N}$ | 0.0 | 0.1 | 0.4 | 0.7 | 1.15 | $0.2113^{NS}$ |
| | $\bar{S}$ | 0.15 | 0.8 | 1.5 | 0.8 | 0.4 | |

NS: Non-significant.

TABLE 7

MONTHLY INCREMENT OF HEIGHT OF STALK PLUS LEAF (CM/MONTH) AND $X^2$ TEST.

| Area observed | Slope | Days after planting 30 | 61 | 91 | $X^2$ value |
|---|---|---|---|---|---|
| Whole lysimeter | $\bar{N}$ | 30.3 | 54.3 | 47.7 | $1.3900^{NS}$ |
| | $\bar{S}$ | 40.8 | 52.7 | 58.9 | |
| Edge plants excluded | $\bar{N}$ | 29.7 | 49.8 | 52.2 | $1.5364^{NS}$ |
| | $\bar{S}$ | 40.3 | 516 | 60.7 | |

NS: Non-significant.

TABLE 8

WEEKLY INCREMENT OF HEIGHT OF TOP VISIBLE DEWLAP (IN /WEEK) AND $X^2$ TEST.

| Area observed | Slope | Days after planting $74^a$ | 81 | 88 | $X^2$ value |
|---|---|---|---|---|---|
| Whole lysimeter | $\bar{N}$ | 3.15 | 3.2 | 4.25 | $0.4290^{NS}$ |
| | $\bar{S}$ | 3.78 | 3.7 | 4.6 | |
| Edge plants excluded | $\bar{N}$ | 2.96 | 3.25 | 5.40 | |
| | $\bar{S}$ | 3.96 | 3.90 | 4.95 | $1.0479^{NS}$ |

NS: Non-significant.
a.: The weekly increment from 74 days after planting is obtained from the measured cumulative value at 74 days divided by 7.

last 3 weeks of the growth period for the whole lysimeter, and the linear regression coefficient was significant at the 10% level, while for central area the regression coefficient was significant at the 5% level (Table 9).

At 74 days plants on the south-facing slopes were 26.4 inches while those on the north-facing slopes were 22.1 inches. At 88 days plants on the south-facing slopes were 34.8 inches while those on the north-facing slopes were 29.5 inches. This indicates that plants on the north-facing slopes grew more slowly than those on the south-facing slopes (Figure 6d). Although these differences in height between north- and south-facing slopes are small, they were still significantly correlated with age of crop (Table 9).

Final observations on stool fresh weight, leaf area (LAI also) and cumulative height of the top visible dewlap are given in Table 10. All three indices showed that growth of cane on the south-facing lysimeters was superior to that on the north, but differences were statistically significant only for the TVD comparison between all plants on the north- and south-facing lysimeters. Stool fresh weight on the north-facing slope was 63% of that on south-facing lysimeters. Stool accumulative height on the north-facing slopes was about 54% of that on the south-facing lysimeters. Stool leaf areas on the north-facing slopes were 92.3% and 55.7% of those on the south-facing slopes for whole lysimeters and central plants, respectively.

TABLE 9

LINEAR REGRESSION EQUATION FOR THE GROWTH DIFFERENCE

BETWEEN NORTH- AND SOUTH-FACING SLOPES WITH TIME.

| Growth parameter, Y | Area[a] observed | Linear regression equation | r value |
|---|---|---|---|
| Increment of leaf number | A | Y = 0.83748 - 0.00007 day | r = 0.019[NS] |
| | B | Y = 0.98376 - 0.00085 day | r = 0.856[NS] |
| Increment of tiller number | A | Y = -1.66418 + 0.03357 day | r = 0.78202[NS] |
| | B | Y = -2.51254 + 0.05071 day | r = 0.71328[NS] |
| Increment of stalk height | A | Y = 3.75618 + 0.15292 day | r = 0.7755[NS] |
| | B | Y = 4.42738 + 0.16823 day | r = 0.93278[NS] |
| Increment of top visible dewlap | A | Y = -0.06751 + 0.06071 day | r = 0.99484[△] |
| | B | Y = 0.72415 + 0.08571 day | r = 0.9988* |

[a]A = whole lysimeter, B = edge plants excluded.

*Significant at 5%.

[△]Significant at 10% significant level.

TABLE 10

EFFECTS OF SLOPE ON GROWTH PARAMETERS PER STOOL OF SUGARCANE AFTER THREE MONTHS GROWTH

| Growth parameter | Area harvested[a] | Lysimeter $S_W$ | $S_E$ | $N_W$ | $N_S$ | t-test (paired t) | Ratio of $\overline{N}/\overline{S}$ |
|---|---|---|---|---|---|---|---|
| Stool fresh weight (gm) | A | 237.6 | 244.8 | 120.6 | 189.8 | 2.77[NS] | 62.6 % |
| | B | 226.5 | 245.6 | 94.0 | 202.3 | 1.98[NS] | 62.8 % |
| Stool leaf area ($cm^2$) | A | --- | 1956.6(2.1)[Δ] | --- | 1805.4(1.9)[Δ] | --- | 92.3 % |
| | B | --- | 2537.8(2.7)[Δ] | --- | 1413.1(1.5)[Δ] | --- | 55.7 % |
| Stool accumulative height of top visible dewlap (cm) | A | 4640.2 | 4076.7 | 2435.5 | 2424.4 | 6.97** | 55.8 % |
| | B | 2086.5 | 1749.4 | 870.7 | 1146.2 | 2.98[NS] | 52.6 % |

[a]A = whole lysimeter, B = edge plants excluded.

[Δ]LAI values.

**Highly significant at 1% (>6.314).

[NS]Nonsignificant.

4. WATER USE IN LYSIMETERS:

In order to separate water components (especially percolation, irrigation, runoff and soil moisture) to avoid any disturbance in computation of water use of lysimeters, the experimental period could be separated into 3 intervals - from December 26, 1975 to January 24, 1976, i.e., from 0 to 30 days after planting, from January 25 to February 24, 1976, or 31 to 60 days after planting and from February 25 to harvest, or 61 to 91 days after planting (Table 29). The water use ($\int ET$) for each interval was calculated as $\int ET = RR + I - PP$ (derived from Equation 1a, page 22). That is to say, water use for a lysimeter for an interval (about 30 days) was obtained by subtracting percolation (PP) from the sum of rainfall (RR) and irrigation (I). Table 11 shows water use for different time intervals (detailed data are presented in Table 29, Appendix IV). Water consumption during the last interval was slightly less than in the previous intervals. The possible contributors could be temperature, wind, nature and cover of soil, solar radiation energy, advection and soil moisture conditions (Veihmeyer, 1964). This experiment did not have enough data for discussion or evaluation of above factors. The difference of water use between north- and south-facing slopes is small enough to be ignored (at maximum 0.04 $cm \cdot day^{-1}$).

TABLE 11

WATER USES FOR DIFFERENT PERIODS BY EARLY SUGARCANE ($CM \cdot DAY^{-1}$).

| Interval (days from planting) | | 0-30 | | 31-60 | | 61-88 | |
|---|---|---|---|---|---|---|---|
| $N_E$ | lysimeter | 0.566 | 0.558+ | 0.558 | 0.554+ | 0.473 | 0.498+ |
| $N_W$ | lysimeter | 0.549 | | 0.550 | | 0.523 | |
| $S_E$ | lysimeter | 0.498 | 0.515+ | 0.588 | 0.585+ | 0.526 | 0.491+ |
| $S_W$ | lysimeter | 0.531 | | 0.582 | | 0.455 | |

+Mean of north- or south-facing lysimeters.

5. TEMPERATURE AND SOIL HEAT FLUX:

Soil temperature at 7.5 cm was measured at 9 sites over each lysimeter in the daytime for the first month (first time interval). There was less than 0.5 C variation among the sites in the central area (29865.6 $cm^2$) of the lysimeter. Soil temperatures at depth of 2.5 cm and 7.5 cm are shown in Table 12. The daily mean temperatures at 2.5 and 7.5 cm were 0.85 and 1.15 C higher, respectively, on the south-facing lysimeters than on the north-facing ones from days 31 to 61. From days 62 to 91, the south-facing lysimeters were 0.2 and 1.0 C higher than the north-facing lysimeters at 2.5 and 7.5 cm depth, respectively.

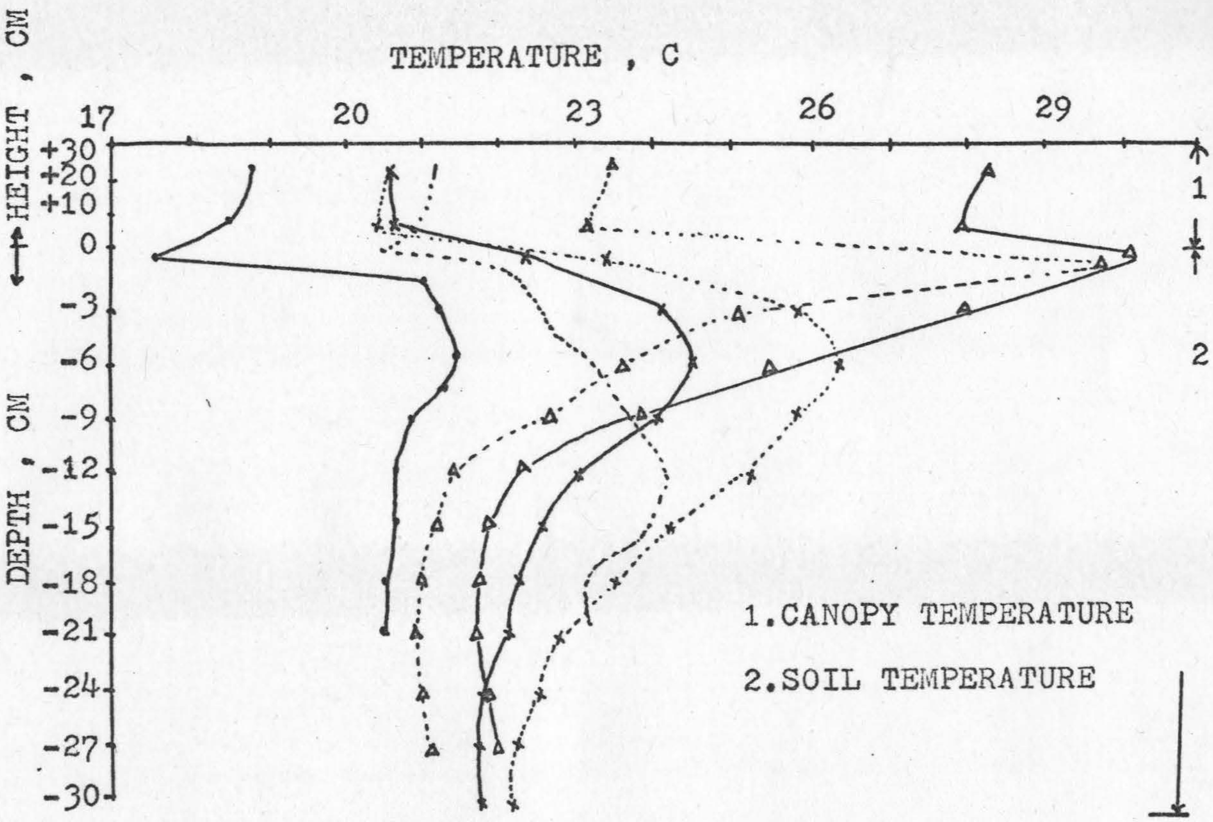
The vertical temperature profiles from 30 cm above the soil to 30 cm in the soil were sampled for selected days (Table 30, Appendix IV). A sample profile is given in Figure 7. Canopy temperature at night above the south-facing slope was warmer than above the north one (February 11), but the order was reversed during the day on 29 February and 20 March. This can be attributed to the growth difference between the two aspects. The denser canopy in the south-facing slope was cooler in the daytime because of a more fully developed leaf canopy, warmer at night because higher solar radiation reached the south-facing slope and there was higher retention of radiant heat. Canopy temperature was higher than the air temperature at 1 meter during the daytime but lower at night. Soil temperature had a minimum at

TABLE 12

SOIL TEMPERATURE (C) FOR NORTH-FACING AND SOUTH-FACING

LYSIMETERS AT DEPTH OF 2.5 CM AND 7.5 CM.

| Interval, days after planting | Depth (cm) | Aspect | Maximum at about 14:00 | Minimum at about 7:00 | Mean | Difference between north and south |
|---|---|---|---|---|---|---|
| 31-61 | 2.5 | N | 27.0 | 17.4 | 22.2 | 0.85 |
| | | S | 28.4 | 17.7 | 23.05 | |
| | 7.5 | N | 26.5 | 17.5 | 22.0 | 1.15 |
| | | S | 27.9 | 18.4 | 23.15 | |
| 62-91 | 2.5 | N | 28.6 | 19.1 | 23.85 | 0.2 |
| | | S | 28.1 | 20.0 | 24.05 | |
| | 7.5 | N | 27.9 | 18.9 | 23.4 | 1.0 |
| | | S | 28.6 | 20.2 | 24.4 | |




LEGEND

| CURVE | SLOPE | TIME | DATE |
|---|---|---|---|
| •—• | N | 2140 | 2/11/76 |
| ..... | S | 2320 | 2/11/76 |
| Δ—Δ | N | 1210 | 3/20/76 |
| Δ···Δ | S | 1220 | 3/20/76 |
| x—x | N | 1650 | 3/20/76 |
| x···x | S | 1655 | 3/20/76 |

FIGURE 7: TEMPERATURE PROFILES AT DIFFERENT TIME FOR NORTH- AND SOUTH- FACING SLOPES.

morning from 5:00 to 7:00 a.m. Soon after sunrise the soil temperature increased rapidly (Table 30, Appendix IV), the soil profile curves shifted to the right (Figure 7). Soil temperature reached a maximum value in the upper layer at about 16:00 (Table 30, Appendix IV). After that, soil temperature curves shifted to the left (Figure 7), and heat was released from the soil. The southern slope apparently was warmer than the northern slope throughout the day. This agreed with the results in Table 12.

The continuous temperature profiles were used to compute the soil heat flux. Because temperature at 21 cm, in most cases, changed little and was expected to have a zero soil temperature gradient above it, i.e., no heat flux downward or upward at the position of the zero soil temperature gradient, the 21 cm depth was taken as the reference depth in computing the soil heat flux. An example of the Null-alignment method of computing soil heat flux is given in Table 28, Appendix IV. A comparison between the north- and south-facing lysimeters in Figure 9 showed that the thermal conductivity of this soil at 21 cm was 0.0689 langleys$\cdot$min$^{-1}$/C$\cdot$cm$^{-1}$ at 40% volumetric water content. This value was obtained from the average of four profiles shown in Figure 8. Figure 8 also showed a higher heat flux downward into the soil on the south- than on the north-facing slope on February 29th, but this was reversed on March 20th. All profiles between 7:00 and 14:00 would have such a reduction in heat

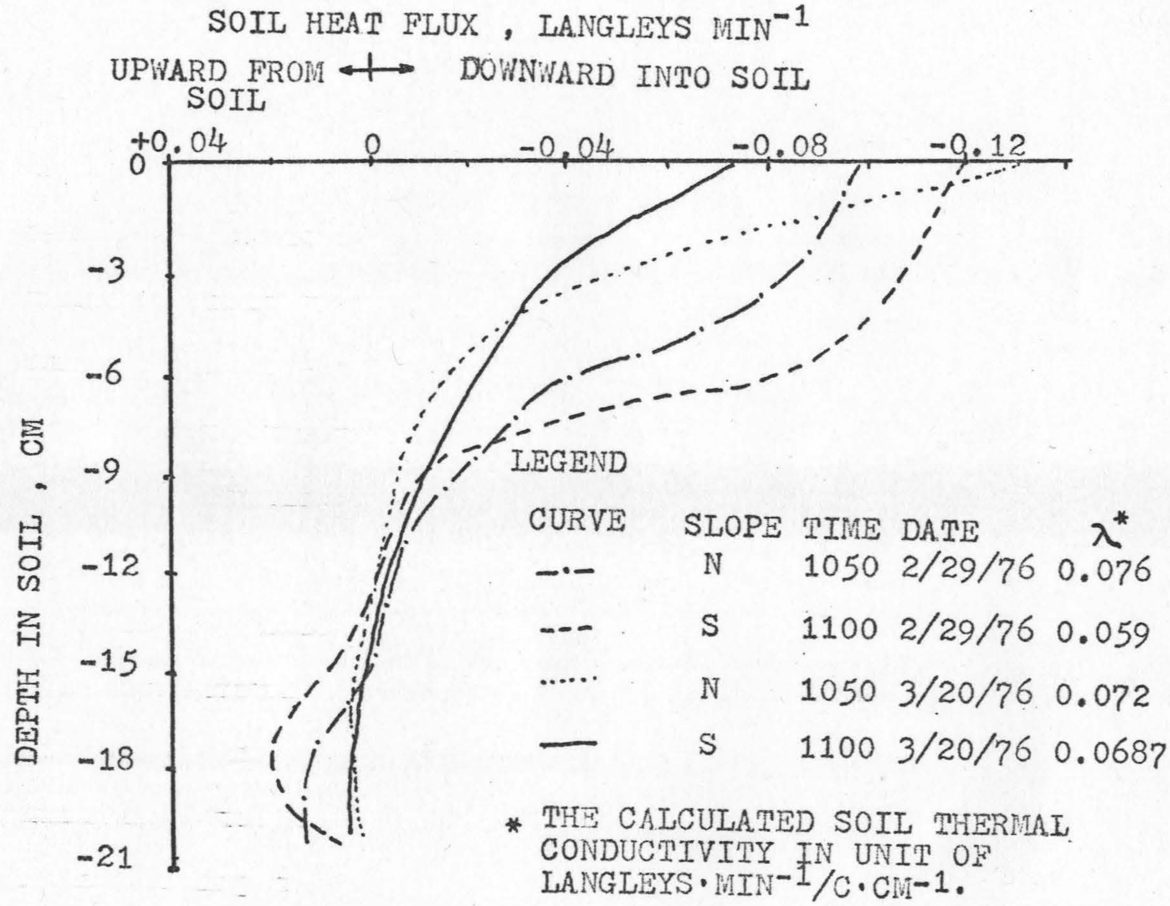



FIGURE 8: SOIL HEAT FLUX PROFILES ,

flux with depth as shown in Figure 8. This was due to the energy consumed to evaporate water and to warm the soil.

6. RADIATION AND HEAT BALANCE:

Mountains running from south-east to north-west with a height of 1,000 feet bordered the experiment site along the south-west and north-east sides (Figure 12a and b, Appendix II). Because of the presence of the mountains, the sky over the experiment site was frequently covered with a layer of orographic clouds. Radiation receipt was also influenced by clouds located above the mountains. Waahila mountain, located just east of the experiment site, shaded the lysimeters in the morning. Direct radiation reached the lysimeters at 9:30 during the first growth interval and at 8:40 later in the experiment (Figure 12b, Appendix II). The reduction of radiation due to shading was estimated as 10 langleys$\cdot$day$^{-1}$ on December 21 and 13 langleys$\cdot$day$^{-1}$ on March 21.

Table 13 gives representative data for 3 days. January 28 was a clear day, January 27 was a clear day with clouds in the early morning (i.e., before 9:30) and March 11 was a cloudy day. The recorded global radiation had maxima of 411.4 and 497.1 langleys$\cdot$day$^{-1}$ for northern and southern slopes, respectively on January 27.

The southern slope generally received higher radiation, especially during early morning and late afternoon. The daily ratio between south- and north-facing global radiation

TABLE 13

GLOBAL RADIATION (LANGLEYS) ON JANUARY 27 AND 28

AND MARCH 11.

| Hour | January 27 | | January 28 | | March 11 | | |
|---|---|---|---|---|---|---|---|
| | N | S | N | S | H* | N | S |
| 6- 7 | 0.1 | 0.1 | 0.1 | 0.1 | 0.5 | 0.1 | 0.1 |
| 7- 8 | 3.0 | 3.8 | 1.7 | 2.1 | 6.1 | 3.8 | 3.9 |
| 8- 9 | 9.9 | 8.7 | 7.0 | 7.2 | 20.1 | 20.3 | 25.1 |
| 9-10 | 36.8 | 44.5 | 24.2 | 28.2 | 28.1 | 25.4 | 39.4 |
| 10-11 | 63.2 | 61.8 | 50.5 | 60.6 | 48.1 | 50.6 | 55.4 |
| 11-12 | 62.1 | 60.1 | 60.0 | 60.6 | 76.1 | 56.9 | 49.1 |
| 12-13 | 60.7 | 59.5 | 60.5 | 60.3 | 32.8 | 28.9 | 22.6 |
| 13-14 | 58.0 | 56.6 | 56.2 | 56.2 | 43.7 | 19.9 | 18.9 |
| 14-15 | 45.0 | 61.5 | 44.0 | 57.0 | 12.6 | 18.4 | 26.6 |
| 15-16 | 29.8 | 57.4 | 30.9 | 54.0 | 11.6 | 15.8 | 17.3 |
| 16-17 | 24.0 | 46.0 | 26.7 | 46.0 | 13.8 | 15.6 | 16.2 |
| 18-19 | 18.0 | 36.3 | 17.0 | 32.4 | 19.6 | 5.2 | 7.3 |
| 18-19 | 0.9 | 0.9 | 1.1 | 1.2 | 1.6 | 0.2 | 0.2 |
| 19-20 | 0.1 | 0.1 | 0.1 | 0.1 | 0.6 | 0.1 | 0.1 |
| sum | 411.4 | 497.1 | 379.8 | 466.0 | 305.3 | 215.7 | 282.0 |

H*Horizontal value at Holmes Hall of Manoa campus, University of Hawaii.

is presented in Table 14. Global radiation on the south-facing slope was estimated to be 4.0 langleys less than the north-facing slope on a day with heavy clouds and 86.1 langleys greater on a clear day. In the growth interval from 25 January to 24 February, global radiation on the south-facing slope was estimated as 30 langleys$\cdot$day$^{-1}$ higher than on the north-facing slope.

Table 15 shows five days of net radiation obtained at the experiment site during February and March. Night time net longwave radiation ranged from -0.019 langley$\cdot$min$^{-1}$ (above the canopy, March 21) to -0.052 langley$\cdot$min$^{-1}$ (within the canopy, February 23). The values were higher (less negative) than those reported previously (-0.15 to -0.25 langley$\cdot$min$^{-1}$ as summarized by Ekern (1965)). This can be attributed to two factors. These were water condensation on the cover of the net radiometer due to inadequate ventilation of the instrument which would cause the sensor to give low readings and possibly due to additional longwave radiation from the nearby mountain slope. The average net longwave radiation from 19:00 to 7:00 (night hours) was adopted as the average net longwave value and daily total net longwave radiation (Table 15) was calculated. No global radiation data were available for these sample dates. Thus, global radiation data was estimated as 0.8 of global radiation measured at Holmes Hall (1 mile south of experiment site, Manoa Campus, University of Hawaii) because the

TABLE 14

DAILY GLOBAL RADIATION RATIO OF SOUTH-FACING TO NORTH-FACING SLOPES AND THE ESTIMATED ADDITIONAL RADIATION RECEIVED ON SOUTH-FACING SLOPES OVER THAT RECEIVED ON NORTH-FACING SLOPES.

| Date[a] | Daily global radiation ratio south/north | Additional radiation received by south-facing slopes[b], $langley \cdot day^{-1}$ |
|---|---|---|
| 23 J | 1.125 | 41.0 |
| 24 J | 1.118 | 36.3 |
| 25 J | 1.081 | 25.1 |
| 26 J | 1.180 | 66.0 |
| 27 J | 1.208 | 85.7 |
| 28 J | 1.227 | 86.1 |
| 29 J | 1.143 | 51.3 |
| 30 J | 1.095 | 26.1 |
| 31 J | 1.253 | 51.6 |
| 1 F | 1.048 | 16.2 |
| 2 F | 1.095 | 31.0 |
| 4 F | 1.076 | 25.2 |
| 7 F | 0.995 | -1.0 |
| 8 F | 1.056 | 10.0 |
| 9 F | 1.041 | 5.0 |
| 10 F | 1.113 | 35.0 |
| 11 F | 1.123 | 42.0 |
| 12 F | 1.061 | 23.0 |
| 13 F | 1.070 | 30.0 |
| 14 F | 1.014 | 12.0 |
| 16 F | 0.988 | -4.0 |
| 17 F | 1.028 | 10.0 |
| 10 M | 1.057 | 20.5 |
| 11 M | 1.310 | 66.3 |

[a]J = January, F = February, M = March.

[b]Means the north-facing slope received higher global radiation than the south-facing slope.

TABLE 15

SAMPLED NET RADIATION MEASURED WITHIN AND ABOVE THE CANE CANOPY

DURING LATE FEBRUARY AND MID-MARCH

| Hour | Within canopy height, above the soil at | | | Above the canopy (15 cm above) | |
|---|---|---|---|---|---|
| | 10 cm | 10 cm | 30 cm | | |
| | 22/2/1976 | 23/2/1976 | 27/2/1976 | 20/3/1976 | 21/3/1976 |
| 0-1 | -0.032 | -0.068 | -0.049 | -0.026 | -0.019 |
| 1-2 | -0.032 | -0.065 | -0.045 | -0.034 | -0.019 |
| 2-3 | -0.292 | -0.065 | -0.044 | -0.037 | -0.021 |
| 3-4 | -0.029 | -0.052 | -0.042 | -0.039 | -0.016 |
| 4-5 | -0.029 | -0.045 | -0.034 | -0.019 | -0.023 |
| 5-6 | -0.032 | -0.036 | -0.031 | -0.033 | -0.026 |
| 6-7 | -0.032 | -0.026 | -0.013 | -0.034 | -0.016 |
| 7-8 | -0.013 | -0.003 | -0.016 | -0.013 | -0.049 |
| 8-9 | 0.057 | 0.049 | 0.021 | 0.146 | 0.260 |
| 9-10 | 0.227 | 0.195 | 0.877 | 0.454 | 0.601 |
| 10-11 | 0.455 | 0.552 | 1.039 | 0.666 | 0.633 |
| 12-13 | 0.909 | 0.690 | 0.341 | 0.860 | 0.649 |
| 13-14 | 0.942 | 1.136 | 0.078 | 1.023 | 0.422 |
| 14-15 | 0.812 | 0.950 | 0.487 | 0.893 | 0.260 |
| 15-16 | 0.617 | 0.390 | 0.422 | 0.633 | 0.179 |
| 16-17 | 0.406 | 0.325 | 0.065 | 0.228 | 0.081 |
| 17-18 | 0.244 | 0.208 | -0.049 | 0.049 | 0.049 |
| 18-19 | 0.002 | 0.000 | -0.065 | 0.003 | 0.008 |
| 19-20 | -0.058 | -0.032 | --- | -0.016 | -0.016 |
| 20-21 | -0.061 | -0.039 | --- | -0.019 | -0.016 |
| 21-22 | -0.065 | -0.068 | --- | -0.022 | -0.021 |
| 22-23 | -0.068 | -0.058 | --- | -0.026 | -0.019 |
| 23-24 | -0.070 | -0.062 | --- | -0.052 | -0.013 |

TABLE 15 (continued)

SAMPLED NET RADIATION MEASURED WITHIN AND ABOVE THE CANE CANOPY

DURING LATE FEBRUARY AND MID-MARCH

| Hour | Within canopy height, above the soil at | | | Above the canopy (15 cm above) | |
|---|---|---|---|---|---|
| | 10 cm | 10 cm | 30 cm | | |
| | 22/2/1976 | 23/2/1976 | 27/2/1976 | 20/3/1976 | 21/3/1976 |
| Daily net radiation, $langley \cdot day^{-1}$ | --- | --- | --- | 315.4 | 225.7 |
| Average net longwave radiation, $langley \cdot min^{-1}$ | -0.049 | -0.052 | -0.037 | -0.031 | -0.019 |
| Daily net longwave radiation, $langley \cdot day^{-1}$ | -70.3 | -80.6 | -53.1 | -44.6 | -27.36 |
| Horizontal global radiation measured in Holmes Hall, University of Hawaii ($langleys \cdot day^{-1}$) | --- | --- | --- | 558.2 | 378.6 |

experiment site had slightly higher cloud cover. The ratio of net radiation to the global radiation at the experiment site was estimated as 0.7. The difference in net radiation between north- and south-facing slopes could be obtained from the global radiation difference times 0.7. In the growth interval from 25 January to 24 February, the net radiation difference between north- and south-facing slopes was 21 langleys$\cdot$day$^{-1}$.

The heat balance difference between north- and south-facing lysimeters was estimated for the interval from day 31 to day 60 by Equation 3 (page 18 ). As mentioned previously, the additional energy received on the south-facing slope relative to the north-facing slope was 21 langleys$\cdot$day$^{-1}$. At the outset of the experiment, it was assumed that no differences in sensible heat ($\Delta$ AA), photosynthetic consumption ($\Delta$ P) or latent heat ($\Delta$ LE, energy consumed in evapotranspiration $\Delta \int$ET) existed between the two slopes (pages 18 and 22 ). A higher soil heat flux on the south-facing slope was obtained as 3.02 langleys$\cdot$day$^{-1}$. This result was obtained from measured soil temperature differences between the south- and north-facing lysimeters of 1 C at 7.5 cm and 0.6 C at 21 cm. Thus the temperature gradient was 0.03 C cm$^{-1}$ (= $\frac{1\ \mathrm{C} - 0.6\ \mathrm{C}}{21\ \mathrm{cm} - 7.5\ \mathrm{cm}}$), and combined with a soil thermal conductivity of 0.07 langleys$\cdot$min$^{-1}$ (rounded from 0.0689 langleys$\cdot$min$^{-1}$, in page 54 ) resulted in a soil heat flux of 0.0021 langleys$\cdot$min$^{-1}$ or 3.02 langleys$\cdot$day$^{-1}$. The additional stored heat in the south-facing lysimeter relative to the north-facing one was 17.98 langleys$\cdot$day$^{-1}$ (21 langleys$\cdot$day$^{-1}$ - 3.02 langleys$\cdot$day$^{-1}$ = 17.98 langleys$\cdot$day$^{-1}$).

The storage portion warmed the wet soil. The daily soil temperature difference caused by this extra storage on the south-facing slope was calculated by the equation (Cassidy, 1970): $\Delta M = \rho_b C_h V \Delta Ts$ Where $\Delta M$ = daily energy difference (cal.) of heat storage in soil between north- and south-facing slopes = difference of net radiation (langleys$\cdot$day$^{-1}$ = cal cm$^{-2}$ day$^{-1}$) times the receipt surface area (lysimeter surface area = 152.4 x 274.3 cm$^2$), $\rho_b$ = bulk density of soil, at 40% water content (0.15 bar) is 1.56 gm cm$^{-3}$, $C_h$ = heat capacity, the value of this soil is estimated as 0.76 cal gm$^{-1}$C$^{-1}$ by De Vries' method (1963), and V = volume of soil, the value was counted as the upper 21 cm depth as 152.4 x 274.3 x 21 cm$^{-3}$; therefore, in average the daily soil temperature on south-facing slope was higher than on north-facing slope by $\Delta Ts = \frac{17.98 \times 152.4 \times 274.3}{152.4 \times 274.3 \times 21 \times 0.76 \times 1.56} =$ 0.72 C.

## 7. RELATIONSHIP BETWEEN CLIMATIC FACTORS AND SUGARCANE GROWTH:

From the investigations of growth parameters of sugarcane in Sections 1, 2 and 3, the growth of sugarcane on the south-facing slopes were superior to those on the north-facing slopes by more weight, more height, more leaf number and more tillers. There only 21 langleys$\cdot$day$^{-1}$ of net radiation more and 0.72 C of soil temperature higher were found on the south-facing slopes. Therefore the better early growth of sugarcane on the south-facing slopes were attributed to these 21 langleys$\cdot$day$^{-1}$ radiant energy or 0.72 C soil temperature in mid-winter. However the higher radiant energy was the source of the higher soil temperature.

# CHAPTER V

# DISCUSSION AND CONCLUSIONS

## 1. EFFECT OF SLOPE ASPECT ON EARLY GROWTH OF SUGARCANE:

The relationship between sugarcane growth parameters (weight, height, tillering, leaf area, leaf number, etc.,) and environmental factors (water, light, soil temperature, $CO_2$ concentration, etc.,) can be expressed as "A growth parameter is a dependent function of all environmental factors if all other effective factors such as management and variety are held constant." In this experiment, the same variety of sugarcane was planted on the same soil while environments differed due to the lysimeters having 20% ($11^\circ 9'$) slopes with south and north aspects. Growth parameters observed included germination rate, first tiller from primary shoot, leaf number, cumulative height of top visible dewlap and stalk height. At harvest time total weight, tiller number and leaf area of the plants were obtained. All growth parameters for the south-facing lysimeters were superior to the north-facing ones. The difference between north- and south-facing lysimeters is assumed to be a function of the combined effect of the differences in environment which existed between the two aspects. The environmental factors observed included soil water balance, soil temperature and solar radiation. The environmental factors such as light, air temperature, air humidity, wind and $CO_2$ concentration in the experiment area were assumed to be identical because all plants were grown within an area of 22.3 $m^2$. Water conditions between the north and south slopes were the same (page 49 ). The soil temperature difference on the south-facing lysimeter was 0.7 C greater than the north-facing lysimeter in the upper 21 cm of soil. Net radiation was on the south-facing slope. As a result of the soil temperature and net radiation differences observed in this study, the following general conclusions were reached.

(i) Germination was 3 days earlier on south-facing than on north-facing slopes.

(ii) The first tiller occurred two weeks earlier on south-facing slopes than on north-facing slopes.

(iii) On the average, the emergence of a specified leaf number on the primary stalk occurred 10 days earlier on plants on south-facing slopes than on north-ones.

(iv) Tiller counts indicated that on the average, a specified number of tillers per stool emerged 10 to 15 days earlier on south-facing slopes than on north ones.

(v) On the average, stalk height of primaries reached a specified value 7 days earlier on south-facing slopes than on north-ones.

(vi) The height of the top visible dewlap reached a specified value 7 to 13 days earlier on south-facing slopes than on north-ones.

(vii) Stool fresh weight on the north-facing slope was 63% of stool fresh weight on the south-facing slope.

(viii) Accumulative height of top visible dewlap on north-facing slope was 54% of south-facing slope.

(ix) Stool total leaf area on the north-facing slope was 92% and 56% of those on the south-facing for whole lysimeter and central area, respectively, when harvested after three months of growth.

The results in this experiment were different from those of Cottle (1932) and Southard and Dirmhirn (1972) who reported lower vegetative cover on a south-facing slope than on a north-facing slope. However, the higher soil temperature and radiation measured on the south-facing slope in this study corresponds to the findings of the above workers. The writer believes that the greater vegetative growth on the south slope in this study was a consequence of maintaining an adequate water supply in the lysimeter. On natural steep mountain slopes, the temperature would likely be higher and the soil status more variable, hence evaluation of growth differences becomes very complicated. Therefore extrapolation of this initial lysimeter experiment result to the field situation should be done with care.

2. THE SELECTION OF SENSITIVE GROWTH PARAMETERS TO RELATE THE ENVIRONMENT FACTORS:

The difference in height of the top visible dewlap of the primary stalk between north- and south-facing slopes increased linearly (Table 9) through the three-month period of growth. The accumulative height of the top visible dewlap on the north- and south-facing lysimeter were significantly different at the 1% level at the time of harvest. It was concluded that the height of the top visible dewlap was the most sensitive growth parameter among those observed in this experiment.

3. THE EFFECT OF BORDER HEAT FROM THE LYSIMETER WALL:

In this experiment soil water content was maintained at from 0.05 bar to 0.25 bar (44% to 38% volumetric water content and about 80% of water saturation, Table 2). At this soil water content, the small differences in growth for the whole lysimeter and for the area excluding edge plants, did not obscure the overall results on the difference between the north- and south-facing slopes (Figure 6 and Tables 5 to 10). Therefore, the effect of border heat can be ignored. However, the effect of border heat on germination and stool total accumulative TVD was significant (Tables 3, 4, and 10).

## 4. SOME ASPECTS OF RADIATION BALANCE AT THE EXPERIMENT SITE:

The theoretical radiation evaluation (Table 1) did not fit the measured data because of the complicated influence of Waahila mountain. The mountain not only affected the longwave radiation balance, but also caused a complex condition which influenced the radiation received at the experiment site (located on the foot of Waahila mountain). The sloping surface of the mountain was presumed to emit longwave radiation which increased the incoming radiation. Thus net longwave radiation and net radiation were higher than expected. The early morning shading by the mountain reduced the global radiation by 10 to 13 langleys$\cdot$day$^{-1}$. The orographic clouds above the mountain reduced global radiation because of attenuation by the clouds but provided additional radiation at times, because of scattering and reflection from the clouds (Kaiser and Hill, 1976). A comparison between two clear days, January 27 and 28 at 9:00 to 10:00 a.m. provides an example. Ten langleys more radiation was received on both north- and south-facing slopes on January 27 than on January 28 because clouds appeared for a short time at 9:00 to 10:00 a.m. on January 27. At 8:00 to 9:00 on March 11, a cloudy day, the radiation value would normally be around 10 langleys$\cdot$hour$^{-1}$ but the actual measured value was around 20 langleys$\cdot$hour$^{-1}$ for both aspects of slope. Therefore, 10 additional langleys were contributed by scattering and reflection from the clouds. All the conditions above could occur in natural field conditions and the results demonstrate that in order to develop a detailed understanding of the radiation balance of a complex area such as the experiment site, additional research must be done.

5. CRITICISM ON THIS EXPERIMENT:

The application of lysimeters to research on agricultural meteorological problems has an advantage in providing detailed information of the water balance. This will make any investigation on the relationship between crop growth and individual components in the water balance equation (*e.g.*, rainfall, irrigation, evapotranspiration, soil moisture condition and percolation water quality) become possible although this experiment was not designed to provide this type of analysis.

Like all field experiments, the collection of data was limited by labor supply, instrumental operation power, weather conditions, and wild animal disturbances.

Because of the small fetch provided by a single lysimeter ($152.4 \times 274.3\ cm^2 = 4.2\ m^2$), the experiment accuracy can be improved by arranging hundreds of lysimeters in order. However one must seek a compromise between cost and accuracy. Increasing the numbers of lysimeters also would provide additional replication which appeared to be needed to improve the accuracy of results.

# APPENDIX I

## LOCATION OF THE EXPERIMENT SITE IN MANOA VALLEY

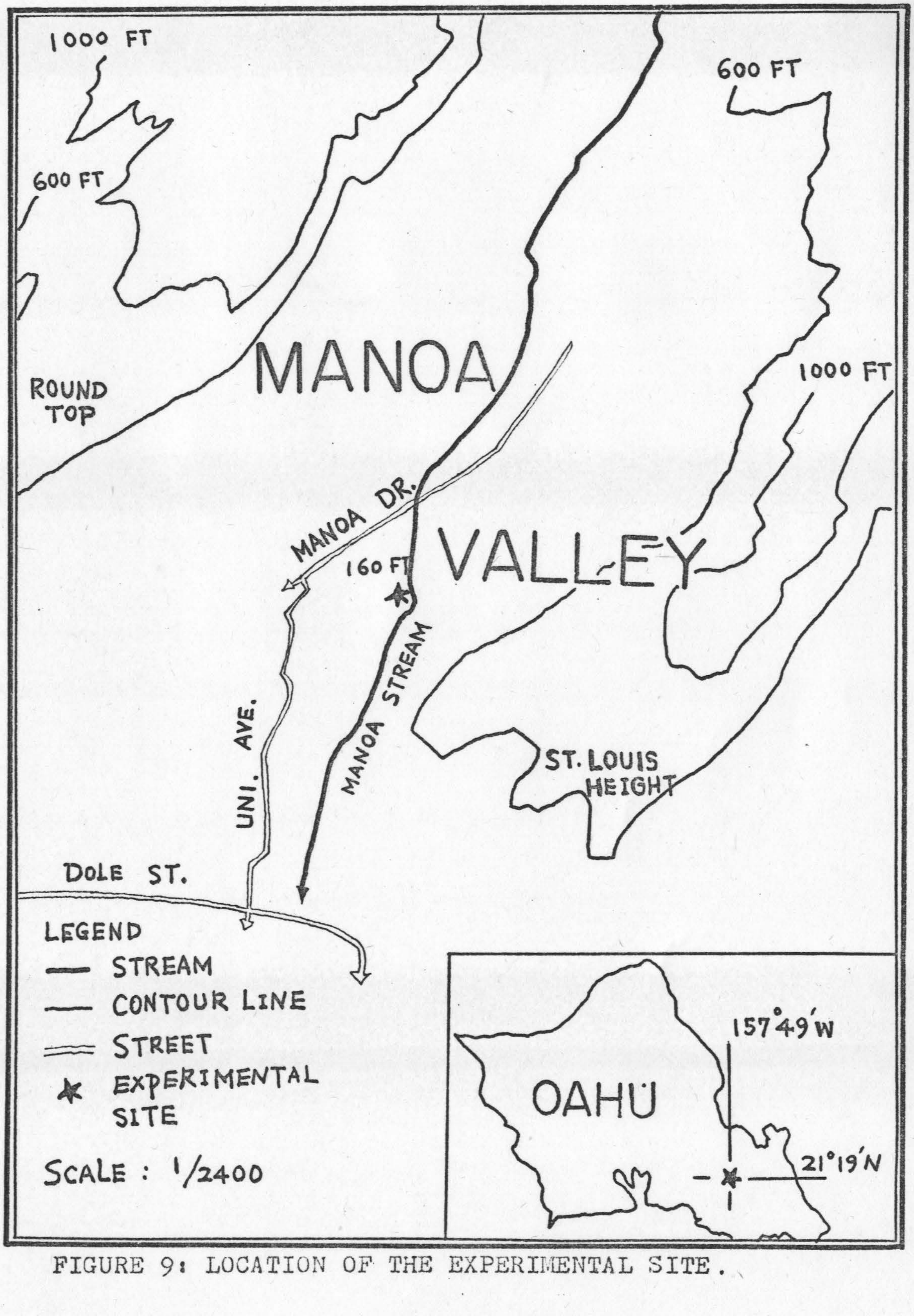



FIGURE 9: LOCATION OF THE EXPERIMENTAL SITE.

# APPENDIX II

## THEORETICAL EVALUATION OF SOLAR RADIATION FOR EXPERIMENTAL SITE

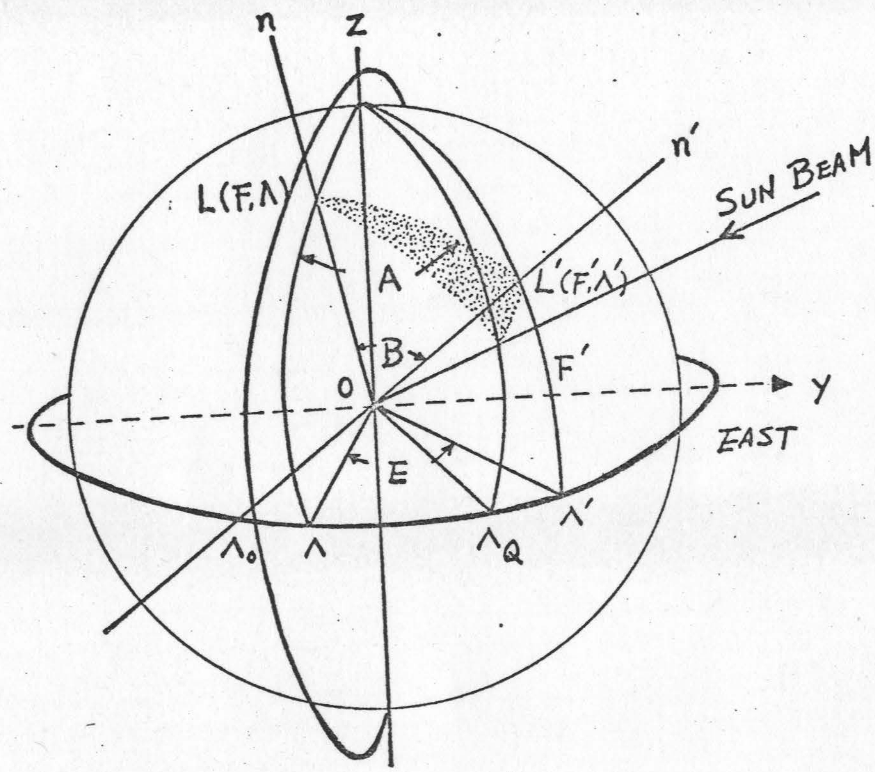



FIGURE 10: GLOYNE'S MODEL FOR CALCULATION OF SUNSHINE DURATION FOR ANY SLOPE AT ANY LOCATION AND AT ANY TIME (AFTER GLOYNE, 1965).

n = Normal to horizontal surface at L
n' = Normal to horizontal surface at L'
$\angle ΛL'L$ = A
$\angle LoL'$ = B
$\angle Λ_Q OQ$ = D
$\angle Λ o Λ'$ = E
$\angle ΛoL$ = F
$\angle Λ' oL'$ = F'

If for any point L (latitude F, longitude Λ) there is a direct south-facing slope of B$^o$ (slope B aspect A) to the horizontal, then, following Unna (1947), a point L' (latitude F', longitude Λ') can be found of angular distance B southwards along the meridian where a horizontal plane will be parallel to the sloping plane at L. During any given day, the declination (D) is constant, $\Lambda_o$ moves from east to west, and $\Lambda Q$ is the coordinate point of the sunbeam at the surface. Therefore, the equation for computing sunshine duration is obtained as

$$\text{Sin } F' = \text{Sin } F \text{ Cos } B - \text{Cos } F \text{ Sin } B \text{ Cos } A$$

$$\text{Cos } E = \frac{\text{Cos } B - \text{Sin } F \text{ Sin } F'}{\text{Cos } F \text{ Cos } F'}$$

$$\text{Cos } \theta' = \text{Sin } D \text{ Sin } F' + \text{Cos } D \text{ Cos } F' \text{ Cos } T'$$

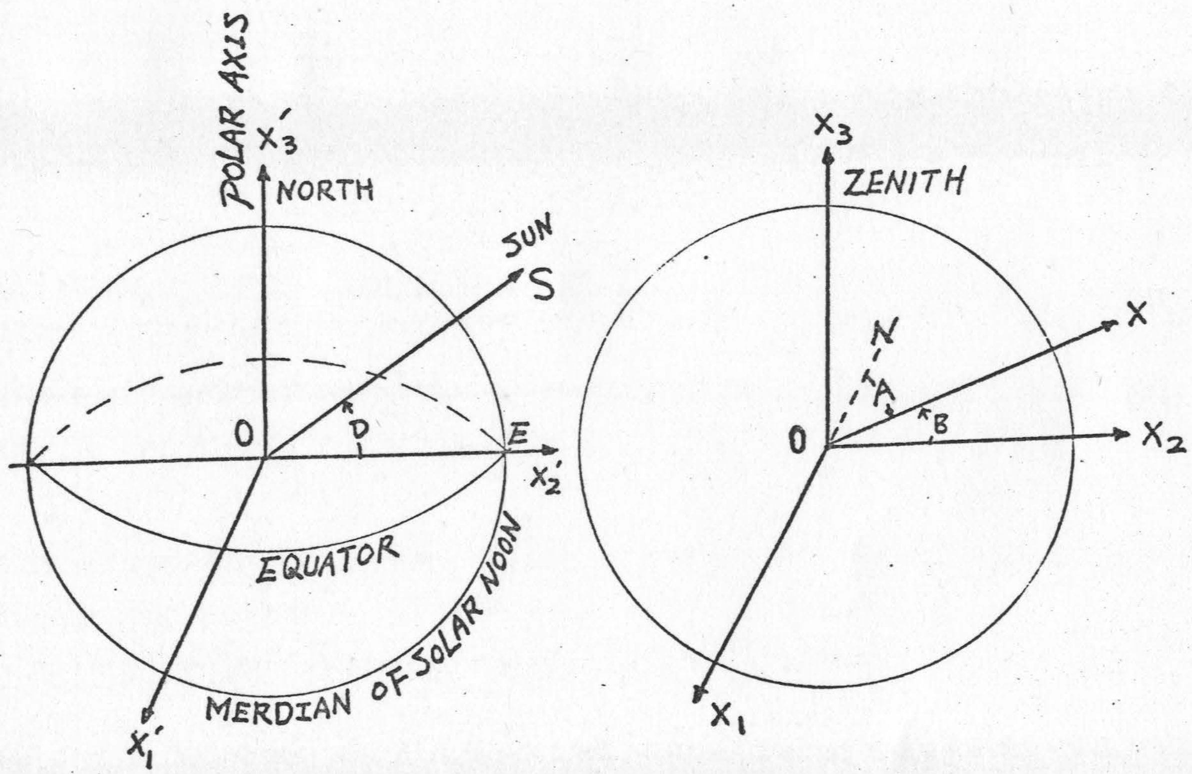



FIGURE 11: GARNIER'S MODEL FOR THE CALCULATION OF DIRECT BEAM RADIATION.

The vector of S = (O, Cos D, Sin D).
The vector of X = ((-Cos A Sin B), (Sin A Sin B), Cos B).
The direct radiation intensity F(T) = Cos (X$\Lambda$S) = -Sin F Cos T Cos A Sin B Cos D - Sin T Sin A Cos B Cos D + Cos F Cos T Cos B Cos D + Cos F Cos A Sin B Sin D + Sin F Cos B Sin D.

TABLE 16

SUNSHINE DURATION (HRS. + MIN.) OF VARIOUS ASPECT WITH 0 TO 40% SLOPE .

| Lati- tude | Slope (%) | Sur- face Aspect | DATE J 7 | J 21 | F 7 | F 21 | M 7 | M 21 | A 7 | A 21 | M 7 | M 21 | J 7 | J 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Equator | 0°* | | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 |
| | | N | 10:44 | 10:46 | 11:08 | 11:22 | 11:42 | 12:00 | 12:00 | 12:00 | 12;00 | 12:00 | 12:00 | 12:00 |
| 0° | 20 | S | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 11:38 | 11:22 | 11:06 | 10:52 | 10:42 | 10:40 |
| | | E,W | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 |
| | | N | 11:22 | 11:26 | 11:34 | 11:42 | 11:52 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 |
| | 40 | S | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 11:50 | 11:42 | 11:32 | 11:26 | 11:22 | 11:20 |
| | | E,W | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 |
| U.H. | 0°* | | 10:46 | 10:54 | 11:10 | 11:26 | 11:42 | 12:00 | 12:20 | 12:38 | 12:54 | 13:06 | 13:16 | 13:18 |
| | | N | 9:58 | 10:12 | 10:38 | 11:04 | 11:32 | 12:00 | 12:20 | 12:36 | 12:54 | 13:06 | 13:16 | 13:18 |
| 21°19'N | 20 | S | 10:46 | 10:54 | 11:10 | 11:26 | 11:42 | 12:00 | 12:10 | 12:16 | 12:24 | 12:34 | 12:34 | 12:34 |
| | | E,W | 10:46 | 10:54 | 11:10 | 11:26 | 11:42 | 12:00 | 12:20 | 12:36 | 12:52 | 13:04 | 13:14 | 13:16 |
| | | N | 8:58 | 9:20 | 10:00 | 10:38 | 11:18 | 12:00 | 12:20 | 12:38 | 12:54 | 13:06 | 13:16 | 13:18 |
| | 40 | S | 10:46 | 10:54 | 11:10 | 11:26 | 11:42 | 12:00 | 12:00 | 12:00 | 11:58 | 11:58 | 11:58 | 11:58 |
| | | E,W | 10:46 | 10:54 | 11:10 | 11:26 | 11:42 | 12:00 | 12:18 | 12:34 | 12:48 | 13:00 | 13:08 | 13:12 |
| 40°N | 0°* | | 9:18 | 9:36 | 10:12 | 10:46 | 11:22 | 12:00 | 12:44 | 13:20 | 13:56 | 14:22 | 14:44 | 14:50 |
| | | N | 7:52 | 8:22 | 9:18 | 10:10 | 11:04 | 12:00 | 12:44 | 13:20 | 13:56 | 14:22 | 14:44 | 14:50 |
| | 20 | S | 9:18 | 9:36 | 10:12 | 10:46 | 11:22 | 12:00 | 12:28 | 12:52 | 13:14 | 13:32 | 13:46 | 13:50 |
| | | E,W | 9:18 | 9:36 | 10:12 | 10:46 | 11:22 | 12:00 | 12:42 | 13:16 | 13:52 | 14:18 | 14:38 | 14:44 |
| | | N | 5:16 | 6:16 | 7:50 | 9:12 | 10:36 | 12:00 | 12:44 | 13:20 | 13:56 | 14:22 | 14:44 | 14:50 |
| | 40 | S | 9:18 | 9:36 | 10:12 | 10:46 | 11:22 | 12:00 | 12:18 | 12:30 | 12:44 | 12:56 | 13:04 | 13:06 |
| | | E,W | 9:18 | 9:36 | 10:12 | 10:46 | 11:22 | 12:00 | 12:40 | 13:10 | 13:42 | 14:06 | 14:24 | 14:30 |

*Error is less than 2% (This error will be kept by Table 17 and 19 because integrating values of them over time were based on this table).

TABLE 16 (Continued)

SUNSHINE DURATION (HRS. + MIN.) OF VARIOUS ASPECTS WITH 0 TO 40% SLOPE

| Latitude | Slope (%) | Surface Aspect | J 7 | J 21 | A 7 | A 21 | S 7 | S 21 | O 7 | O 21 | N 7 | N 21 | D 7 | D 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Equator | 0°* | | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 |
| 0° | 20 | N | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 11:44 | 11:26 | 11:08 | 10:54 | 10:44 | 10:40 |
| | | S | 10:42 | 10:50 | 11:05 | 11:20 | 11:40 | 11:56 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 |
| | | E,W | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 |
| | 40 | N | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 11:52 | 11:44 | 11:34 | 11:26 | 11:22 | 11:20 |
| | | S | 11:22 | 11:26 | 11:32 | 11:40 | 11:50 | 11:58 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 |
| | | E,W | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 | 12:00 |
| U.H. | 0°* | | 13:16 | 13:08 | 12:54 | 12:40 | 12:20 | 12:04 | 11:44 | 11:28 | 11:08 | 10:56 | 10:46 | 10:42 |
| 21°19'N | 20 | N | 13:16 | 13:08 | 12:54 | 12:40 | 12:20 | 12:04 | 11:34 | 11:06 | 10:36 | 10:14 | 9:56 | 9:50 |
| | | S | 12:34 | 12:30 | 12:24 | 12:18 | 12:08 | 12:02 | 11:44 | 11:28 | 11:08 | 10:56 | 10:46 | 10:42 |
| | | E,W | 13:14 | 13:06 | 12:52 | 12:38 | 12:20 | 12:04 | 11:44 | 11:28 | 11:08 | 10:56 | 10:46 | 10:42 |
| | 40 | N | 13:16 | 13:08 | 12:54 | 12:40 | 12:20 | 12:04 | 11:20 | 10:40 | 9:54 | 9:22 | 8:58 | 8:48 |
| | | S | 11:58 | 11:58 | 11:58 | 12:00 | 12:00 | 12:00 | 11:44 | 11:28 | 11:08 | 10:56 | 10:46 | 10:42 |
| | | E,W | 13:08 | 13:02 | 12:50 | 12:36 | 12:18 | 12:02 | 11:44 | 11:28 | 11:08 | 10:56 | 10:46 | 10:42 |
| 40°N | 0°* | | 14:44 | 14:28 | 13:56 | 13:24 | 12:42 | 12:06 | 11:24 | 10:46 | 10:08 | 9:40 | 9:18 | 9:10 |
| | 20 | N | 14:44 | 14:28 | 13:56 | 13:24 | 12:42 | 12:06 | 11:08 | 10:14 | 9:12 | 8:26 | 7:50 | 7:38 |
| | | S | 13:46 | 13:34 | 13:16 | 12:56 | 12:28 | 12:04 | 11:24 | 10:48 | 10:08 | 9:40 | 9:18 | 9:10 |
| | | E,W | 14:38 | 14:22 | 13:52 | 13:22 | 12:42 | 12:06 | 11:24 | 10:48 | 10:08 | 9:40 | 9:18 | 9:10 |
| | 40 | N | 14:44 | 14:28 | 13:56 | 13:24 | 12:42 | 12:06 | 10:42 | 9:20 | 7:40 | 6:22 | 5:14 | 4:48 |
| | | S | 13:04 | 12:56 | 12:46 | 12:34 | 12:16 | 12:02 | 11:24 | 10:48 | 10:08 | 9:40 | 9:18 | 9:10 |
| | | E,W | 14:24 | 14:10 | 13:42 | 13:16 | 12:38 | 12:06 | 11:24 | 10:48 | 10:08 | 9:40 | 9:18 | 9:10 |

*Error is less than 2% (This error will be kept by Table 17 and 19 because integrating values of them over time were based on this table).

TABLE 17

VARIATION IN THE DIRECT RADIATION WITH SLOPE AND ASPECT AT THE EQUATOR AND THE EXPERIMENT SITE.

| Latitude | Slope (%) | Surface Aspect | J 7 | J 21 | F 7 | F 21 | M 7 | M 21 | A 7 | A 21 | M 7 | M 21 | J 7 | J 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Equator | 0 | | 586 | 599 | 619 | 635 | 646 | 650 | 645 | 633 | 615 | 599 | 585 | 581 |
| (0°) | 20 | N | 511 | 529 | 561 | 590 | 617 | 637 | 652 | 655 | 652 | 645 | 638 | 636 |
| | | S | 639 | 645 | 653 | 655 | 650 | 638 | 612 | 586 | 554 | 528 | 509 | 503 |
| | | E,W | 575 | 587 | 608 | 623 | 634 | 638 | 632 | 621 | 603 | 588 | 574 | 570 |
| | 40 | N | 423 | 446 | 489 | 528 | 568 | 603 | 635 | 653 | 663 | 665 | 665 | 665 |
| | | S | 665 | 665 | 661 | 651 | 631 | 604 | 561 | 522 | 479 | 447 | 421 | 413 |
| | | E,W | 549 | 561 | 580 | 595 | 605 | 609 | 604 | 593 | 576 | 561 | 547 | 543 |
| Experiment site | 0 | | 380 | 405 | 453 | 499 | 547 | 592 | 637 | 666 | 688 | 700 | 708 | 709 |
| (21°19') | 20 | N | 288 | 315 | 367 | 420 | 478 | 535 | 597 | 641 | 678 | 702 | 718 | 722 |
| | | S | 458 | 480 | 522 | 559 | 595 | 626 | 653 | 665 | 671 | 672 | 670 | 669 |
| | | E,W | 373 | 398 | 445 | 490 | 537 | 581 | 626 | 653 | 675 | 687 | 694 | 696 |
| | 40 | N | 193 | 220 | 274.8 | 332 | 397 | 463 | 540 | 595 | 646 | 679 | 702 | 709 |
| | | S | 513 | 533 | 567 | 595 | 619 | 636 | 644 | 641 | 632 | 622 | 612 | 608 |
| | | E,W | 357 | 381 | 426 | 469 | 514 | 555 | 598 | 624 | 645 | 656 | 662 | 664 |

TABLE 17 (Continued)

VARIATION IN THE DIRECT RADIATION WITH SLOPE AND ASPECT AT THE EQUATOR AND THE EXPERIMENT SITE.

| Latitude | Slope (%) | Surface Aspect | DATE J 7 | J 21 | A 7 | A 21 | S 7 | S 21 | O 7 | O 21 | N 7 | N 21 | D 7 | D 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Equator | 0 | | 585 | 595 | 615 | 630 | 645 | 650 | 647 | 636 | 617 | 600 | 586 | 581 |
| (0°) | 20 | N | 638 | 644 | 651 | 655 | 651 | 640 | 618 | 593 | 558 | 531 | 510 | 503 |
| | | S | 509 | 525 | 554 | 581 | 613 | 634 | 650 | 655 | 652 | 646 | 639 | 636 |
| | | E,W | 574 | 585 | 603 | 619 | 633 | 638 | 634 | 624 | 606 | 589 | 575 | 570 |
| | 40 | N | 665 | 666 | 663 | 655 | 635 | 609 | 571 | 532 | 484 | 449 | 423 | 413 |
| | | S | 421 | 441 | 478 | 516 | 562 | 597 | 630 | 649 | 662 | 665 | 665 | 665 |
| | | E,W | 547 | 558 | 576 | 590 | 604 | 609 | 606 | 596 | 578 | 562 | 548 | 543 |
| Experiment site (21°19') | 0 | | 708 | 702 | 689 | 670 | 636 | 600 | 550 | 503 | 448 | 409 | 379 | 369 |
| | 20 | N | 718 | 706 | 679 | 647 | 596 | 546 | 481 | 425 | 361 | 319 | 287 | 276 |
| | | S | 670 | 671 | 671 | 667 | 652 | 631 | 598 | 562 | 517 | 484 | 457 | 448 |
| | | E,W | 694 | 689 | 676 | 657 | 625 | 589 | 540 | 494 | 440 | 401 | 372 | 363 |
| | 40 | N | 702 | 684 | 647 | 603 | 538 | 476 | 401 | 337 | 269 | 224 | 192 | 182 |
| | | S | 612 | 620 | 632 | 640 | 644 | 638 | 620 | 597 | 563 | 536 | 513 | 505 |
| | | E,W | 662 | 657 | 645 | 628 | 597 | 563 | 516 | 473 | 421 | 384 | 356 | 347 |

TABLE 18

THE RATIO OF DIFFUSE RADIATION ON SLOPES OF VARYING ANGLES RELATIVE TO THAT ON A HORIZONTAL SURFACE (HS/H).

| SLOPE | Hs/Ho |
|---|---|
| $0^{o}$ | 1 |
| $10^{o}$ | 0.99 |
| $11^{o}09'$(20%) | 0.99 |
| $20^{o}$ | 0.987 |
| $21^{o}19'$(40%) | 0.97 |
| $30^{o}$ | 0.93 |
| $40^{o}$ | 0.88 |
| $45^{o}$ | 0.85 |

TABLE 19

EFFECT OF DATE AND LATITUDE ON ANGOT'S VALUES FOR EXTRATERRESTRIAL RADIATION.

| | | DATE | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | J | | F | | M | | A | | M | | J | |
| Latitude | | 7 | 21 | 7 | 21 | 7 | 21 | 7 | 21 | 7 | 21 | 7 | 21 |
| $0^{o}$ | Eq. 6a | 854.4 | 866.8 | 885.5 | 897.8 | 903.6 | 901.0 | 886.5 | 867.3 | 841.4 | 819.6 | 800.5 | 794.0 |
| | Liu* | 856.5 | | 882.6 | | 890.4 | | 863.7 | | 817.3 | | 787.4 | |
| $20^{o}$ | Liu* | 632.5 | | 726.8 | | 818.2 | | 891.5 | | 827.5 | | 929.2 | |
| $21^{o}19'$ | Eq. 6a | 604.6 | 634.5 | 689.3 | 740.5 | 792.2 | 838.9 | 884.6 | 911.9 | 932.0 | 942.1 | 946.7 | 946.7 |
| $25^{o}$ | Liu* | 567.4 | | 674.0 | | 784.2 | | 882.1 | | 932.8 | | 950.6 | |

*The standard value is calibrated from Liu's result with 1.94 langley·min$^{-1}$ (solar constant). Liu's data are adapted from Chang (1971), which were contributed to B. Y. H. Liu.

TABLE 19 (Continued)

EFFECT OF DATE AND LATITUDE ON ANGOT'S VALUES FOR EXTRATERRESTRIAL RADIATION

| Latitude | | J 7 | J 21 | A 7 | A 21 | S 7 | S 21 | O 7 | O 21 | N 7 | N 21 | D 7 | D 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $0^{\circ}$ | Eq. 6a | 797.7 | 810.3 | 832.9 | 853.6 | 875.5 | 887.6 | 892.2 | 888.1 | 875.6 | 862.6 | 851.2 | 847.7 |
| | Liu* | 797.1 | | 835.7 | | 873.6 | | 881.6 | | 859.4 | | 839.7 | |
| $20^{\circ}$ | Liu* | 924.3 | | 901.4 | | 846.5 | | 733.1 | | 661.3 | | 606.9 | |
| $21^{\circ}19'$ | Eq. 6a | 943.3 | 937.1 | 923.5 | 905.1 | 872.2 | 835.9 | 785.2 | 736.2 | 677.1 | 634.5 | 601.9 | 591.2 |
| $25^{\circ}$ | Liu* | 941.6 | | 901.8 | | 823.7 | | 714.8 | | 600.1 | | 539.2 | |

*The standard value is calibrated from Liu's result with 1.94 langley$\cdot$min$^{-1}$ (solar constant). Liu's data are adapted from Chang (1971), which were contributed to B. Y. H. Liu.

TABLE 20

EFFECT OF SLOPE AND DATE ON DIFFUSE RADIATION AT 0° AND AT THE EXPERIMENT SITE (21°19').

| Latitude | Slope (%) | DATE J 7 | J 21 | F 7 | F 21 | M 7 | M 21 | A 7 | A 21 | M 7 | M 21 | J 7 | J 21 | J 7 | J 21 | A 7 | A 21 | S 7 | S 21 | O 7 | O 21 | N 7 | N 21 | D 7 | D 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0° | 20 | 95 | 94 | 92 | 90 | 87 | 84 | 80 | 77 | 75 | 73 | 71 | 70 | 70 | 70 | 71 | 73 | 75 | 78 | 82 | 85 | 89 | 92 | 94 | 95 |
| | 40 | 92 | 92 | 90 | 88 | 85 | 82 | 78 | 75 | 73 | 71 | 69 | 69 | 68 | 68 | 69 | 71 | 73 | 76 | 80 | 83 | 87 | 89 | 91 | 92 |
| 21°19'N | 20 | 84 | 85 | 86 | 86 | 86 | 85 | 83 | 81 | 79 | 78 | 76 | 75 | 75 | 75 | 75 | 76 | 78 | 80 | 81 | 83 | 83 | 83 | 83 | 84 |
| | 40 | 82 | 83 | 84 | 84 | 84 | 83 | 81 | 79 | 77 | 76 | 74 | 73 | 73 | 73 | 73 | 74 | 76 | 78 | 79 | 80 | 81 | 81 | 81 | 81 |

TABLE 21

CALCULATED GLOBAL RADIATION ON SLOPES OF VARIOUS ASPECTS

AT 0° AND AT THE EXPERIMENT SITE (21°19').

| Latitude | Slope (%) | Surface Aspect | DATE | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | J | | F | | M | | A | | M | | J | |
| Equator | 0 | | 681 | 693 | 712 | 725 | 733 | 734 | 725 | 710 | 690 | 672 | 656 | 651 |
| (0°) | 20 | N | 605 | 623 | 654 | 680 | 704 | 721 | 732 | 732 | 726 | 718 | 709 | 706 |
| | | S | 734 | 739 | 745 | 745 | 737 | 722 | 693 | 663 | 629 | 602 | 580 | 573 |
| | | E,W | 670 | 682 | 700 | 713 | 721 | 722 | 713 | 698 | 678 | 660 | 645 | 640 |
| | 40 | N | 515 | 538 | 578 | 616 | 653 | 685 | 714 | 728 | 735 | 736 | 734 | 733 |
| | | S | 758 | 757 | 751 | 738 | 716 | 686 | 639 | 598 | 552 | 518 | 490 | 482 |
| | | E,W | 641 | 652 | 670 | 683 | 690 | 691 | 682 | 668 | 649 | 632 | 617 | 612 |
| U.H. | 0 | | 464 | 491 | 539 | 586 | 633 | 677 | 720 | 747 | 767 | 778 | 784 | 785 |
| (21°19') | 20 | N | 372 | 400 | 453 | 507 | 564 | 620 | 680 | 722 | 758 | 780 | 794 | 796 |
| | | S | 542 | 566 | 608 | 646 | 681 | 711 | 735 | 746 | 750 | 749 | 746 | 744 |
| | | E,W | 457 | 483 | 531 | 577 | 623 | 666 | 709 | 735 | 755 | 765 | 770 | 771 |
| | 40 | N | 275 | 303 | 359 | 416 | 481 | 546 | 621 | 674 | 723 | 755 | 777 | 782 |
| | | S | 596 | 616 | 651 | 679 | 703 | 718 | 725 | 720 | 709 | 697 | 686 | 682 |
| | | E,W | 439 | 464 | 510 | 553 | 597 | 638 | 679 | 703 | 722 | 731 | 736 | 737 |

TABLE 21 (Continued)

CALCULATED GLOBAL RADIATION ON SLOPES OF VARIOUS ASPECTS

AT 0° AND AT THE EXPERIMENT SITE (21°19').

| Latitude | Slope (%) | Surface Aspect | DATE | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | J | | A | | S | | O | | N | | D | |
| Equator | 0 | | 655 | 666 | 686 | 703 | 720 | 728 | 728 | 721 | 706 | 692 | 679 | 675 |
| (0°) | 20 | N | 708 | 714 | 722 | 727 | 727 | 718 | 700 | 678 | 647 | 623 | 604 | 597 |
| | | S | 579 | 595 | 625 | 654 | 688 | 712 | 732 | 740 | 741 | 737 | 732 | 730 |
| | | E,W | 644 | 655 | 674 | 691 | 708 | 716 | 716 | 709 | 695 | 681 | 668 | 664 |
| | 40 | N | 733 | 734 | 732 | 726 | 708 | 685 | 650 | 615 | 571 | 538 | 514 | 506 |
| | | S | 489 | 509 | 547 | 586 | 636 | 674 | 710 | 732 | 749 | 754 | 756 | 757 |
| | | E,W | 616 | 626 | 645 | 661 | 677 | 685 | 685 | 679 | 665 | 651 | 639 | 636 |
| U.H. | 0 | | 782 | 777 | 764 | 746 | 714 | 680 | 632 | 586 | 531 | 492 | 463 | 453 |
| (21°19') | 20 | N | 793 | 780 | 754 | 723 | 674 | 625 | 563 | 507 | 445 | 402 | 370 | 360 |
| | | S | 744 | 746 | 746 | 743 | 730 | 711 | 679 | 645 | 601 | 567 | 540 | 531 |
| | | E,W | 769 | 764 | 751 | 734 | 702 | 668 | 621 | 576 | 523 | 485 | 456 | 446 |
| | 40 | N | 775 | 767 | 720 | 677 | 614 | 554 | 480 | 417 | 350 | 305 | 274 | 263 |
| | | S | 684 | 692 | 705 | 715 | 720 | 715 | 700 | 678 | 644 | 617 | 594 | 586 |
| | | E,W | 735 | 730 | 718 | 702 | 673 | 640 | 596 | 553 | 502 | 465 | 438 | 428 |

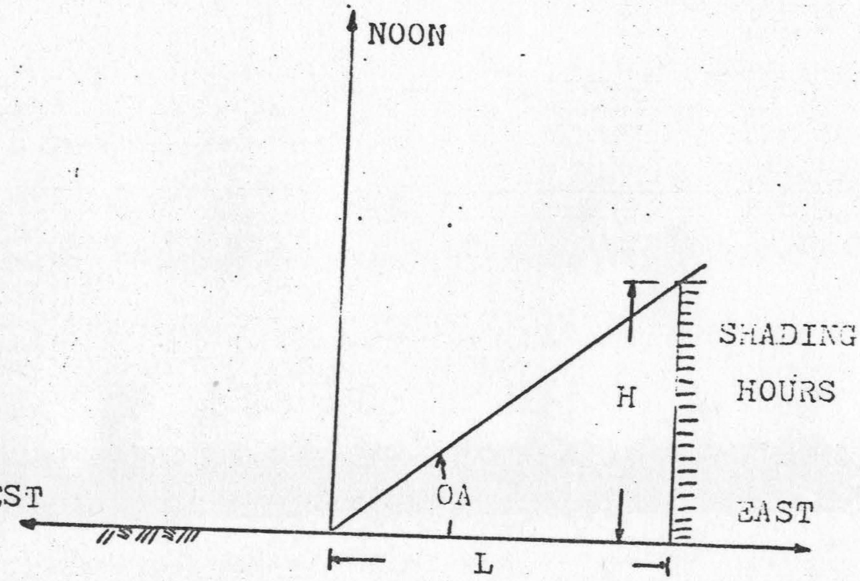



FIGURE 12a: THE NECESSITY OF THE EVALUATION OF SHADING EFFECT

Figure 12a shows the necessity for evaluating the shading effect of adjacent objects. The diurnal paths of the sun shown in Figure 12b are (1) March 21, the sun crosses the sky with a southward angle of $21^{\circ}$ and (2) December 21, the sun crosses the sky with a $44^{\circ}$ southward angle. The obstacle angle (OA) is introduced as the arctangent value of the ratio of the relative relief between top of the obstacle and the radiation measuring site to the projected horizontal distance between them. If there is no elevation difference, OA = $0^{\circ}$ and no shading occurs. If the experiment site is completely shaded for half the day (until the sun is exactly overhead) OA = $90^{\circ}$. For the experiment site, OA was obtained from Figure 12b. On December 21 and March 21

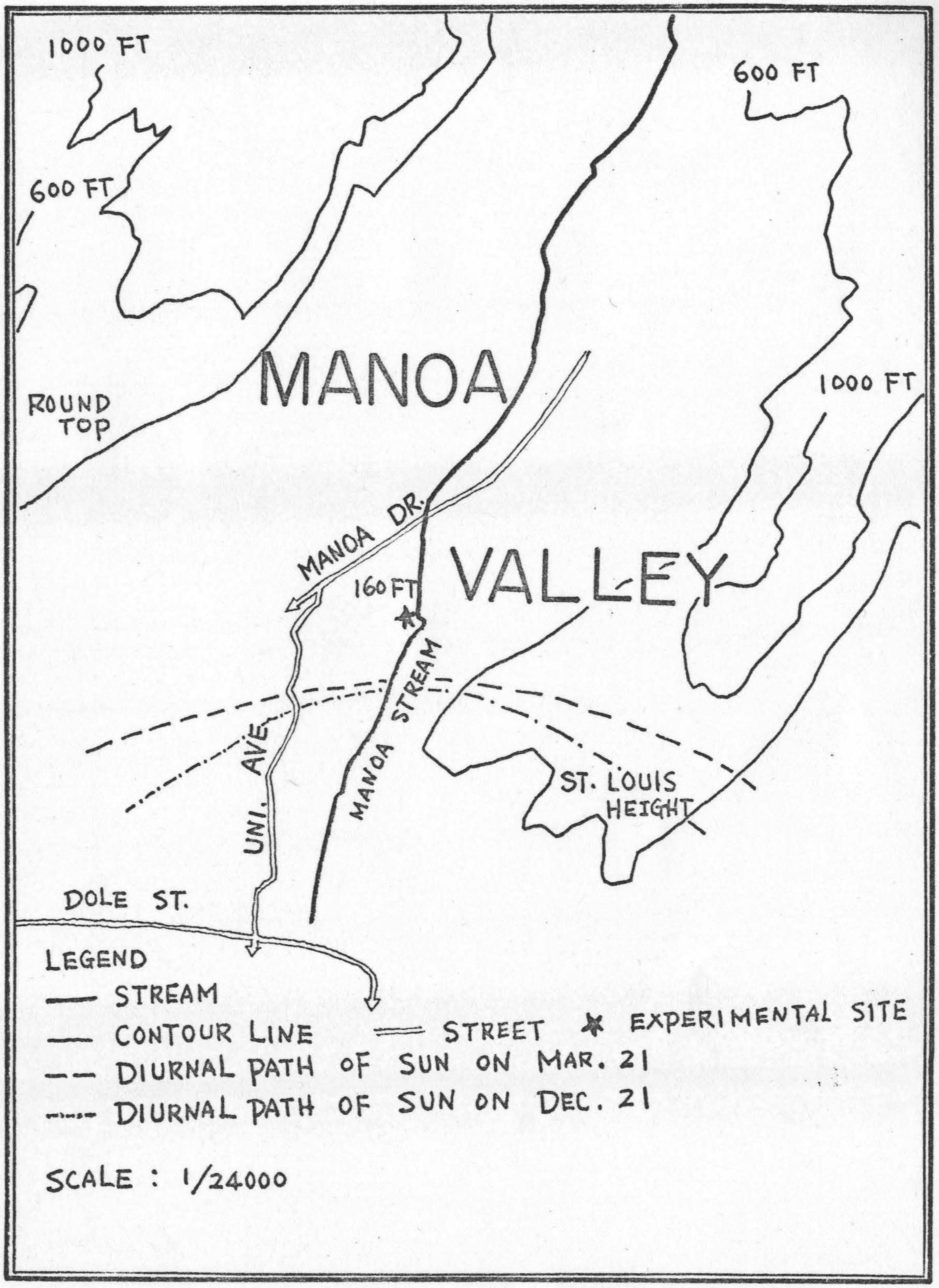



FIGURE 12b: TOPOGRAPHY OF EXPERIMENT SITE AND DIURNAL PATHS OF SUN.

OA is equal to $13^{\circ}.3$. The shading effect of the object on direct radiation is obtained by

$$SE = \frac{DR'}{2} \times (1 - KK) \times C \times \sin OA \qquad \text{Equation 8}$$

Because shading hours always happen in early morning and late afternoon, C is arbitrarily chosen as a calibration factor for cloud penetration. The value 0.5 was used here. On December 21, $SE = \frac{369}{2}(1 - 0.5) \times 0.23 \times 0.5 = 10$ langley day$^{-1}$. On March 21, $SE = \frac{569}{2}(1 - 0.6) \times 0.25 \times 0.5 = 13$ langley day$^{-1}$.

TABLE 22

ALBEDO (%) OF SEVERAL TYPES OF SURFACES

(CHANG, 1968, EKERN, 1965 AND 1972).

| Soil Surface | Albedo | Solar Height or Time |
|---|---|---|
| Lava | 5 | |
| Black earth, dark-grey, dry, level | 13 | |
| " " " moist, " | 8 | |
| " " " dry, ploughed | 8 | |
| " " " moist, " | 4 | |
| Chestnut soil, grey, dry, level | 20 | |
| " " " moist, " | 12 | |
| " " " dry, ploughed | 15 | |
| " " " moist, level | 7 | |
| Potato height 40-50 cm, open ground 50% green color | 18 | 63° |
| Potato faded pot-herb leaves, coverage 50% | 11 | 71° |
| Maize, height 15-20 cm, coverage 40-50% | 16 | 69° |
| " " 200-250, full ripeness | 23 | 69° |
| Pineapple | 7.5-10 | 10:00-12:00 |
| Cane | 15 -21 | |

From above, albedo is chosen as 17%.

TABLE 23

MONTHLY CLOUDINESS ON CENTRAL OAHU (AFTER EKERN, 1967).

| Month | Honolulu Federal $31^{o}$ lat. 1918-61 | Wheeler Field 1925-41 |
|---|---|---|
| January | .67 | .42 |
| February | .60 | .38 |
| March | .69 | .37 |
| April | .68 | .38 |
| May | .69 | .41 |
| June | .69 | .45 |
| July | .73 | .48 |
| August | .74 | .47 |
| September | .76 | .48 |
| October | .72 | .44 |
| November | .65 | .38 |
| December | .59 | .36 |
| Annually | .69 | .42 |

The reduction in radiation received as a result of clouds was obtained as follows. Assume 0.2 of DR penetrates a cloud (a 0.8 reduction in intensity) and that DR in a clear area is 1.0 (no reduction). Therefore with 0.5 cloud cover, the total reduction would be: CF = 0.5 x 0.8 x DR. The cloudiness for the experiment site on December and March were chosen from Table 24 as 0.5 and 0.6 respectively. The calculation is shown in Table 24.

TABLE 24

THE ESTIMATED REDUCTION IN RADIATION RECEIVED ($LANGLEYS \cdot DAY^{-1}$) AT THE EXPERIMENTAL SITE DUE TO THE PRESENCE OF CLOUDS.

| Slope | Date: December 21 | Date: March 21 |
|---|---|---|
| Horizontal | 0.5 x 0.8 x 369 = 148 | 0.6 x 0.8 x 592 = 284 |
| North | 0.5 x 0.8 x 276 = 110 | 0.6 x 0.8 x 535 = 257 |
| South | 0.5 x 0.8 x 448 = 179 | 0.6 x 0.8 x 626 = 300 |
| East and West | 0.5 x 0.8 x 363 = 145 | 0.6 x 0.8 x 581 = 279 |

TABLE 25

MEASURED VALUES OF EMISSIVITY IN THE ATMOSPHERIC TRANSPARENCY WINDOW OF 8-12 $\mu$ (AFTER GAYEVSKY, 1951; BUETTMER, ET AL. 1969)

| Surface | Emissivity |
| --- | --- |
| Fine dry sand | 0.949 |
| Fine wet sand | 0.962 |
| Dry sandy loam | 0.954 |
| Wet " " | 0.968 |
| Dry peat | 0.970 |
| Wet peat | 0.983 |
| Thick green grass | 0.986 |
| Thin green grass on wet sandy loam | 0.975 |
| Quartz | 0.712 |
| Granite | 0.815 |
| Basalt | 0.904 |
| Rough basalt | 0.934 |
| Dolomite | 0.929 |
| Coarse quartz sand | 0.914 |
| Clear water | 0.993 |

The 10-12 $\mu$ interval is the most suitable for the determination of temperature of the surfaces by the radiation radiometric method, since the relative emissivity of a surface in this interval is comparatively stable and close to unity. All aspects are assumed to have the same temperature, say 20 C in December and 21 C in March. $\delta = 0.9$ is chosen. Thus on December 21, $L\uparrow = \delta T_s^4 = 775$ langleys$\cdot$day$^{-1}$, and on March 21, $L\uparrow = 797$ langleys$\cdot$day$^{-1}$.

TABLE 26

KW VALUES FOR EVALUATING NET LONGWAVE RADIATION UNDER CLOUDY CONDITIONS (BUDYKO, 1958).

| KW | 0.04 | 0.08 | 0.10 | 0.17 | 0.2 | 0.24 |
|---|---|---|---|---|---|---|
| Cloud Form | Cirrus | Cirrostratus | Cumulus | Altocumulus | Altostratus | Stratus<br>High fog<br>Ground fog |
| Cloud Symbol | Ci | Cs | Cu | Ac | As | At |

Observation of the sky conditions over the experiment site indicated that fog and stratus cloud forms predominated. For calculations, if there is reduction in radiation due to clouds, St = 0.24 is chosen as the K value. If cloudiness is 0.5 according to Table 25, the net longwave radiation under cloudy condition can be estimated by Brunt's equation as follows: SW = clear net longwave + $(KW)\cdot(KK)^2\cdot$(clear net longwave + outgoing longwave). On December 21, $SW = -224 = 0.24(0.5)^2(-224 + 775) = -181$ langleys$\cdot$day$^{-1}$, and on March 21, $SW = -219 + 0.24(0.6)^2(-219 + 797) = -184$ langleys$\cdot$day$^{-1}$.

TABLE 27

THE THEORETICAL RADIATION BALANCE (LANGLEYS·DAY$^{-1}$) OF VARIOUS SURFACES WITH 20% SLOPE AT THE EXPERIMENT SITE ON DECEMBER 21 AND MARCH 21.

| Radiation Components | December 21 | | | | |
|---|---|---|---|---|---|
| | 0* | N | E | S | W |
| Direct (DR' or DR) | 369 | 276 | 363 | 448 | 363 |
| Cloudiness (-CF) | 148 | 110 | 145 | 179 | 145 |
| Shading effect (-SE) | 10 | 10 | 10 | 10 | 10 |
| Diffuse (H or HS) | 95 | 95 | 95 | 95 | 95 |
| Reflection (-R' or -R) | 79 | 63 | 78 | 92 | 78 |
| Net short-wave | 227.0 | 188.0 | 225 | 262 | 225 |
| Net short-wave / Global | 0.49 | 0.51 | 0.49 | 0.48 | 0.49 |
| Outgoing (-L ) | 775 | 775 | 775 | 775 | 775 |
| Thermal (S ) | 551 | 551 | 551 | 551 | 551 |
| Net longwave (Sw) | -224 | -224 | -224 | -224 | -224 |
| Cloudy net longwave | -181 | -181 | -181 | -181 | -181 |
| Net radiation | 46 | 7 | 44 | 81 | 44 |
| Net radiation / Global | 0.099 | 0.019 | 0.096 | 0.149 | 0.096 |

*0 means horizontal plane, N means N-facing slopes and so forth.

TABLE 27 (Continued)

THE THEORETICAL RADIATION BALANCE (LANGLEYS·DAY$^{-1}$) OF VARIOUS SURFACES WITH 20% SLOPE AT THE EXPERIMENT SITE ON DECEMBER 21 AND MARCH 21.

| | March 21 | | | | |
|---|---|---|---|---|---|
| Radiation Components | 0* | N | E | S | W |
| Direct (DR' or DR) | 592 | 535 | 581 | 626 | 581 |
| Cloudiness (-CF) | 284 | 257 | 279 | 300 | 279 |
| Shading effect (-SE) | 13 | 13 | 13 | 13 | 13 |
| Diffuse (H or HS) | 84 | 84 | 84 | 84 | 84 |
| Reflection (-R' or -R) | 115 | 105 | 113 | 121 | 113 |
| Net short-wave | 264 | 244 | 260 | 276 | 260 |
| $\frac{\text{Net short-wave}}{\text{Global}}$ | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 |
| Outgoing (-L ) | 797 | 797 | 797 | 797 | 797 |
| Thermal (S ) | 578 | 578 | 578 | 578 | 578 |
| Net longwave (Sw) | -219 | -219 | -219 | -219 | -219 |
| Cloudy net longwave | -184 | -184 | -184 | -184 | -184 |
| Net radiation | 80 | 60 | 76 | 92 | 76 |
| $\frac{\text{Net radiation}}{\text{Global}}$ | 0.118 | 0.097 | 0.114 | 0.130 | 0.114 |

*0 means horizontal plane, N means N-facing slopes and so forth.

# APPENDIX III

LISTING OF FORTRAN IV PROGRAM FOR SUNSHINE DURATION, DIRECT BEAM, ANGOT'S VALUE, DIFFUSE, AND GLOBAL RADIATION

```
      C     ***CALCULATION OF RADIATION REGIMES AT LOW LATITUDE ON SLOPE
            DIMENSION A(4),AA(4),D(24),E(4),EE(4),FS(4),FFS(4),T(24),TS(4,24),
           *TE(4,24),DATE(24),DB(5,24),X(80),DF(24),G(80),FR(5,25),Z(80),SS(80
           *),DGG(24)
            INTEGER DATE
            REAL M,X
      C DB=DIRECT BEAM  DF=DIFFUSE RADIATION GR=GLOBAL RADIATION
      C        DATA INPUT FROM DATA DECK -RADIANS   EXCEPT A IN DEGREES
a           READ(5,1)(A(I),I=1,4),B,F
          1 FORMAT(6F10.0)
            READ(5,2)(D(J),J=1,24)
          2 FORMAT(8F10.3/8F10.3/8F10.3)
      C     CALCULATION OF DIRECT-BEAM SHINING DURATIONS
      C     A=AA=ASPECT B=SLOPE F=LATITUDE D=DECLINATION E=NON-SHIFT=EE
      C    FS=CORRESPONDING LATITUDE OF SLOPE=FFS T=DURATION ON PLANE
      C    TS=APPARENT DURATION ON SLOPE  TE=TURE DURATION ON SLOPE
      C     CALCULATION OF T,FS,E,TS
            DO 11 J=1,24
            C=D(J)
            TTXJX=ARCOS(SIN(C)*SIN(F)/(-COS(C)*COS(F)))
            CALL HOUR(TTXJX,T(J))
         11 CONTINUE
            DO 13 I=1,4
            CALL CON(A(I),Y)
            FS(I)=ARSIN(SIN(F)*COS(B)-(COS(F)*SIN(B)*COS(Y)))
            FF=FS(I)
```

```
      E(I)=ARCOS((COS(B)-(SIN(F)*SIN(FF)))/(COS(F)*COS(FF)))
      DO 12 J=1,24
      V=D(J)
      TTS=ARCOS(SIN(V)*SIN(FF))/(-COS(V)*COS(FF)))
      CALL HOUR(TTS,TS(I,J))
C      FIND TRUE VALUE ON SLOPES
      IF(T(J).GE.TS(I,J))TE(I,J)=TS(I,J)
      IF(T(J),LT.TS(I,J))TE(I,J)=T(J)
   12 CONTINUE
C     CONVERTIONS
      AA(I)=A(I)
      CALL CONV(FS(I),FFS(I))
      CALL HOUR(E(I),EE(I))
   13 CONTINUE
C     PRINT TABLE 1
      WRITE(6,40)
   40 FORMAT('   TABLE 1:DIRECT-BEAM SHINING DURATIONS FOR DIFFERENT SUR
     *FACE CONDITIONS AT THE LOCATION OF LATITUDE N21D19,EXPRESSED BY --
     *DEGREE ')
      WRITE(6,41)
   41 FORMAT('     OR--HOUR--MIN. DEPARTED FROM NOON')
      PRINT 4,(AA(I),I=1,4),(EE(I),I=1,4),(FFS(I),I=1,4),(T(J),(TS(I,J),
     *TE(I,J),I=1,4),J=1,24)
    4 FORMAT(1H,5X,'SLOPE',5X,'PLANE',8X'SORTH',15X,'NOUTH',15X,'EAST',1
     *6X,'WEST'/' ', 4X,'ASPECT',4(9X,F12.2)/' ','NOON-SHIFT',4(16X,F5.2)
     */' ','COLATITUDE',4(16X,F5.2)/' ','JANUARY 7 ',9F10.2/' ',23(11X,9
     *F10.2/)' ','DECEMBER 21',5X,'T(J)',3X,'TS(1,J)',3X,'TE(1,J)',3X,'
     *TS(2,J)',3X,'TE(2,J)',3X,'TS(3,J)',3X,'TE(3,J)',3X,'TS(4,J)',3X,'T
     *E(4,J)'////)
```

```
       WRITE(6,44)
  44   FORMAT(/' ','TABLE  2:RESIDUES OF ANGOT  VALU AFTER  ATM ABS'/)
C IT IS IMPORTANT TO NOTE THAT THE DIFFERENT BETWEEN GLOYNE EQ AND GARNE
C   CALCULATION OF DIRECT BEAM ON DIFFERENT SLOPE SURFACES
C  CONVERT INPUT DATA BY 180=0-A    ;PLANE ISN'T AFFECTED BY A
C   THEREFORE,A=0,N;E=90 ;W=270=-90 S==180
       READ(5,90)(DATE(J),J-1,24)
  90   FORMAT(24I3)
       DO 100 I=1,5
       DO 101 J=1,24
       DD=D(J)
C      SUN/EARTH DISTANCE OF A GIVEN DATE
       DA=DATE(J)
       R=0.01676*COS(3.1415927-0.0172615*(DA-3.0))+1.0
       IF(I.EQ.1)GO TO 102
C  INTEGRATION OF DR FOR A GIVEN DURATION OF SLOPES
       II=I-1
       CALL NO(TE(II,J),KE)
b      B=0.381
       CX=180.0-A(II)
       CALL CON(CX,CXXXX)
       CALL INTEG(R,KE,DD,F,B,CXXXX,DR)
       DB(I,J)=DR
       GO TO 101
C  INTEGRATION OF DIRECT BEAM FOR GIVEN DURATION ON PLANE
 102   IX=I
       B=0.0
       CALL NO(T(J),KK)
       CX=180.0-A(IX)
```

```
      CALL CON(CX,AXXXX)
      CALL INTEG(R,KK,DD,F,B,AXXXX,DR)
      DB(I,J)=DR
C        (3): CALCULATION OF DIFFUSE RADIATION
C     G=RECIPROCAL OF M
b     BB=0.381/2.0
      BX=COS(BB)*COS(BB)
      O=AXXXX
      CALL INTE (R,KK,DD,F,B,O,DG)
      DGG(J)=DG
      DF(J)=0.5*(DGG(J)-DB(1,J))*BX
  101 CONTINUE
  100 CONTINUE
C   (4) :  CALCULATION OF GLOBAL RADIATION
      DO 105 I=1,5
      DO 106 J=1,24
      GR(I,J)=DB(I,J)+DF(J)
  106 CONTINUE
  105 CONTINUE
      WRITE(6,45)(DGG(J),J-1,24)
   45 FORMAT(/2(10X,12F10.1/)///)
      WRITE(6,42)
   42 FORMAT('   TABLE  3  : DIRECT BEAM ON DIFFERENT SURFACES'///' ','J
     *ANUARY 7     TO     JUNE  21     ++     JULY  7     TO     DECEMBER 21')
      PRINT 103,((DB(I,J),J=1,24),I=1,5)
  103 FORMAT(/' ','PLANE',2(12F9.1/)/'   SOUTH',2(12F9.1/)/'   NORTH'.2(
     *12F9.1/)/'   EAST',2(12F9.1/)/' WEST ',2(12F9.1/)//)
      WRITE(6,43)
```

```
 43  FORMAT('    TABLE 4 :  DIFFUSE RADIATION AT A GIVEN DAY, LY.')
     PRINT 104,(DR(J),J=1,24)
104  FORMAT(/' ',3(8F10.1/))
     WRITE(6,47)
 47  FORMAT('   TABLE 5 :  GLOBAL RADIATION AT A GIVEN DAY, LY. '///)
     PRINT 48,((GR(I,J),J=1,24),I=1,5)
 48  FORMAT(5X,'PLANE',2(12F10.1/)/'  SOUTH',2(12F10.1/)/'  NORTH',2(12
    *F10.1/)/'  EAST ',2(12F10.1/)/'  WEST ',2(12F10.1/)//)
     STOP
     END
```

---

[a]Input of B (slope) and F (latitude) can be changed to any specified values.

[b]These two cards can be changed to any specified slopes. B=0.381 means radian 0.381. BB means the value of half of B.

## APPENDIX III (Continued)

### INTE

```
      SUBROUTINE INTE (R,KK,DD,F,B,O,DG)
      DIMENSION SS(80),G(80)
      DO 302 K=1,KK
      TW=0.01090827+0.02181654*(K-1)
      Q=(-SIN(F)*COS(TW)*SIN(B)*COS(O)-SIN(TW)*SIN(O)*SIN(B)+COS(F)*COS(
     *TW)*COS(B))*COS(DD)+(COS(F)*COS(O)*SIN(B)+SIN(F)*COS(B))*SIN(DD)
      IF(Q.LT.0)Q=0
      G(K)=Q
      IF(TW.GT.0)TZ=-TW
      S=(-SIN(F)*COS(TZ)*SIN(B)*COS(D)-SIN(TZ)*SIN(O)*SIN(B)+COS(F)*COS(
     *TZ)*COS(B))*COS(DD)+(COS(F)*COS(O)*SIN(B)+SIN(F)*COS(B))*SIN(DD)
      IF (S.LT.0)S=0
      SS(K)=S
302   CONTINUE
      DG=0.91*1.94*5.0*(SUM(KK,G)+SUM(KK,SS))/(R*R)
      RETURN
      END
```

### HOUR

```
      SUBROUTINE HOUR(D,T)
      DD=D*180.0/3.1415927
      TT=DD/15.0
      T=INT(TT)+0.01*(TT-INT(TT))*60.0
      RETURN
      END
```

APPENDIX III (Continued)

NO

```
      SUBROUTINE NO(X,K)
C     COUNTING OF NUMBER OF 5-MIN INTERVALS FOR A GIVEN DATE
      XK=INT(X)*60.0+100.0*(X+0,02-INT(X))
      K=XK/5
      RETURN
      END
```

INTEG

```
      SUBROUTINE INTEG(R,N,DD,F,B,A,DR)
C   GENERATION AND SUMMATION OF TOTAL INTERVALS OF A DAY
      REAL M,X(80),Z(80)
      DO 301 K=1,N
C     TK IS POSITIVE IN AFTERNOON
      TK=0.01090827+0.02181654*(K-1)
C    OPTICAL AIR MASS AT ANY MOMENT K
      M=1.0/(COS(DD)*COS(F)*COS(TK)+SIN(DD)*SIN(F))
      H=(-SIN(F)*COS(TK)*SIN(B)*COS(A)-SIN(TK)*SIN(A)*SIN(B)+COS(F)*COS(
     *TK)*COS(B))*COS(DD)+(COS(F)*COS(A)*SIN(B)+SIN(F)*COS(B))*SIN(DD)
      IF(P.LT.0)P=0
      X(K)=(0.8**M)*H
C     TK IS NEGATIVE IN MORNING ;M IS NOT AFFECTED BY SIGN OF TK
      IF(TK.GTO)TM=-TK
      P=(-SIN(F)*COS(TM)*SIN(B)*COS(A)-SIN(TM)*SIN(A)*SIN(B)+COS(F)*COS(
     *TM)*COS(B))*COS(DD)+(COS(F)*COS(A)*SIN(B)+SIN(F)*COS(B))*SIN(DD)
      IF(P.LT.0)P=0
      Z(K)=(0.8**M)*P
  301 CONTINUE
      DR=1.94*5.0*(SUM(N,X)+SUM(N,Z))/R*R
      RETURN
      END
```

APPENDIX III (Continued)

CONV

```
      SUBROUTINE CONV(R,P)
      PP=R*180.0/3.1415927
      P=INT(PP)+0.01*(PP-INT(PP))*60.0
      RETURN
      END
```

CON

```
      SUBROUTINE CON(W,U)
      U=W*3.1415927/180.0
      RETURN
      END
```

SUM

```
      FUNCTION SUM(N,X)
C     SUMMATION OF A SINGLE ARRAY
      REAL X(80)
      SUM=0.0
      DO 10000 I=1,N
1000  SUM=SUM+X(I)
      RETURN
      END
```

# APPENDIX IV

## MISCELLANEOUS EXPERIMENTAL DATA IN RESULTS

TABLE 28

AN EXAMPLE OF THE NULL-ALIGNMENT METHOD FOR COMPUTING SOIL HEAT FLUX (DATA WERE COLLECTED AT 1010 AND 1050 ON FEBRUARY 29, 1976).

| Depth Z, Cm | Temperature, Ts, C at 1010 | Temperature, Ts, C at 1050 | Temperature gradient with time $\Delta Ts/\Delta T$, $C\cdot min^{-1}$ | Temperature gradient with depth, $dTs/dz$, $C\cdot cm^{-1}$ | Soil heat flux $langleys\cdot min^{-1}$ Se | Soil heat flux $langleys\cdot min^{-1}$ Sa | True thermal conductivity, $langleys\cdot min^{-1}/C\cdot cm^{-1}$ |
|---|---|---|---|---|---|---|---|
| 0 | 28.0 | 29.0 | 0.025 | -1.433 | | -0.109 | |
| -3 | 21.2 | 25.0 | 0.095 | -1.053 | | -0.08 | |
| -6 | 19.7 | 21.6 | 0.0225 | -0.5 | | -0.038 | |
| -9 | 19.3 | 20.3 | 0.025 | -0.2 | | -0.0152 | |
| -12 | 19.3 | 20.3 | 0.0175 | -0.04 | | -0.0006 | |
| -15 | 19.7 | 20.0 | 0.0075 | -0.1 | -0.0152 | -0.0076 | |
| -18 | 20.2 | 20.4 | 0.005 | 0.21 | -0.0061 | 0.016 | |
| -21 | 20.6 | 20.8 | 0.005 | 0.2 | 0.0031 | 0.0152 | 0.076 |

1. Assuming soil thermal conductivity at 21 cm is $\lambda$-21 = 0.0151 $langleys\cdot min^{-1}/C\cdot cm^{-1}$

2. The estimated soil heat flux at 21 cm depth is Se-21 = $-21(\frac{dTs}{dz})-21 = 0.0031\ langleys\cdot min^{-1}$

3. The estimated soil heat flux at any layer above the reference depth (21 cm) can be calculated as Sei-1 = $Si - Chi(\Delta z)i(\frac{\Delta Ts}{\Delta T})i$,
where i means $i^{th}$ layer of soil, Chi = soil heat capacity $= 0.47\,x_{mi} + 0.6x_{oi} + x_{wi}$, at water content of 0.13 bar, $Ch = 0.46 \times 0.4 + 0.6 \times 0.024 + 0.041 \times 1 = 0.0084\ cal\cdot gm^{-1}$, according to Table 1.

Here, assuming all Chi are the same because the soil water content is similar between 0.05 and 0.25 bars,

$\therefore$ Se-18 = 0.0031 - 0.6084 x 3 x 0.005 = -0.0061

Se-15 = -0.0061 - 0.6084 x 3 x 0.005 = -0.0152

4. At $\frac{dTs}{dz}$ = 0, Se = correction factor = $\frac{(-0.0061-0.0152)}{(0.21)-(-0.1)}$ x (0 - 0.21) x (-0.0061) = -0.0121 cal $gm^{-1}$.

A linear proportioning of the estimated soil heat flux showed that -0.0121 langleys$\cdot$min$^{-1}$ must be subtracted from each of the estimated soil heat flux values in order to align the null of the heat flux with the null of the temperature gradient.

5. The actual soil heat flux at the 21 cm depth is Sa = Se - Se $\therefore$ Sa - 21 = 0.0031 - (-0.0121) = 0.01521 langley$\cdot$min$^{-1}$

6. The true soil thermal conductivity is $\lambda'$-21 = Sa - 21/ ($\frac{dTs}{dz}$)-21 = 0.076 langleys$\cdot$min$^{-1}$/ C$\cdot$cm$^{-1}$

7. Sai = $\lambda'$-21($\frac{dTs}{dz}$)i for the rest above the depth of 21 cm.

TABLE 29

COMPUTATION OF INCHES OF WATER USE ($\int$ ET).

| Growth[a] interval | Date | RR | NW I | NW PP | SW I | SW PP | SE I | SE PP | NE I | NE PP |
|---|---|---|---|---|---|---|---|---|---|---|
| | 26 D to 31 D | | 3.0 | | 3.0 | | 3.0 | | 3.0 | |
| | 1 J | 0.1 | | | | | | | | |
| | 2 | | 0.1 | | 0.1 | | 0.1 | | 0.1 | |
| | 5 | 0.02 | | | | | | | | |
| 26 D | 6 | 0.24 | 0.1 | | 0.1 | | 0.1 | | 0.1 | |
| | 7 | | 0.1 | | 0.1 | | --- | | --- | |
| to | 8 | 0.02 | 0.5 | | 0.5 | | 0.5 | | 0.5 | |
| | 9 | 0.22 | | | | | | | | |
| 24 J | 10 | 0.18 | | | | | | | | |
| | 13 | | 0.5 | | 0.5 | | 0.5 | | 0.5 | |
| | 14 | 0.02 | | | | | | | | |
| | 15 | | 0.5 | | 0.5 | | 0.5 | | 0.5 | |
| | 16 | 0.54 | | -0.31 | | -0.52 | | -0.81 | | --- |
| | 18 | 0.15 | | | | | | | | |
| | 21 | | 0.50 | | 0.5 | | 0.5 | | 0.5 | |
| $\int$ ET | Sum | | 6.79-0.31=6.48 | | 6.79-0.52=6.27 | | 6.69-0.81=5.88 | | 6.69-0=6.69 | |
| | Mean (daily) | | 0.216"=0.549 cm | | 0.209"=0.531 cm | | 0.196"=0.498 cm | | 0.223"=0.566 cm | |

TABLE 29 (Continued)

COMPUTATION OF INCHES OF WATER USE ( ∫ ET).

| Growth [a] interval | Date | RR | NW I | NW PP | SW I | SW PP | SE I | SE PP | NE I | NE PP |
|---|---|---|---|---|---|---|---|---|---|---|
| | 27 J | | 0.5 | | 0.5 | | 0.5 | | 0.5 | |
| | 29 | | 0.5 | | 0.5 | | 0.5 | | 0.5 | |
| | 31 | | 1.11 | | 1.11 | | 1.11 | | 1.11 | |
| | 3 F | | | --- | | -1.01 | | -0.77 | | -0.04 |
| | 4 | | | -1.44 | | --- | | --- | | -0.59 |
| | 6 | 3.59 | | -1.15 | | --- | | -1.56 | | -1.56 |
| | | | | -0.26* | | -0.37* | | -0.09* | | -0.08* |
| | 7 | 1.47 | | -1.15 | | -2.08 | | -0.88 | | -1.55 |
| | 8 | 1.75 | | -1.04 | | -1.10 | | -0.9 | | -1.08 |
| 25 J | 9 | 0.05 | | | | | | | | |
| | 10 | 0.01 | | -0.73 | | -1.14 | | -1.29 | | -0.8 |
| to | 11 | -0.28 | | -0.3 | | -0.18 | | -0.41 | | -0.18 |
| | 12 | 0.02 | | | | | | | | |
| 25 F | 13 | 0.2 | | | | | | | | |
| | 14 | 0.34 | | | | | | | | |
| | 15 | 0.38 | | | | | | | | |
| | 16 | 0.09 | | | | | | | | |
| | 17 | 0.18 | | | | | | | | |
| | 18 | 0.03 | | | | | | | | |
| | 19 | 0.06 | | | | | | | | |
| | 20 | 0.08 | | | | | | | | |
| | 21 | 0.12 | | | | | | | | |
| | 22 | 1.41 | | | | | | | | |
| | 23 | 1.81 | | | | | | | | |
| | 25 | | | -1.2 | | -1.0 | | -0.9 | | -1.29 |
| ∫ ET | Sum | | 13.98-7.27=6.71 | | 13.98-6.88=7.10 | | 13.98-6.8=7.18 | | 13.98-7.17=6.81 | |
| | Mean (daily) | | 0.216"=0.550 cm | | 0.229"=0.582 cm | | 0.232"=0.588 cm | | 0.220"=0.558 cm | |

TABLE 29 (Continued)

COMPUTATION OF INCHES OF WATER USE ($\int$ ET).

| STAGE [a] | Date | RR | NW I | NW PP | SW I | SW PP | SE I | SE PP | NE I | NE PP |
|---|---|---|---|---|---|---|---|---|---|---|
| | 27 | | 0.50 | | 0.50 | | 0.50 | | 0.50 | |
| | 29 | 0.01 | 0.1 | | 0.10 | | 0.10 | | 0.10 | |
| | 1 M | 0.42 | | | | | | | | |
| | 3 | | 0.1 | | 0.10 | | 0.10 | | 0.10 | |
| | 4 | 0.40 | | | | | | | | |
| | 5 | 0.24 | | | | | | | | |
| | 6 | 0.06 | | | | | | | | |
| | 7 | 0.17 | | | | | | | | |
| | 8 | 0.32 | | | | | | | | |
| 25 F | 9 | 0.23 | | | | | | | | |
| | 10 | 0.06 | | | | | | | | |
| to | 11 | 0.03 | | | | | | | | |
| | 12 | | 0.50 | | 0.50 | | 0.50 | | 0.50 | |
| 24 M | 14 | | 0.10 | | 0.10 | | 0.10 | | 0.10 | |
| | 15 | | 0.50 | | 0.50 | | 0.50 | | 0.50 | |
| | 17 | 1.72 | | | | | | | | |
| | 18 | 0.10 | | | | | | | | |
| | 20 | 0.01 | | -0.73 | | -1.5 | | -0.7 | | -1.30 |
| | 21 | 0.21 | | | | | | | | |
| | 22 | 0.18 | | | | | | | | |
| | 23 | 0.74 | | | | | | | | |
| $\int$ET | Sum | | 6.7-0.73=5.97 | | 6.7-1.5=5.2 | | 6.7-0.7=6.0 | | 6.7-1.3=5.4 | |
| | Mean (daily) | | 0.206"=0.523 cm | | 0.179"=0.455 cm | | 0.207"=0.526 cm | | 0.186"=0.473 cm | |

*Runoff

[a] D=December, J=January, F=February and M=March

TABLE 30a

THE SAMPLED VERTICAL TEMPERATURE PROFILES IN THE LYSIMETERS ON FEBRUARY 11, 1976.

| Aspect | N | S | N | S | S | S | S | S | S | S | S | S | S | S | S | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Time | 1540 | 1550 | 2140 | 2320 | 2400 | 0040 | 0120 | 0200 | 0240 | 0320 | 0400 | 0440 | 0520 | 0620 | 0700 | 0730 |
| Depth | Temperature, C | | | | | | | | | | | | | | | |
| +25 | --- | --- | 18.8 | 21.2 | 21.0 | 20.9 | 20.8 | 20.2 | 20.2 | 20.2 | 20.1 | 20.1 | 20.0 | 20.0 | 20.0 | 20.3 |
| +10 | --- | --- | 18.4 | 21.1 | 21.0 | 20.7 | 20.6 | 19.5 | 19.2 | 19.0 | 19.0 | 18.7 | 18.7 | 19.5 | 19.5 | 19.0 |
| 0 | 30.2 | 30.4 | 17.5 | 20.5 | 20.5 | 20.2 | 20.0 | 19.2 | 18.0 | 17.2 | 17.0 | 16.7 | 16.3 | 17.2 | --- | 18.2 |
| -1.5 | 25.2 | 28.8 | 21.0 | 22.3 | 22.3 | 22.1 | 21.4 | 21.0 | 20.6 | 20.4 | 20.0 | 19.0 | 19.1 | 19.1 | 19.7 | --- |
| -3.0 | 25.0 | 28.7 | 21.2 | 22.5 | 22.5 | 22.3 | 22.2 | 21.8 | 21.4 | 20.9 | 20.4 | 20.2 | 20.0 | 19.9 | 20.8 | --- |
| -4.5 | 25.0 | 28.2 | 21.2 | 22.7 | 22.4 | 22.3 | 22.2 | 22.1 | 21.9 | 21.3 | 21.2 | 21.0 | 20.8 | 20.9 | 21.0 | 20.8 |
| -6.0 | 24.6 | 27.2 | 21.4 | 23.2 | 22.6 | 22.5 | 22.4 | 22.1 | 21.8 | 21.6 | 20.5 | 20.3 | 20.4 | 20.4 | 21.0 | 21.0 |
| -7.5 | 24.0 | 26.2 | 21.3 | 23.4 | 23.2 | 23.1 | 23.0 | 23.0 | 22.5 | 21.5 | 19.7 | 20.0 | 20.0 | 20.3 | --- | --- |
| -9.0 | 23.3 | 25.3 | 20.8 | 23.7 | 23.3 | 23.2 | 23.1 | 22.9 | 21.7 | 20.8 | 20.2 | 19.9 | 20.2 | 20.7 | --- | 21.5 |
| -12.0 | 22.5 | 24.2 | 20.6 | 24.2 | 23.4 | 23.3 | 23.1 | 22.6 | 21.8 | 21.0 | 20.6 | 20.4 | 19.9 | 19.7 | 21.5 | 22.8 |
| -15.0 | --- | --- | 20.6 | 24.0 | 23.4 | 23.4 | 23.3 | 22.1 | 21.8 | 21.3 | 20.7 | 20.6 | 20.3 | 20.4 | --- | --- |
| -18.0 | --- | --- | 20.5 | 23.0 | 23.0 | 23.0 | --- | 21.9 | 21.7 | 21.5 | 20.7 | 20.9 | 20.5 | 21.8 | --- | --- |
| -21.0 | --- | --- | 20.5 | 23.0 | 23.0 | 23.0 | 23.0 | 21.9 | 21.7 | 21.5 | 20.7 | 20.9 | 20.7 | 21.9 | --- | 22.4 |

TABLE 30b

THE SAMPLED VERTICAL TEMPERATURE PROFILES IN THE LYSIMETERS ON FEBRUARY 15, 1976.

| Aspect | N | S | N | S | N | S | S | S |
|---|---|---|---|---|---|---|---|---|
| Time | 1500 | 1520 | 1540 | 1635 | 1705 | 1725 | 1805 | 1835 |
| Depth | | | | Temperature, C | | | | |
| +20 | --- | --- | --- | --- | --- | --- | --- | --- |
| +10 | 23.8 | 25.3 | 23.7 | 23.2 | 21.8 | 23.0 | 21.7 | 21.0 |
| 0 | 27.7 | 34.3 | 27.4 | --- | 24.1 | 24.8 | 23.8 | 20.0 |
| -1.5 | 25.0 | 31.3 | 22.8 | 32.8 | 22.7 | 26.7 | 25.4 | 22.4 |
| -3.0 | 24.4 | 30.8 | 26.7 | 32.3 | 22.2 | 27.0 | 25.7 | 23.4 |
| -4.5 | 24.0 | 30.5 | 26.4 | 31.8 | 22.0 | 26.5 | 26.3 | 24.4 |
| -6.0 | 23.6 | 29.6 | 26.1 | 30.8 | 21.9 | 26.3 | 26.5 | 24.4 |
| -7.5 | 23.2 | 29.2 | 25.7 | 30.2 | 21.7 | 26.1 | 25.5 | 24.2 |
| -9.0 | 23.0 | 28.8 | 25.1 | 29.4 | 21.6 | 25.9 | 25.4 | 24.0 |
| -12.0 | 22.5 | 28.0 | 24.4 | 28.4 | 21.2 | 25.7 | 25.3 | 23.6 |
| -15.0 | 22.4 | 27.3 | 24.0 | 27.6 | 21.3 | 25.5 | 25.2 | 23.5 |
| -18.0 | 22.3 | 26.7 | 23.6 | 26.8 | 21.5 | 25.3 | 25.2 | 23.4 |
| -21.0 | 22.2 | 26.5 | 23.5 | 26.5 | 20.6 | 25.2 | 25.1 | 23.4 |
| -24.0 | --- | --- | --- | --- | --- | --- | --- | --- |
| -27.0 | --- | --- | --- | --- | --- | --- | --- | --- |
| -30.0 | --- | --- | --- | --- | --- | --- | --- | --- |
| air* | --- | --- | --- | --- | --- | 21.7 | 21.2 | 20.6 |

*Air temperature is measured at 1 m above the ground.

TABLE 30c

THE SAMPLED VERTICAL TEMPERATURE PROFILES IN THE LYSIMETERS ON FEBRUARY 29, 1976.

| Aspect | N | S | N | S | N | S | N | S | N | S |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | 850 | 910 | 930 | 950 | 1010 | 1020 | 1050 | 1100 | 1130 | 1140 |
| Depth | | | | | Temperature, C | | | | | |
| +30 | 18.3 | 19.7 | 20.0 | 22.6 | 27.0 | 24.0 | 26.5 | 24.6 | 27.6 | 25.4 |
| +20 | 18.0 | 19.8 | 19.6 | 22.7 | 26.7 | 24.5 | 26.7 | 24.6 | 27.6 | 25.5 |
| +10 | 17.7 | 20.1 | 19.3 | 23.1 | 26.8 | 24.2 | 26.9 | 24.8 | 27.6 | 25.6 |
| 0 | 19.3 | 23.6 | 25.5 | 27.6 | 28.0 | 28.0 | 29.0 | 29.0 | 30.7 | 28.5 |
| -1.5 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| -3.0 | 17.1 | 17.4 | 19.3 | 19.6 | 21.2 | 22.6 | 25.0 | 23.3 | 26.2 | 24.5 |
| -4.5 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| -6.0 | 17.5 | 17.6 | 18.6 | 18.3 | 19.7 | 19.6 | 21.6 | 20.5 | 22.5 | 21.7 |
| -7.5 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| -9.0 | 18.6 | 18.2 | 18.9 | 18.4 | 19.3 | 19.1 | 20.3 | 19.7 | 21.0 | 20.2 |
| -12.0 | 19.3 | 18.7 | 19.3 | 18.7 | 19.3 | 19.2 | 20.0 | 19.4 | 20.4 | 20.0 |
| -15.0 | 20.3 | 19.4 | 20.0 | 19.4 | 19.7 | 19.7 | 20.0 | 19.6 | 20.1 | 19.9 |
| -18.0 | 20.7 | 20.1 | 20.5 | 19.6 | 20.2 | 19.7 | 20.4 | 20.1 | 20.4 | 20.2 |
| -21.0 | 21.2 | 20.2 | 20.7 | 20.1 | 20.6 | 20.1 | 20.8 | 20.4 | 20.8 | 20.3 |
| -24.0 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| -27.0 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| -30.0 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| air* | 20.0 | --- | 22.2 | --- | 23.5 | --- | 24.6 | --- | 25.5 | --- |

*Air temperature measured at 1 m above the ground.

TABLE 30d

THE SAMPLED VERTICAL TEMPERATURE PROFILES IN THE LYSIMETERS ON MARCH 20 AND 21, 1976.

| | March 20 | | | | | | | | | | | | | | March 21 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aspect | N | S | N | S | N | S | N | S | N | S | N | S | N | S | N | S |
| Time | 1010 | 1020 | 1050 | 1100 | 1130 | 1140 | 1210 | 1220 | 1530 | 1550 | 1610 | 1620 | 1650 | 1655 | 910 | 915 |
| Depth | Temperature, C | | | | | | | | | | | | | | | |
| +25 | 25.6 | 22.1 | 25.0 | 22.8 | 26.2 | 22.0 | 28.4 | 23.5 | 26.5 | 24.0 | 23.0 | 21.2 | 20.6 | 20.6 | 25.0 | 22.8 |
| +10 | 25.5 | 22.0 | 25.1 | 23.1 | 26.0 | 21.8 | 28.0 | 23.1 | 26.5 | 24.1 | 23.0 | 21.2 | 20.6 | 20.4 | 24.8 | 22.6 |
| 0 | 25.2 | 23.7 | 27.3 | 26.7 | 29.0 | 28.8 | 30.1 | 29.8 | 27.3 | 27.6 | 23.8 | 24.2 | 22.3 | 23.3 | 24.0 | 23.4 |
| -1.5 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| -3.0 | 22.5 | 22.8 | 22.7 | 23.8 | 24.5 | 25.3 | 25.1 | 28.0 | 26.8 | 29.2 | 24.6 | 27.0 | 24.1 | 25.8 | 22.7 | 22.4 |
| -4.5 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| -6.0 | 21.5 | 22.3 | 21.9 | 23.4 | 23.2 | 24.0 | 23.6 | 25.5 | 24.7 | 28.2 | 24.6 | 27.5 | 24.5 | 26.3 | 22.3 | 21.7 |
| -7.5 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| -9.0 | 21.0 | 21.7 | 21.2 | 22.3 | 22.2 | --- | 22.6 | 23.8 | 23.1 | 26.4 | 23.7 | 26.6 | 24.0 | 25.8 | 21.5 | 21.6 |
| -12.0 | 20.7 | 21.5 | 20.9 | 21.7 | 21.3 | 22.1 | 21.4 | 22.3 | 22.1 | 24.4 | 22.8 | 24.8 | 23.0 | 25.2 | 21.2 | 21.5 |
| -15.0 | 20.8 | 21.6 | 20.9 | 21.6 | 21.1 | 22.0 | 21.2 | 21.9 | 21.7 | 23.7 | 22.2 | 24.1 | 22.5 | 24.1 | 21.3 | 21.6 |
| -18.0 | 21.0 | 21.7 | 21.0 | 21.7 | 21.0 | 21.8 | 21.1 | 21.8 | 21.5 | 23.0 | 21.9 | 23.5 | 22.2 | 23.4 | 21.6 | 21.8 |
| -21.0 | 21.1 | 21.8 | 21.1 | 21.8 | 21.1 | 22.0 | 21.0 | 21.8 | 21.3 | 22.5 | 21.7 | 22.8 | 22.1 | 22.7 | 21.8 | 22.1 |
| -24.0 | 21.3 | 22.0 | 21.3 | 20.0 | 21.3 | 22.0 | 21.1 | 21.9 | 21.3 | 22.2 | 21.5 | 22.6 | 21.8 | 22.5 | 22.0 | 22.2 |
| -27.0 | --- | --- | --- | --- | --- | 22.1 | 21.3 | 22.0 | 21.3 | 22.2 | 21.5 | 22.4 | 21.8 | 22.2 | 22.0 | 22.2 |
| -30.0 | --- | --- | --- | --- | --- | --- | --- | --- | 22.0 | 22.0 | 21.5 | 22.3 | 21.8 | 22.1 | 22.0 | 22.2 |
| Air* | 21.1 | --- | --- | --- | --- | --- | 28.4 | --- | 26.5 | 26.0 | 22.7 | --- | 20.9 | --- | --- | --- |

*Air temperature measured at 1 m above the ground.

TABLE 31

GERMINATION COUNT PER 5 DAYS FOR FOUR LYSIMETERS.

| Area observed | Slope | Days after planting 10 | 15 | 20 | 25 | 30 |
|---|---|---|---|---|---|---|
| Whole lysimeter | $N_W$ | 0 | 7 | 28 | 9 | 0 |
| | $N_E$ | 1 | 6 | 25 | 11 | 1 |
| | $S_W$ | 0 | 13 | 28 | 2 | 1 |
| | $S_E$ | 0 | 25 | 14 | 4 | 1 |
| Edge plants excluded | $N_W$ | 0 | 0 | 14 | 7 | 0 |
| | $N_E$ | 0 | 0 | 13 | 6 | 1 |
| | $S_W$ | 0 | 3 | 16 | 1 | 0 |
| | $S_E$ | 0 | 9 | 8 | 3 | 0 |

TABLE 32

THE RATE OF EMERGENCE OF FIRST TILLER PER 5

DAYS FOR FOUR LYSIMETERS.

| Area observed | Slope | Days after planting 51 | 56 | 61 | 66 | 71 | 76 | 81 | 86 | 91 |
|---|---|---|---|---|---|---|---|---|---|---|
| Whole lysimeter | $N_W$ | 0 | 0 | 0 | 3 | 5 | 11 | 10 | 2 | 3 |
| | $N_E$ | 0 | 0 | 4 | 7 | 5 | 11 | 3 | 6 | 7 |
| | $S_W$ | 0 | 3 | 6 | 16 | 12 | 3 | 1 | 1 | 1 |
| | $S_E$ | 1 | 3 | 12 | 10 | 7 | 5 | 2 | 0 | 3 |
| Edge plants excluded | $N_W$ | 0 | 0 | 0 | 0 | 0 | 5 | 5 | 2 | 3 |
| | $N_E$ | 0 | 0 | 0 | 0 | 3 | 7 | 1 | 2 | 5 |
| | $S_W$ | 0 | 0 | 0 | 7 | 9 | 2 | 1 | 0 | 1 |
| | $S_E$ | 0 | 1 | 6 | 6 | 2 | 2 | 2 | 0 | 1 |

TABLE 33

MONTHLY INCREMENT OF NUMBER OF LEAVES FOR FOUR LYSIMETERS.

| Area observed | Slope | Days after planting | | |
|---|---|---|---|---|
| | | 30 | 60 | 88 |
| Whole lysimeter | $N_W$ | 2.6 | 3.6 | 1.9 |
| | $N_E$ | 3.1 | 3.0 | 2.7 |
| | $S_W$ | 3.8 | 3.2 | 2.3 |
| | $S_E$ | 3.7 | 3.0 | 3.1 |
| Edge plants excluded | $N_W$ | 2.8 | 3.1 | 2.0 |
| | $N_E$ | 2.7 | 3.0 | 3.1 |
| | $S_W$ | 3.9 | 2.8 | 2.5 |
| | $S_E$ | 3.5 | 3.3 | 2.7 |

TABLE 34

WEEKLY TILLERING RATE PER PLANT FOR FOUR LYSIMETERS.

| Area observed | Slope | Days | | | | |
|---|---|---|---|---|---|---|
| | | 60 | 67 | 74 | 81 | 88 |
| Whole lysimeter | $N_W$ | 0.0 | 0.2 | 0.8 | 0.7 | 1.0 |
| | $N_E$ | 0.1 | 0.8 | 0.6 | 0.6 | 0.9 |
| | $S_W$ | 0.2 | 1.0 | 1.8 | 0.6 | 0.5 |
| | $S_E$ | 0.4 | 0.9 | 1.0 | 0.7 | 0.7 |
| Edge plants excluded | $N_W$ | 0.0 | 0.0 | 0.2 | 0.8 | 1.0 |
| | $N_E$ | 0.0 | 0.2 | 0.6 | 0.6 | 1.3 |
| | $S_W$ | 0.0 | 0.5 | 2.0 | 1.0 | 0.1 |
| | $S_E$ | 0.3 | 1.1 | 1.0 | 0.6 | 0.7 |

TABLE 35

MONTHLY INCREMENT OF HEIGHT OF STALK PLUS LEAF

(CM MONTH$^{-1}$) FOR FOUR LYSIMETERS.

| Area observed | Slope | Days after planting 30 | 61 | 91 |
|---|---|---|---|---|
| Whole lysimeter | $N_W$ | 29.5 | 50.3 | 45.6 |
| | $N_E$ | 31.0 | 58.7 | 49.8 |
| | $S_W$ | 41.7 | 52.5 | 57.5 |
| | $S_E$ | 39.9 | 52.8 | 60.4 |
| Edge plants excluded | $N_W$ | 24.3 | 52.4 | 48.1 |
| | $N_E$ | 25.1 | 57.1 | 56.4 |
| | $S_W$ | 42.0 | 49.5 | 59.3 |
| | $S_E$ | 38.6 | 53.7 | 62.1 |

TABLE 36

CUMULATIVE HEIGHT OF TOP VISIBLE DEWLAP (IN)

FOR FOUR LYSIMETERS.

| Area observed | Slope | Days after planting 74 | 81 | 88 |
|---|---|---|---|---|
| Whole lysimeter | $N_W$ | 19.9 | 23.3 | 26.9 |
| | $N_E$ | 24.2 | 27.2 | 32.1 |
| | $S_W$ | 26.5 | 30.4 | 34.8 |
| | $S_E$ | 26.4 | 29.9 | 34.7 |
| Edge plants excluded | $N_W$ | 19.3 | 22.7 | 26.3 |
| | $N_E$ | 22.1 | 25.2 | 30.4 |
| | $S_W$ | 27.4 | 31.7 | 36.3 |
| | $S_E$ | 28.1 | 31.6 | 36.9 |

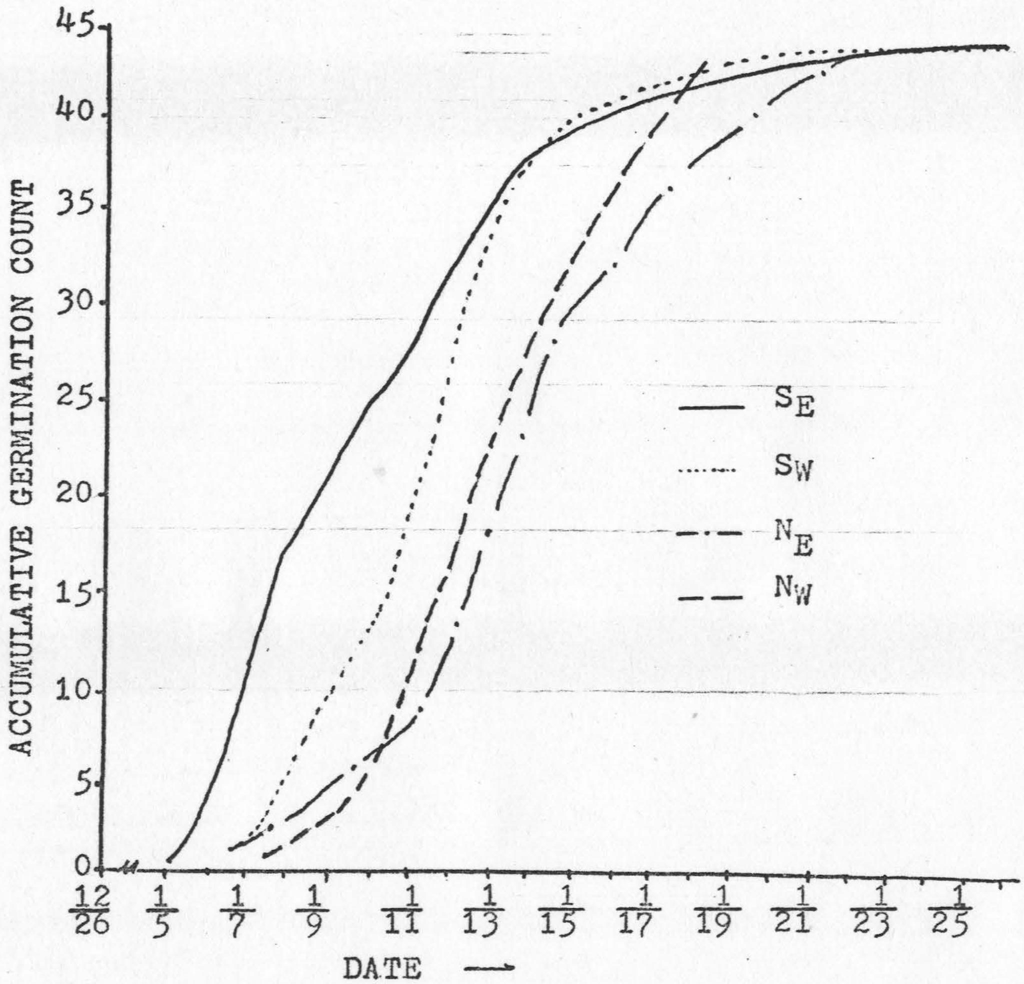



FIGURE 13a: GERMINATION RATE FOR WHOLE LYSIMETER.

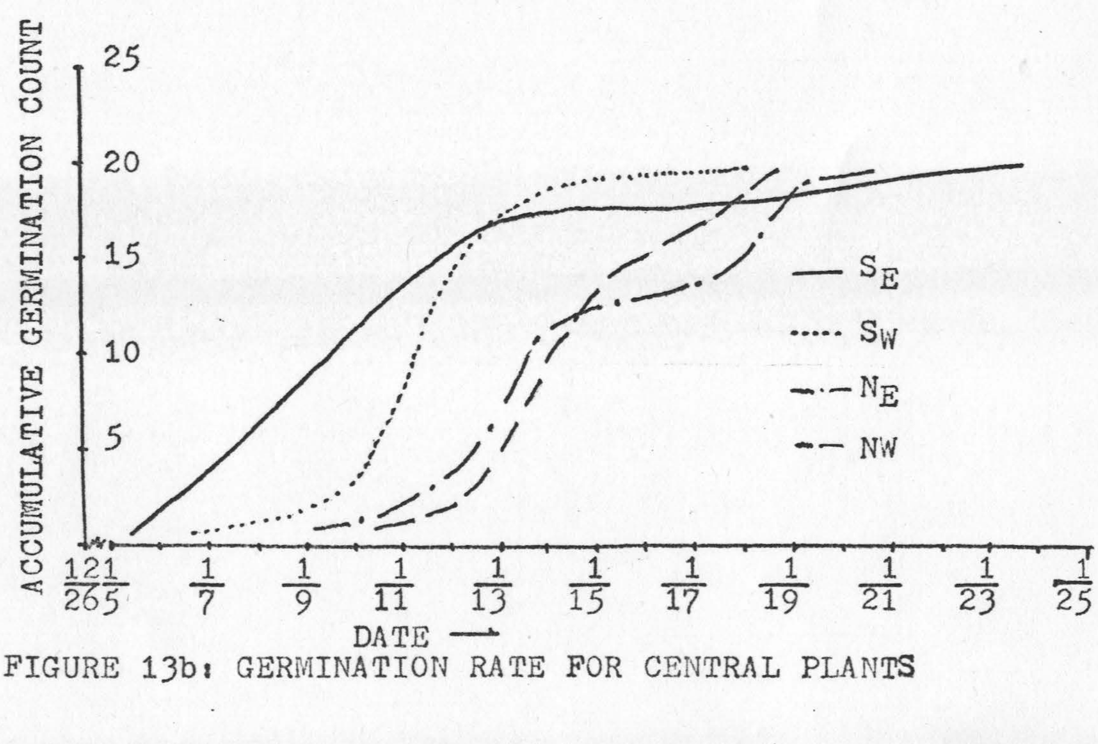



FIGURE 13b: GERMINATION RATE FOR CENTRAL PLANTS

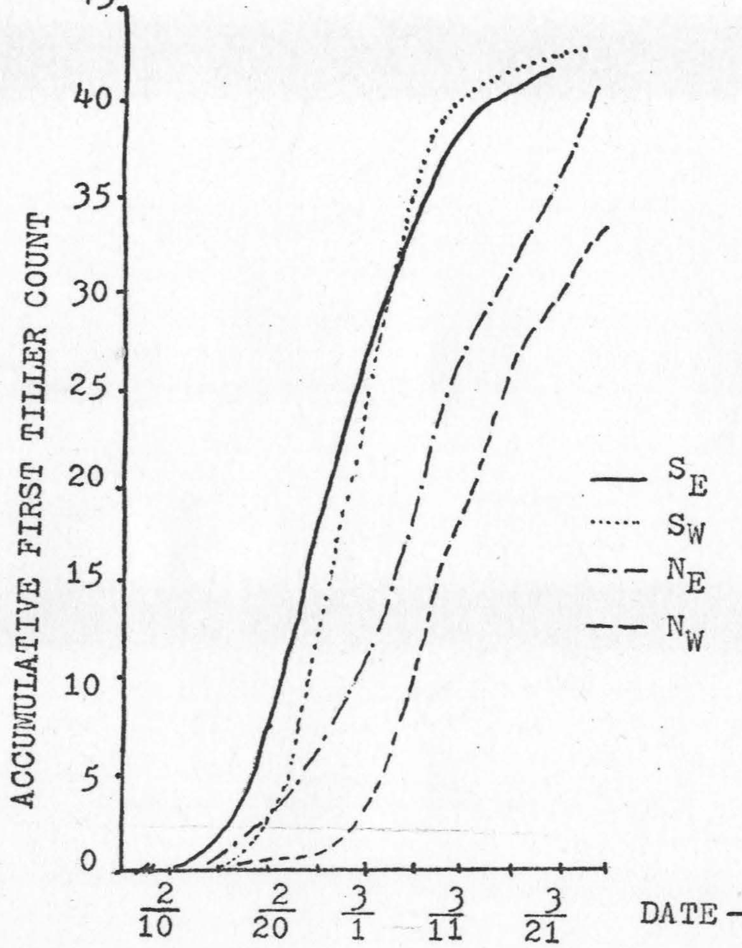



FIGURE 14a: FIRST TILLER RATE FOR WHOLE LYSIMETER.

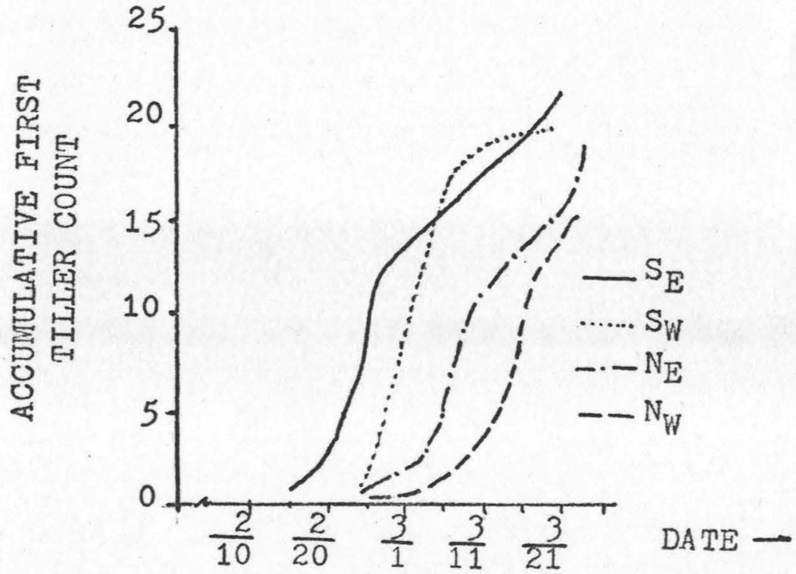



FIGURE 14b: FIRST TILLER RATE FOR CENTRAL PLANTS

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