THE MOISTURE BALANCE OF BARBADOS AND ITS INFLUENCE ON SUGAR CANE YIELD

by

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Master of Science.

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Maps and Diagrams

P R E F A C E

This study embodies the ideas and reflects the help given by many generous people. Special thanks go to Professors Hare and Hills who guided the author's research program, both at McGill and in the field, and to Mr. Ivan Smith in Barbados who put his resources, both human and material, at the author's disposal. Appreciation is extended to members of the Barbados' Department of Agriculture and to various plantation managers in Barbados, all of whom responded readily to requests for information and help. Further acknowledgement goes to the National Research Council of Canada whose grant-in-aid did much to alleviate the financial strain encountered in graduate research. Final thanks is reserved for my wife Margaret, whose help and encouragement means so much.

CHAPTER I INTRODUCTION

Objective of Thesis

Barbados has the distinction of a one crop economy, that crop being sugar cane. This situation has existed for over 300 years, and during the latter part of this period, particularly since 1924, the cane breeding section of the Department of Agriculture has carried on extensive work in developing high yielding varieties of sugar cane especially suited to the island. The nature of investigation has, however, being virtually confined to this one direction, and study of the other important growth factors such as edaphic and especially climatic control has lagged far behind. Fortunately in 1959 a microclimatic station was set up at Waterford under the auspices of the Geography Department of McGill University, and in the last 2 years a considerable knowledge of various climatic parameters has been amassed, and an insight into the moisture balance regime achieved. It is felt that the time is opportune to combine the specific knowledge gained at Waterford with the general knowledge of rainfall for the whole island, to obtain a regional picture of moisture-balance; and in turn to ascertain the influence of the regional moisture regime on sugar agriculture. Such an attempt is the objective of this thesis.

General Introduction

Barbados is the most easterly of the Leeward Islands of the West Indies (Fig. 1). At latitude 13°N it rests well within the tropics and is located about a similar distance north of the equator as for Madras, Bangkok and Manilla. At longtitude 59°W it lies on a north-south line

BARBADOS 5

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Figure 1

through Cape Breton Island and Buenos Aires.

21 miles long by 14 miles wide, the island has a total area of 166 square miles, or 106,240 acres. It is distinctly pear-shaped, the stem of the pear facing northward (Fig. 1) The long axis of the island points 18° west of north.

To obtain the best glimpse of Barbados' physical aspects in one journey it is best to start at South Point, the southernmost extremity of the island, and follow a northward course to North Point (Fig. 1). From the narrow sandy beach, an ascent over a 30 ft. cliff-face leads the traveller to a level coastal plain. Altitude increases only very gradually toward the north until at a height of 300 ft. the east-west trending Christ Church Ridge is surmounted. Immediately to the north, and paralleling the ridge, stretches the fertile St. George Valley. Geologically this is the youngest part of the island, which, following the Pleistocene epoch, was inundated by the sea, probably dividing present-day Barbados into two islands. Although the traverse has already led through land given mainly to sugar agriculture, the importance of cane is even more evident in the valley, where only the small pieces of preparation land in sour grass, yams, potatoes, and corn relieve the dark-green of the sugar landscape.

North of the St. George Valley the land ascends rapidly and relief increases. To the south-west, Bridgetown the commercial heart and only city of Barbados radiates out from Carlisle Bay. As the traverse continues the landscape seems to display a fairly constant pattern, with fields of cane surrounding the large plantation buildings; a scattering of compact peasant villages surrounded by small garden plots; and intersecting ravines, often deeply cut into the coral limestone by small periodical streams. Mahogany trees line the roadsides while the entrance lanes to plantation homes are bordered by stately royal palms. Sugar refineries with their overhanging cranes are a familiar sight, being spaced at fairly regular intervals throughout Barbados.

Mount Hillaby at 1115 ft. is the highest summit in the island. It marks approximately the half-way point in the journey, and affords an unexcelled view of most of Barbados. The lushness of the vegetation is in striking contrast to the semi-arid southern coast, and is a reminder that the available moisture has been increasing steadily along the traverse due to the influence of increasing altitude on the north-easterly trades.

From atop Mt. Hillaby the scene to the west is dominated by a series of limestone terraces descending in step-like fashion to the drier Caribbean coast. Rapidly-growing casuarina trees line the cane fields and serve as wind breaks. To the north it seems even drier, but still cane fields everywhere emphasize Barbados' one crop economy. In the direction of the Atlantic the strongly dissected and often bare rock of the Scotland district juts forth. Conditions are obviously semi-arid, but in some places coconut palm, banana, manioc and breadfruit crops find a place alongside sugar cane on the peasant farms.

The last half of the journey passes through the neck of the pear. Turner's Hall Woods is a forest preserve covering 40 acres of steep hillside. Growing here are many of the broad-leaved trees which must have once covered much of Barbados. Toward the north the altitude decreases steadily and brings an equally steady increase in aridity. The journey terminates at the north coast cliff-face, where the ocean constantly pounds the bare coral rock; undernourished goats search out the widelyspaced tufts of xerophytic grass; and the unopposed wind whistles through clumps of cacti.

History

The economy of Barbados is and always has been largely based on agriculture. Tobacco and cotton were the dominant products of the island after it was first settled in 1627. Sugar cane was introduced in 1640, probably from Brazil, and by 1652 sugar manufacturing had been brought to perfection. With the introduction of slaves all the agricultural land came under control of large plantations. A slave economy became firmly entrenched and lasted until emancipation in 1834. Bourbon cane was the standby for a long period, and not until 1895 did it succumb to drought and the moth borer. During this latter period competition became very keen and an agricultural crisis was at hand. This crisis was augmented by a devastating hurricane in 1898. Basic changes had to be made in the farming of sugar cane. Absentee landowners were persuaded to sell out, and a number of factories, each controlling groups of estates, were set up. In addition, several estates were cut into lots and sold, so that by 1913, 13,000 peasants owned plots of 5 acres and under.

At the turn of the century a Department of Agriculture was established, and it has done an excellent job in creating new and more suitable cane breeds. Its present research includes soil studies, cultivation experiments etc., and there is cooperation with other groups who are concerned with sugar production.

Topography, Geology, and Drainage

Heights in Barbados range from sea-level to 1115 ft. (Fig. 2). Ascent from the west coast takes place through a series of well-defined limestone terraces, while to the north, east, and south, step-like rises

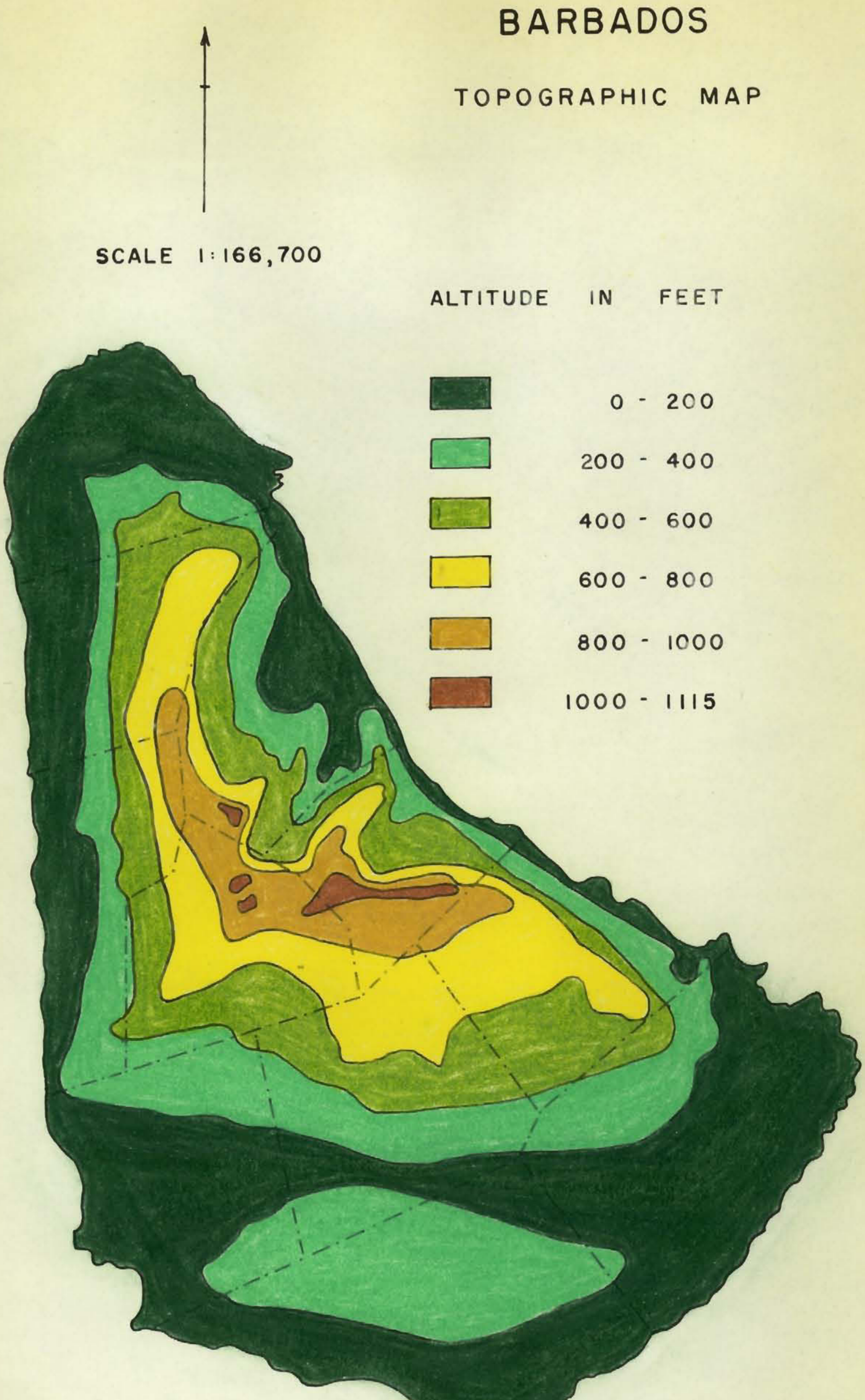
BARBADOS
TOPOGRAPHIC MAP
SCALE 1:166,700
ALTITUDE IN FEET
0 - 200
200 - 400
400 - 600
600 - 800
800 - 1000
1000 - 1115

FIGURE 2

are less obvious and the heavily dissected terrain merely becomes more hilly. Water erosion along fault lines has sometimes created ravines which run obliquely to the slope. Along the St. John, St. Joseph and St. Andrew coasts, the highly distorted folds of the Scotland formation rise sharply from the sea and in places create a definite cliff. Isolated topographic features include sand dunes along the south-east coast and the east-west trending Christ Church Ridge and St. George Valley.

Senn (23) who has carried on detailed investigation of geology and hydrology in Barbados states that all the bedrock, exclusive of the Scotland formation, consists of Coral-rock which reaches a probable maximum thickness of 300 ft. The rock was laid down during the Pleistocene epoch, the deposit consisting of one contemporaneous reef. These coralline limestones are mainly massive and unbedded although in places well-bedded strata characterized by an abundance of Formanifera are found. The Christ Church Ridge and St. George Valley correspond geologically to an anticline and syncline respectively, but the main structure of the island is controlled by the large central dome of Coral-rock which dips seaward in all directions. Erosion has stripped off part of this dome to bare the older Scotland formation (Fig. 3). This district covers one-seventh of Barbados' total area and consists of older clay, marl, and sandy formations which have been highly folded and overthrust. Other smaller structural features surround the dome.

Drainage is largely controlled by rock permeability and the slope of the land. Except in the Scotland area, the streams rarely proceed far on the surface before dropping out of sight. Rain water is readily absorbed in the areas with no soil covering, where it can directly infiltrate into the fine pores of the Coral-rock and into open fissures, crevices and sink-holes. When there is a soil cover which must be first saturated, a heavy rain will run off, and the water, choked with masses of the clay soil, may plug the sink-holes, creating a circular pond. This latter situation is alleviated by the use of "suck wells", which suck to an open fissure in the rock and dispose of all the superfluous water. After percolating to an impervious layer, the water follows the downward slope to the sea, but cannot escape freely, owing to the higher specific gravity of sea-water. The water is dammed up and rises in the Coral-rock to sea level, creating a reservoir, which is particularly important in the St. George Valley. The older formations of the Scotland region are practically impermeable and most of the rain is lost by surface runoff, as is evidenced by the number of permanent rivers in this area. Only on the talus slopes and alluvial valleys is there significant percolation and ground water storage.

Ground Water Resources

Rain water that percolates through the Coral-rock is arrested by the underlying impervious layer, and stored in the basal part of the porous limestone. Such storage water is designated as sheet-water by Senn, but it should not be thought that it forms to an even depth over the impervious layer--rather, because of the opening of solution channels, it is concentrated into small veinlets which become wider with progressing solution and finally join together to form larger subterranean water streams.

Senn states that "the sheet-water reservoirs contain tremendous reserves of water..........but their whole content is not available for use and only an amount of water can be drawn from them which is annually flowing into them". He goes on to describe the reserves in the various catchment areas (Fig. 3), and to estimate irrigation possibilities. This estimate assumes that no more water can be withdrawn from the catchment basins than annually flows in. In the following discussion, the estimates of irrigation possibilities comes from Senn who gives the number of irrigable acres in each catchment basin and the author has merely expressed the number of acres as a percentage of total cane acreage.

In over 8 square miles of the north-east area of St. Lucy, the coral rock is not everywhere underlain by an impervious formation, but there is still enough potential to irrigate regularly approximately 17% of the crop land. Because heavy breakers continuously hit the coastal cliff and have opened up large caverns, sea water easily penetrates inland and causes the ground water to become brackish. It is necessary, therefore, to open irrigation wells near the inland side of the catchment area.

The western catchment basin includes all of St. Peter and St. James parishes; western St. Thomas, and south-western St. Lucy, and comprises an area of approximately 34 square miles. High salinity is very localized and does not constitute a major problem. A maximum of 30% of the crop area could be irrigated in a "normal rainfall" year.

The south-western catchment zone includes most of St. Michaels Parish, eastern St. Thomas, western St. George, and small parts of St. John and Christ Church. In a total area of 32 square miles the only salinity is along the coast and even here it is low, for in contrast to St. Lucy, this catchment area is on the leeward side of the island. Although there is already a large domestic consumption from this heavily-populated area, it should be possible to irrigate 25% of the cropland.

The southern catchment area lies to the south of the Christ

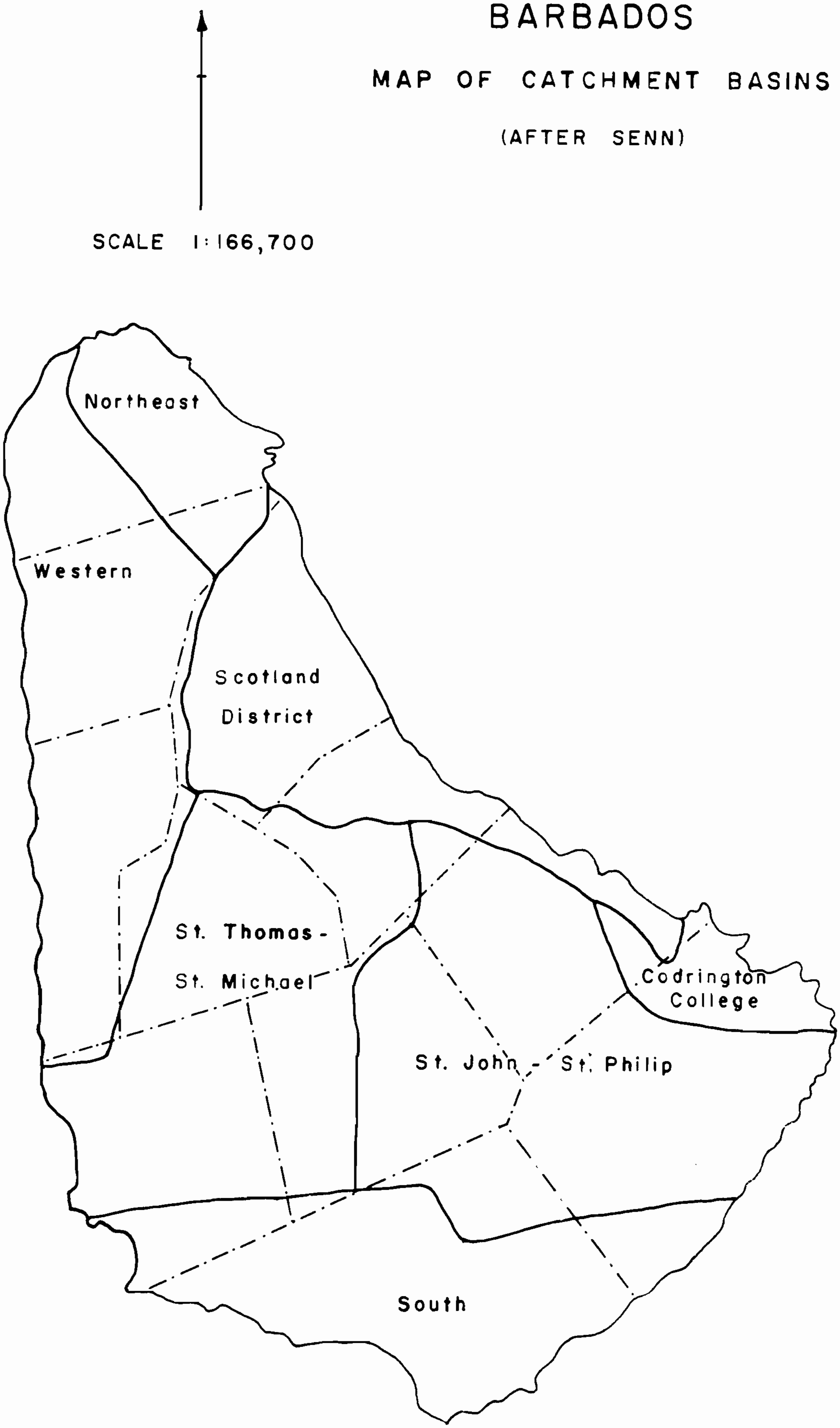
BARBADOS
MAP OF CATCHMENT BASINS
(AFTER SENN)
SCALE 1:166,700
Northeast
Western
Scotland
District
St. Thomas -
St. Michael
Codrington
College
St. John - St. Philip
South

FIGURE 3

Church Ridge and comprises almost 22 square miles. High salinity presents a problem along the ocean-facing south coast. Only 5-10% of the cropland could be regularly irrigated.

The St. John-St. Phillip region comprises almost 40 square miles and includes eastern St. George and a small northern strip of Christ Church. It includes much of the St. George syncline. The heavy surf along the St. Phillip coast has created conditions of relatively high salinity in the coastal reaches, but further inland the water is perfectly fresh. Senn estimates that only about 18% of the cropland could be irrigated, but speculates that water with higher salinity might be successfully used.

A small catchment basin of 6.5 square miles centres on Codrington College. The sheet-water is very localized in narrow subterranean streams, and ground water is generally scarce. There are no considerable reserves of unused water for irrigation, which is unfortunate, since this is one of the driest areas of Barbados.

Senn does not attempt to estimate the water reserves in the Scotland area but claims they are relatively insignificant. The steep slopes, lack of forest-vegetation, and consequent heavy erosion, leaves nothing which can arrest the runoff water and facilitate absorption.

It would seem reasonable to conclude that with some exceptions, the ground-water resources of Barbados are sufficient to allow significant irrigational development. As will be discussed later, however, the areas most in need of an extra water supply are frequently those with the least potential.

Soils

There is at present a dearth of knowledge regarding Barbados'

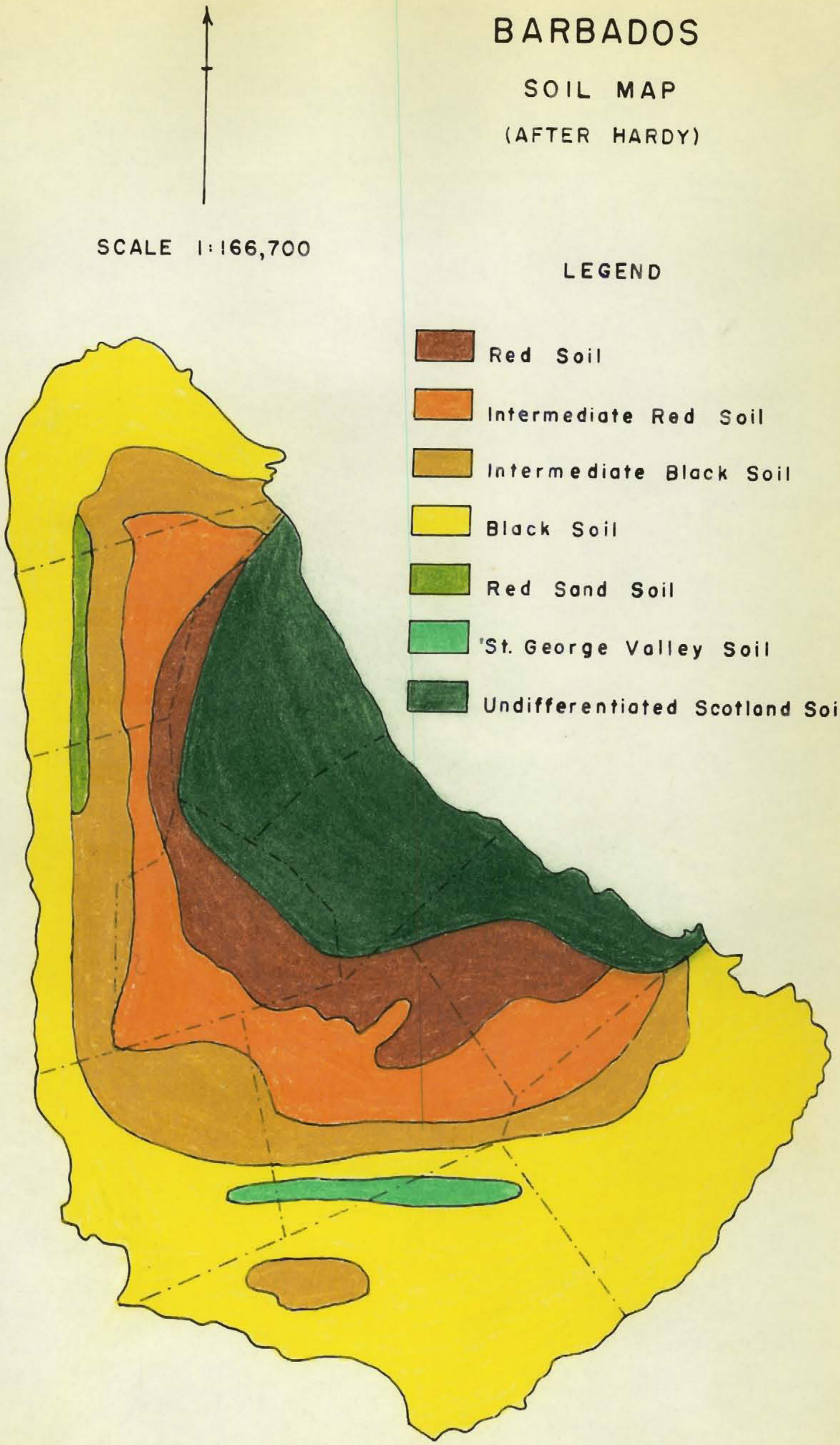
BARBADOS
SOIL MAP
(AFTER HARDY)
SCALE 1:166,700
LEGEND
Red Soil
Intermediate Red Soil
Intermediate Black Soil
Black Soil
Red Sand Soil
St. George Valley Soil
Undifferentiated Scotland Soil

FIGURE 4

soils. A soil survey of the island and research into soil-moisture relationships will do much to rectify this situation within the next three years. The following will be a general account of what is known of Barbados' soils. A more detailed discussion of soil-moisture relationships will be presented during the consideration of moisture balance.

The only picture of overall soil distribution is given by a map produced by Hardy (Fig. 4). As can be seen from this map, the red, black, and undifferentiated Scotland soils cover the major portion of Barbados. The red soils are associated with the high rainfall upland areas while the black soils are confined to low rainfall lowland zones. In the Barbados Agricultural Journal (13), it is stated that water moves more quickly in the red than the black soils--this probably referring to downward percolation. In a breakdown of soils which closely corresponds to Hardy's classification, the soils have assigned clay contents which range from 55 to 75%, with the exception of the sandy trough of the St. Peter lowland where clay content falls as low as 14%. Soil saturation capacities vary from very low in the red sands to quite high in the black soils.

Price (17) states that the soils form a heavy mantle, which averages 2 ft. in thickness and has rarely developed to a depth greater than 3 ft. They are formed from limestone which is from 93 to 99% pure. Volcanic ash from Soufriere on St. Vincent which erupted at the turn of the century was possibly carried eastward in the upper air currents to play an important part in the present-day soil characteristics. The red soils of the upland, Price notes, have more organic matter and clay, less lime, silica-alumina, and a lower base saturation capacity than the black soils of the lowland. The heavy clays of the Scotland district are cracked when dry and in flux when wet.

Earth flows resulting from this instability form ampitheatres at the heads of valleys.

Climate

Barbados lies within the "humid tropics" as delimited by both Garnier and Kuchler (4). The word "humid" should not be misconstrued. In the case of Barbados it means "not arid" rather than "continuously wet". The following discussion is based on data from the microclimatic station at Waterford (5).

It is the rainfall that is the most variable climatic parameter and also the most economically significant one. Rainfall shows a significant areal differentiation within the island, as well as considerable annual variations. In a single year one station may record 35 in. more rainfall than another. Year to year variations at any one station may range as high as 48 in. The precipitation extremes are considerable. As much as 33 in. of rain may fall in one month while there may be no rain for another month. It is common for over 2 in. to fall within a 24 hour period, and in July 1901, 20 in. fell in the parish of St. Lucy (Skeete (24)). A rough division into 2 moisture seasons can be made. Approximately 75% of the rain falls during the 7 month wet season which extends from June to December, leaving only 25% for the 5 month dry period from January to May. September and October are usually the wettest months while March is invariably the driest.

In contrast to the rainfall regime the temperature is very constant from day to day, month to month, and year to year. The mean daily temperature varies only 3.9°F between February and June, which are the coolest and warmest months respectively. Temperature extremes are also small. The temperature rarely falls below 62° or climbs above 89°, and the grass minimum temperature seldom descends below 55°. Data[1] on soil temperature from depths of 2, 4 and 8 inches reveal a mean annual temperature of 84, 82, and 81 degrees respectively. As would be expected, the lowest temperatures of 75, 73, 75°, are reached in February, and the highest, at 95, 92, 86°, in May and June. The annual range of 9, 9, 6°, indicates that there is a considerable dampening effect on temperature change at depths lower than 4 inches, but that above this level, changes in air temperature exert more influence on the soil.

The north-east trade winds which blow throughout the year are an important feature of Barbados' climate. Wind direction dominantly remains within an arc from ESE through E to ENE. In January the winds come from ENE 45% of the time and from E another 35%. By May the wind comes from ENE only 14% of the time having shifted to the ESE (56%), but by August it is again dominantly from ENE (45%) and blows from the ESE only 30% of the time. October marks the height of the hurricane season, and now although the wind blows predominantly from the E and ESE (69%) it frequently swings to N and S directions and even to the NW and SW, due to the hurricane disturbances. Wind speeds show a single-cycle regime. From a low mean monthly speed of 7.8 mph in October, mean speeds increase very steadily to a high of 13.5 mph in June, after which they fall off evenly. The greatest change is between July and August when a drop of 2.5 mph takes place. The mean annual wind speed is 11.0 mph. Short range extremes may vary from a dead calm to up to 150 mph in a hurricane. As with speed, the most wind miles run are in June, the least in September-October. An examination of the relations between wind and rainfall

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1. Soil temperature data are based on one year of observation only.

leads to the observation that the windiest weather occurs during the drier months.

The number of bright sunshine hours varies both with day-length and with changing cloud cover, the latter having a more important influence. The months of shortest day-length correspond to the dry season, but due to the low incidence of cloudy skies they have a greater number of bright sunshine hours than the wet season months of longer day-length. The difference in mean monthly sunshine between February and September-October is 40 hours.

In summary it should be noted that there is greater wind and sunshine potential for evaporation during the dry season and that this is accompanied by only a slight drop in mean temperature. When water is most scarce evaporation potential is highest.

Agriculture

In Barbados, "agriculture" and "sugar-cane culture" are almost synonymous terms. Approximately 90% of all the arable land is in cane or in cane preparation land[1]. Of all the sugar under cultivation, 73% is on plantations of over 10 acres in size, the remainder being grown on small peasant plots.

Although it varies from plantation to plantation, sugar cane is generally planted in late October and early November near the end of the rainy season. The cane grows throughout the following year and is reaped during the early months of the subsequent year, giving a growing period of approximately 17 months. It is therefore planted in the wet season, grows throughout one complete dry and wet season, and is harvested during

1. Cane preparation land is the rest land in the estate's rotation scheme and is usually planted in yams, potatoes or corn. By law it must be at least 12% of the arable land.

the second dry season. The ratoon crop[1] matures in 12 months and is harvested during the same period as the plant cane. Barbados then has only one planting and one harvesting time each year.

As with rainfall, there are significant areal and annual variations in sugar cane yields (Foster(6)). Differences as great as 15 tons/acre have occurred between plantations in low and high rainfall areas in the same year, while extreme differences between years at any one plantation may reach as high as 28 tons/acre. Considering that yields rarely rise above 50 tons/acre these differences become most important.

Saint (21) notes that in the last 100 years the annual sugar production has increased 280% from 45,000 to 162,000 tons. Most of this change has occurred since 1924, and has been due mainly to the development of cane varieties more suited to the particular soil and climatic conditions, and the increased use of fertilizers, especially potash which allows more extensive ratooning. Since 1936 the practice of harvesting ratoon crops has decreased plant cane acreage by 65%. It is from the ratoon crop that a farmer makes much of his money, for it not only gives a return in a shorter period of time, but also bypasses most of the planting costs. Up to 5 ratoons are now grown on many plantations.

Irrigation is used on only 3 plantations. The author found that the water was applied in a very haphazard fashion. One grower applied 2 inches/month during the dry season, while another irrigated when he thought the crop needed it. Irrigation practices are too recent to estimate their influence on crop yields.

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1. A ratoon crop is the subsequent year's growth which springs from the original plant root. It later develops its own root system.

CHAPTER II RAINFALL, TEMPERATURE, SOIL MOISTURE AND MOISTURE BALANCE

Rainfall

Rainfall data for Barbados are remarkably comprehensive. From records housed at the Department of Agriculture the author was able to obtain figures for over 60 stations, each covering a period of at least 30 years. A check of all the rain gauges made it necessary to ignore some of the data, due to faulty location or poor equipment, and in the end the results of 58 stations were used. These give an adequate coverage for the island (Fig. 5), except for the parishes of St. Andrew and St. Lucy where figures for only 3 and 2 stations respectively were available. For these latter two parishes it was necessary in mapping to extrapolate values, using a technique which will be mentioned later.

Mean Annual Rainfall

A comparison of Figures 2 and 11(inset in back cover), shows the close correlation between height and mean annual rainfall. The lowest rainfall areas (44-51 in.), are found exclusively in zones of less than 300 ft. in altitude, whilst the highest zone of rainfall (80-86 in.), is located at heights greater than 800 ft. Similarly, middling rain amounts correspond to intermediate altitudinal zonation. It will be noted that along parts of the west coast, precipitation values are higher than would be expected at such low altitudes. A linear correlation of rainfall with altitude for leeward and windward exposures shows that the rainfall increases 2.4 in./100 ft. rise in altitude on the leeward slopes and only 1.4 in./100 ft. on the windward side of the island, a difference of over 70%. These higher values to the lee of the island may be the result of two influences. The first is probably the fact that most of the oro-

BARBADOS

DISTRIBUTION OF RAIN GAUGES

SCALE 1:166,700

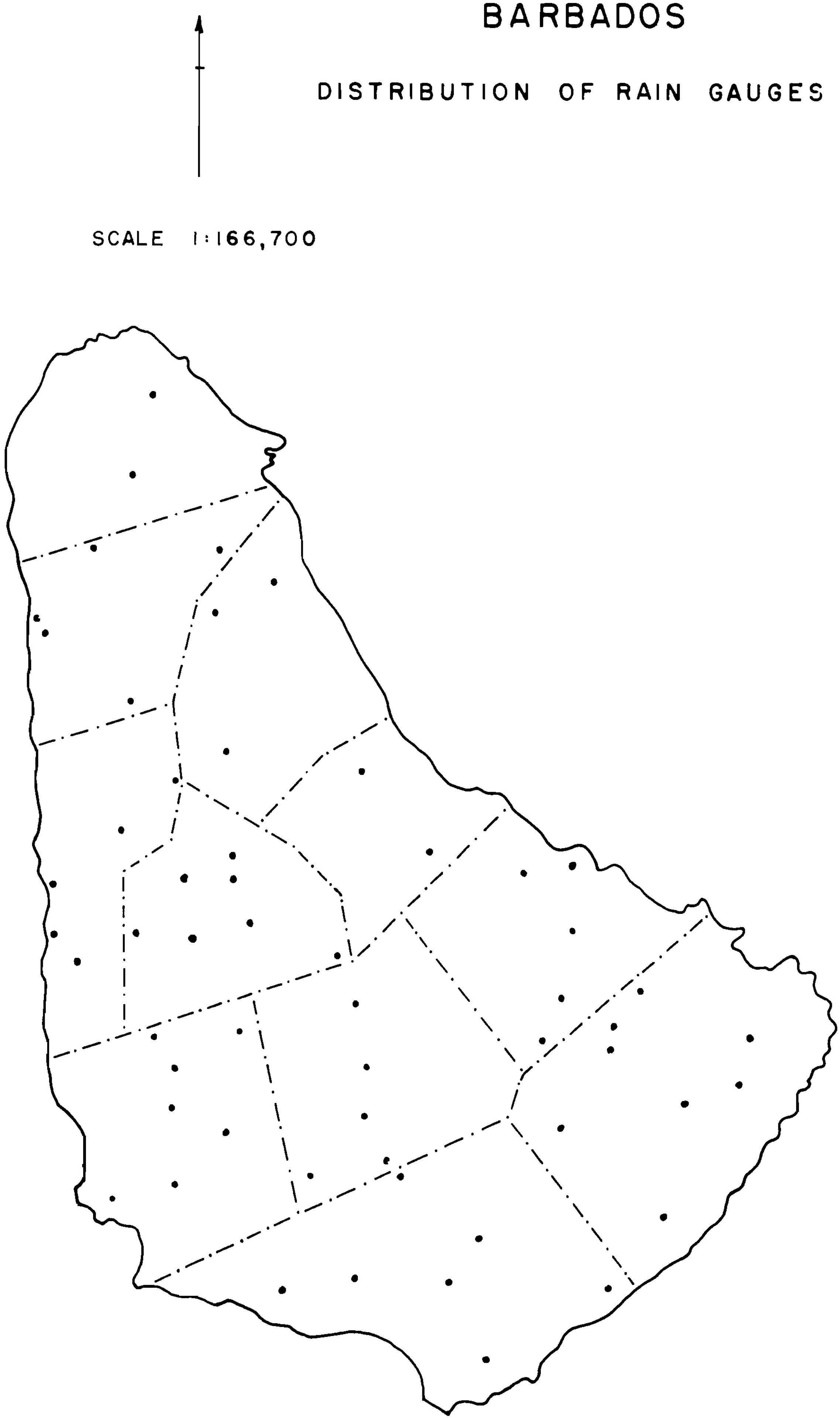

FIGURE 5

graphic rain from the condensation of moisture-laden air of the trades which has been forced upward does not reach the ground until it is west of the height of land. A second influence is caused by intensive heating of the earth's surface during the rainy season. Because of the relative abundance of moisture for evaporation and transpiration the lower layers of the atmosphere are quickly charged with water vapour. The lower wind speeds of the rainy season do not remove the surface air as readily as in the dry months. Heat energy from the earth's surface-radiation accumulates in the lower air levels and creates conditions of instability, where light warm air underlies cooler, potentially denser air. Such instability triggers a turbulent exchange of the warm, moisture-laden air upwards, where it cools and condenses to form cumulus clouds. These are carried westward by the trades and at the same time gain altitude until cooled sufficiently for the water to precipitate. Skeete (24) who has observed daily weather in Barbados for a considerable time refers to the rain which is initiated by surface heating as follows:

> "Convectional rain is dependent on low wind velocity, a considerable amount of sunshine to heat the surface air, and at least a moderately high humidity..........the time of formation of convectional rain within the year is mainly confined to the months of August to November owing to the fact that the combination of high humidity and low wind velocity is more frequent during these months........"

Most rain from this source falls into the ocean off the leeward coast and can be seen in the late afternoons of most days during the rainy season, but a sufficient amount reaches the western coast to account for the anomalously higher rainfall.

Rainfall Variability

The mean annual rainfall gives only a limited picture of precipitation characteristics in Barbados, as any sugar cane grower will quickly

BARBADOS

LOWER QUARTILE AS PERCENTAGE OF MEAN ANNUAL RAINFALL

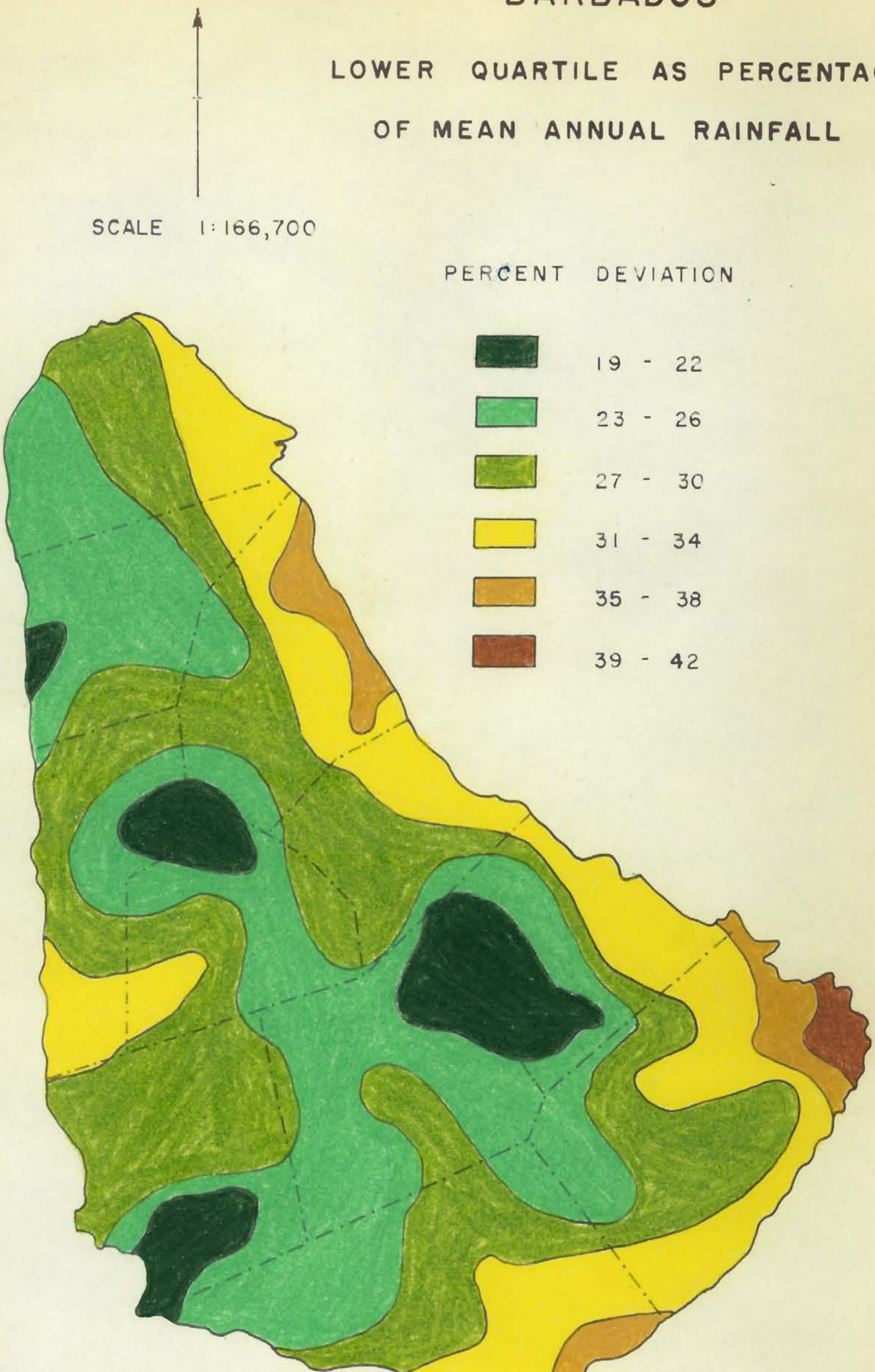

FIGURE 6(a)

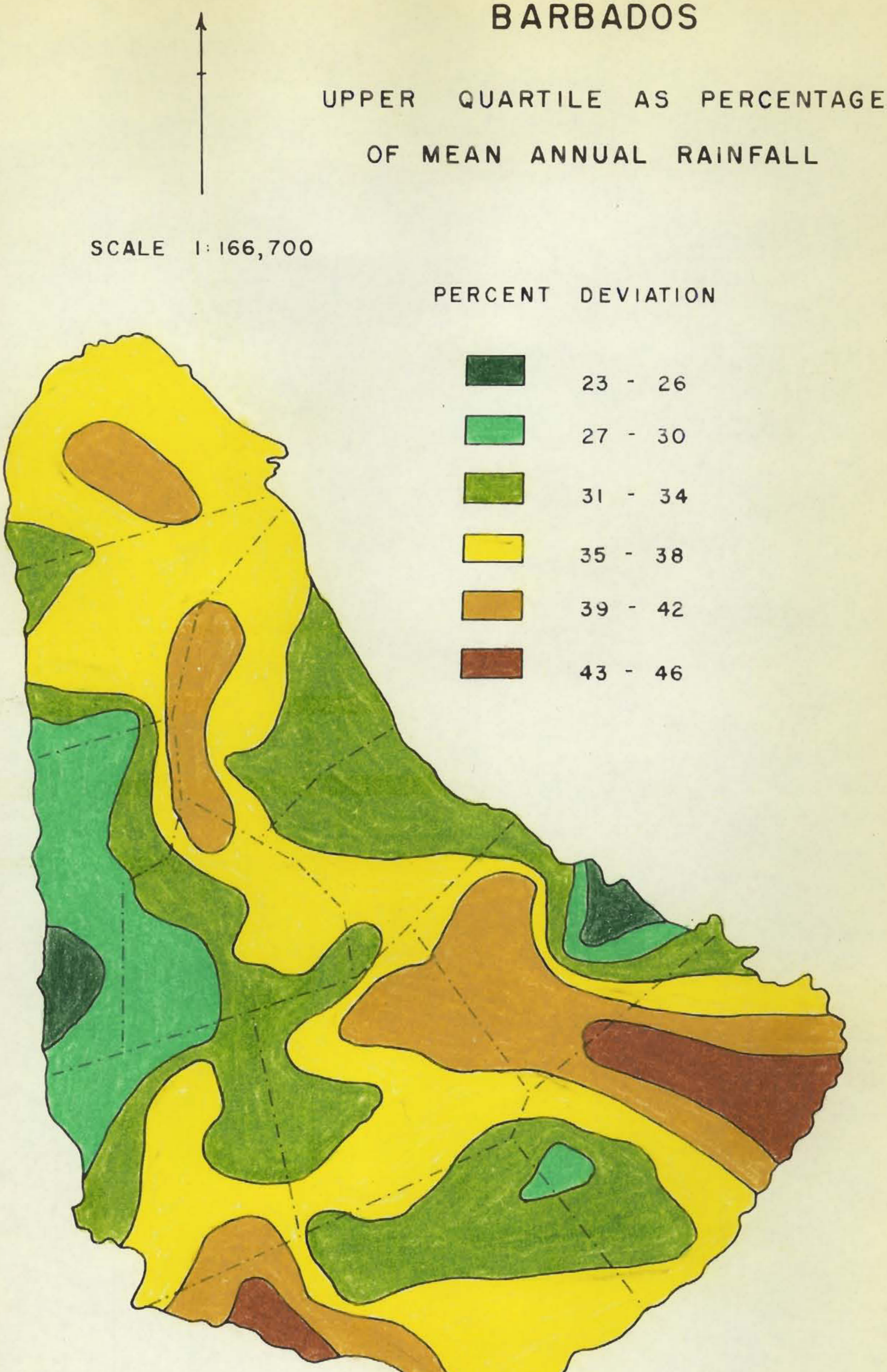
BARBADOS
UPPER QUARTILE AS PERCENTAGE
OF MEAN ANNUAL RAINFALL
SCALE 1:166,700
PERCENT DEVIATION
23 - 26
27 - 30
31 - 34
35 - 38
39 - 42
43 - 46

FIGURE 6(b)

acknowledge. Deviations of annual rainfall of up to 70% from the mean annual value have occurred during the present century. Upper and lower quartile values of rainfall for each station are given in Figure 6(a&b). As would be expected, the regions where the lower quartile values deviate most from the mean generally correspond to low rainfall zones, with the important exception of the south-western coastal area. Again it is felt that orographic rain will cause the greatest fluctuations in precipitation and that to the west, potential deviations have been alleviated by the rainfall caused by surface heating. Similarly, though less obviously, deviations of the upper quartile values from the mean are greatest in areas of high rainfall, and of lesser extent along the west coast where orographic rain is of less influence.

With the great fluctuations in yearly rainfall the writer suspected that mean annual rainfall might not denote average conditions and that median values might be more representative. This was not the case, however, and although the greatest difference between mean and median for representative stations was 5%, a total of the deviations found them to be equally spaced above and below the mean value. Since the mean rainfall is more readily calculated, it has been used in the formulation of moisture balance.

Temperature

Temperature data are available for 3 stations in Barbados, at altitudes of 180, 430 and 1070 ft. The data at 180 ft. can be averaged for 50 years, but only 8 year records are available at the other two stations. Moreover, the temperatures at the latter two stations were taken during the last quarter of the 19th century. The author feels, nevertheless, that they are reliable. The annual curve of mean monthly temperatures at these two stations corresponds closely to the 50 year

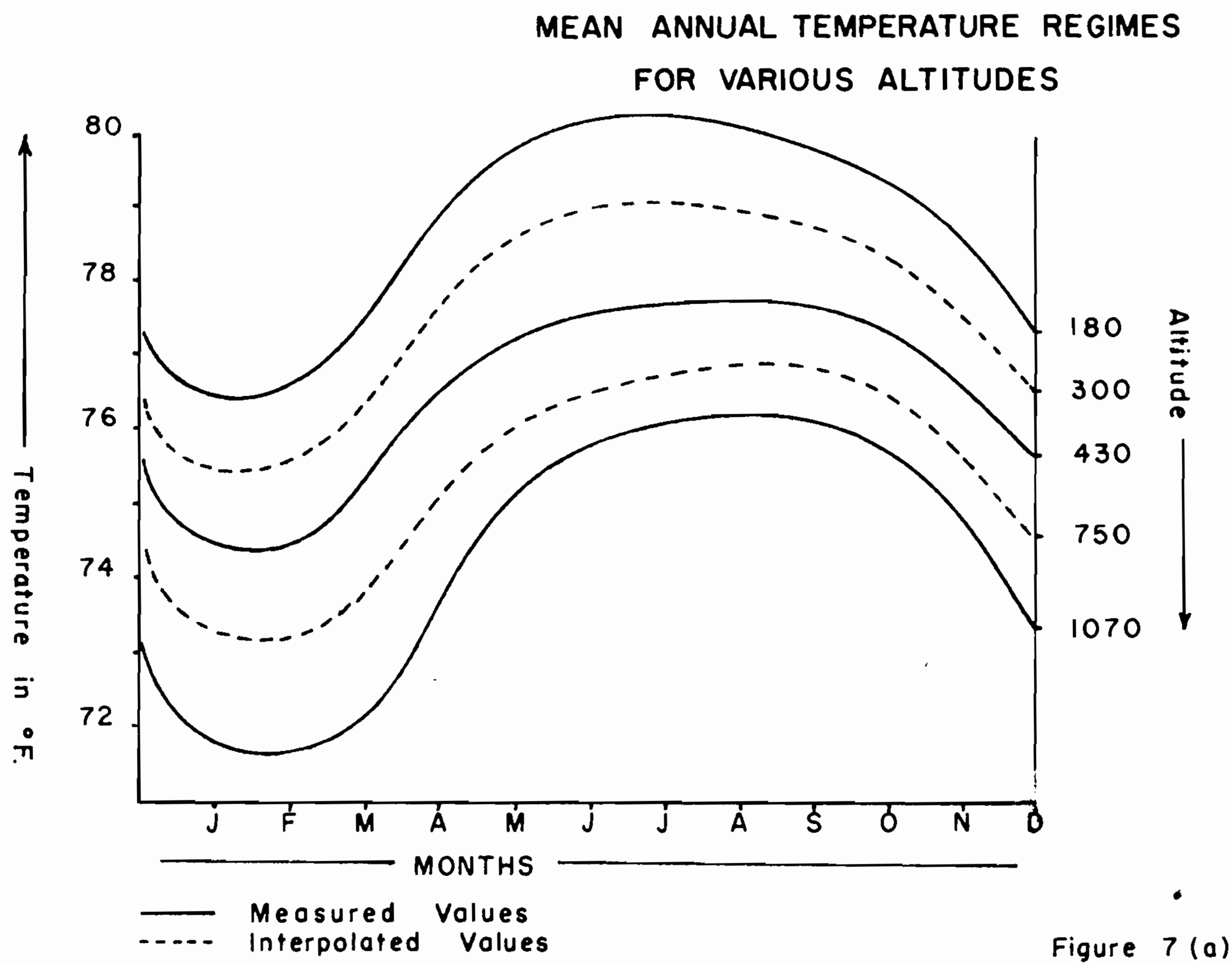

Figure 7 (a)

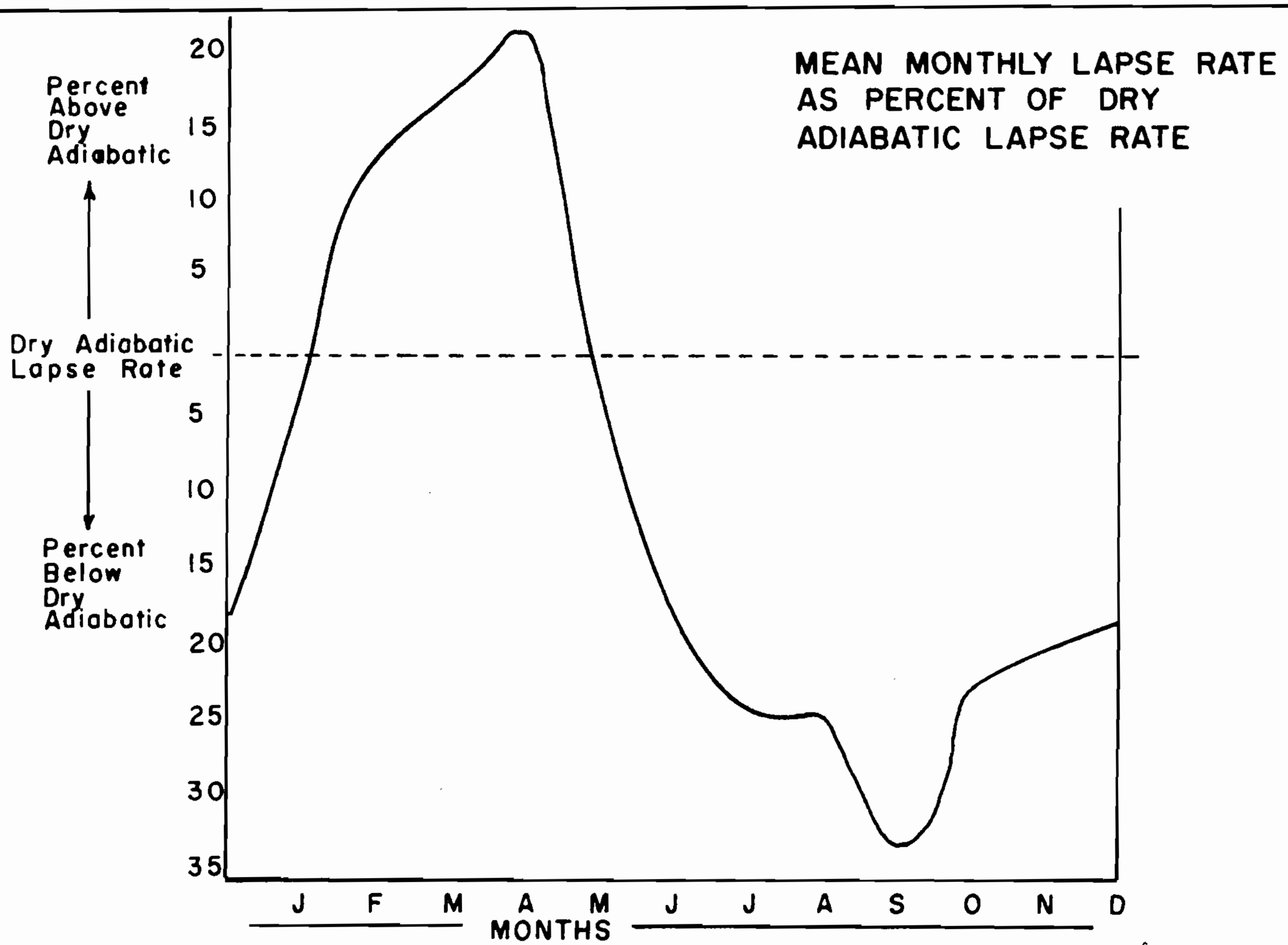

Figure 7 (b)

average values at 180 ft.; the stations were set up under a scientifically-versed governor; and an average of temperature values for 8 years should be representative due to the very limited temperature fluctuations in the tropics. With such an altitudinal range, temperature values for intermediate altitudes can be derived by interpolation. Actual and interpolated temperature values are shown in Figure 7(a).

The mean annual lapse rate is 5.0°F/1000 ft., but monthly variations range from a high of 6.1 in March to a September low of 4.2. Actual lapse rates for each month are shown as percent of the dry adiabatic lapse rate in Figure 7(b). It is significant that the lapse rate during the 5 dry months (January to May) is 1°F/1000 ft. greater than during the 7 wet months (June to December). This is probably the result of the greater availability of moisture and consequent higher actual evapotranspiration during the rainy season. Because of the higher evapotranspiration much of the solar energy is used in the vaporization processes, and escapes from the lower levels of the atmosphere in the form of latent heat. Conversely, with the lower actual evapotranspiration of the dry season, more sensible heat is reradiated from the soil and plants, and is free to heat the lower levels of air convectively.

Soil Moisture Retention

As mentioned previously, Barbados' soils are mainly clays of unknown moisture-holding capacity. Since soil-moisture relationships are important in any discussion of moisture balance, it has been necessary to correlate all existing information with the author's textural sampling in the field. By using Thornthwaite's texture-moisture retention values (32), for a medium-rooted crop (sugar cane), it was possible to assign inches of soil moisture at field capacity to each soil type. These values range from 4 in. for the sterile clays of the Scotland district, through 5 in. for the sands of the St. Peter lowland and 6 in. for the heavy red clays of higher altitudes, to a high for the black clay-loams of lowland areas of 8 in. These values are suitable as a relative indicator although their absolute values are open to question. It is noteworthy that Banting (2), working in tropical Africa, assigned field capacities of 4 and 6 inches for a medium rooted crop in light and heavy soils respectively.

Moisture Balance

For developing the moisture balance in Barbados, a slightly modified version of Thornthwaite's system (29), has been employed. Not only does this method give a more illuminating picture of moisture relationships than does mean annual rainfall, but it has the distinct practical advantage over other methods for estimating moisture balance in that its use demands a knowledge of only 3 climatic parameters; rainfall, temperature, and soil moisture.

In Thornthwaite's system, a combination of potential evapotranspiration which is derived monthly from mean temperature data, and a correction for the number of bright sunshine hours at a given latitude, gives a quantity known as actual potential evapotranspiration. This is the amount of water which will be evaporated and transpired from crops, providing that water is available in the soil reservoir. For Barbados, all the stations depending on their altitudes were assigned one of the five temperature regimes shown in Figure 7(a). Sunshine hour correction was for 13° N. latitude. Thornthwaite's method next considers monthly rainfall. When the precipitation equals or exceeds potential evapotranspiration for the month, the actual evapotranspiration and potential evapotranspiration are equal. If rainfall exceeds potential evapotranspiration, the excess will be stored in the soil up to field capacity which varies with the soil type as mentioned above. However, any excess moisture after field capacity has been reached is lost as runoff. When precipitation is less than potential evapotranspiration, the plant must draw on the soil moisture reserve to satisfy its water needs until this source is depleted to its hygroscopic water level. The rate of soil moisture withdrawal in dry periods has been determined experimentally by Thornthwaite and Mather (31). If soil moisture has all been utilized and rainfall is still below potential evapotranspiration (PE), the actual evapotranspiration (AE) will be equal only to this rainfall, and a moisture deficit develops.

It is necessary at this point to note the limitations of Thornthwaite's method. Firstly, the measurement of PE is of necessity based on empirical evidence, since a practical theoretical expression of evaporative potential has yet to be developed. Secondly, the method uses temperature as a reliable indicator of the available energy for evapotranspiration. That this may not be valid will be discussed below. In addition, there is a lag of temperature behind radiation which results from the thermal storage in the soil and which according to Pelton et al. (16) creates an error in monthly PE estimates. Finally, Thornthwaite's estimate is applicable only to relatively large areas where the soil has a complete vegetation cover so that influences from horizontal advective heat transfer are minimized.

In applying this system to Barbados, a significant problem was encountered. Thornthwaite's PE which was empirically developed for middle latitude climates did not agree with the measured PE given by the evapotranspirometer tanks at Waterford, Barbados (5). The estimated values generally fell below measured values during the dry season, and were somewhat greater during the wet months (Fig. 8(a)). Over the whole year, Thornthwaite's values underestimated the measured evapotranspiration. Chang (3) found an even greater anomaly in Hawaii, where the Thornthwaite estimate was only 54% of the open pan evaporation, the difference being especially large in summer. Chang found in turn that open pan evaporation compared reasonably with the actual water consumption of sugar cane. In order to discover the reasons for this anomaly, the writer consulted the various climatic parameters which are measured at Waterford, such as wind speed, actual hours of sunshine, total incoming solar radiation etc. Whereas potential sunshine hours and screen temperatures were generally less during the winter months (dry season), the solar radiation actually was greater in the dry months than during the wet season (Fig. 8(b)). Moreover, a linear regression of measured PE on temperature showed a coefficient of correlation nearly equal to zero. This led the author to the conclusion that mean monthly temperature at Waterford is not a valid indicator of available energy for evapotranspiration. Such a conclusion agrees with other investigations. Pelton et al. (16) state that air temperature itself is not a measure of the energy available for evapotranspiration except when the sensible heat flux is small. In Barbados, the sensible heat flux at the earth's surface is not small, particularly during the dry season. Total incoming solar radiation on the other hand gave a coefficient of correlation with measured PE of 0.90 over a 14 month period. The formula for the linear regression which is shown in Figure 9(a)[1] is:

$$PE = 0.53 - 4.14$$

where $\underline{PE}$ is the measured PE at Waterford
and $\underline{I}$ is incoming solar radiation

1. Due to space limitations, none of the coordinate axes of the regression curves in this thesis have their origins at zero.

TEMPERATURE AND SOLAR RADIATION REGIMES FOR THE YEAR 1960-61

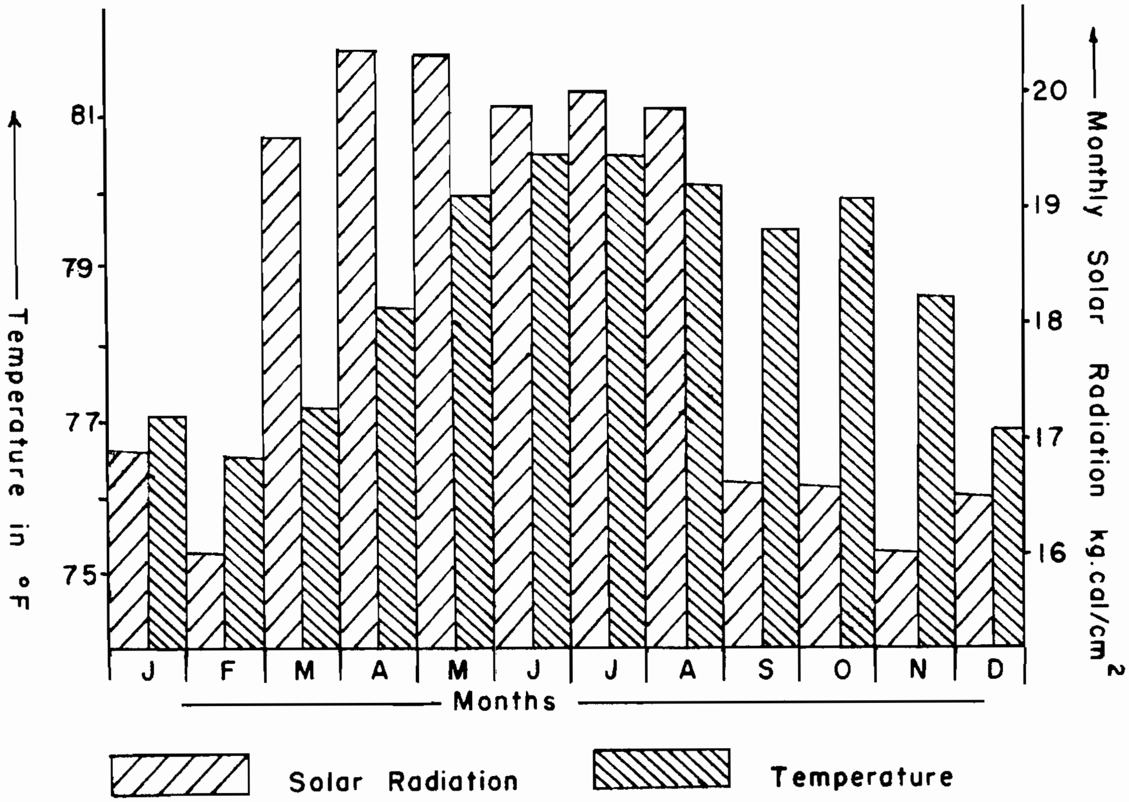

FIGURE 8(a)

POTENTIAL EVAPOTRANSPIRATION FOR THE YEAR 1960-61 AS

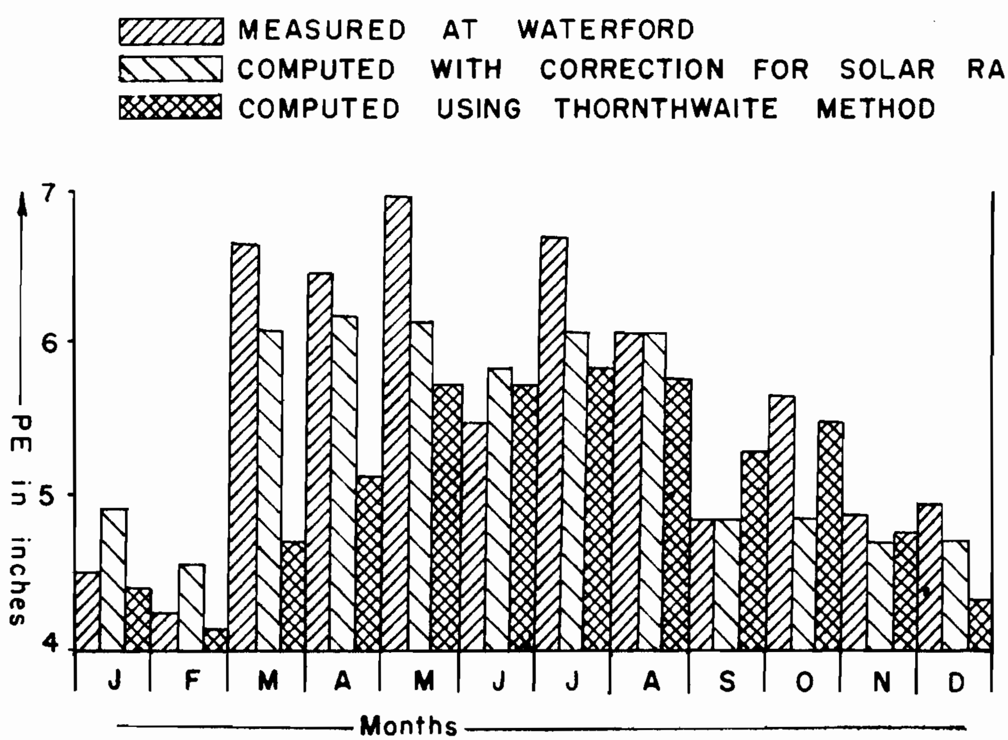

FIGURE 8(b)

LINEAR REGRESSION OF MEASURED PE WITH SOLAR RADIATION

$PE = 0.53I - 4.14$

$r = 0.90$

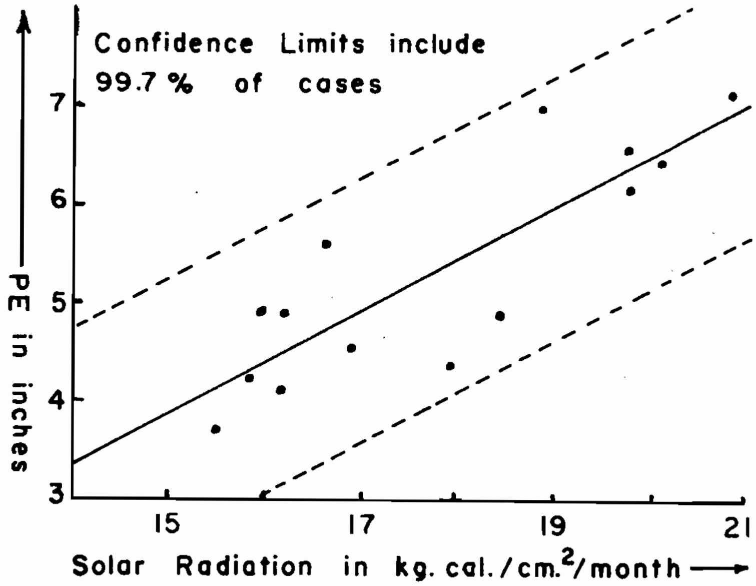

Figure 9(a)

ACTUAL PE AT FIVE DIFFERENT ALTITUDES

Altitude 0-230 Ft.

Months	J	F	M	A	M	J	J	A	S	O	N	D	Y
Thornthwaite PE	4.41	4.10	4.94	5.30	5.94	5.78	5.94	5.83	5.51	5.15	4.89	4.70	62.49
Correction	1.11	1.10	1.26	1.20	1.08	1.02	1.03	1.04	0.91	0.89	0.97	1.08	
Actual PE	4.90	4.50	6.22	6.35	6.41	5.90	6.11	5.95	5.02	4.59	4.75	5.08	65.78

Altitude 231-380

Months	J	F	M	A	M	J	J	A	S	O	N	D	Y
Thornthwaite PE	4.11	3.82	4.64	5.00	5.61	5.51	5.61	5.51	5.20	5.16	4.61	4.27	58.99
Correction	1.11	1.10	1.26	1.20	1.08	1.02	1.03	1.04	0.91	0.89	0.97	1.08	
Actual PE	4.57	4.20	5.85	6.00	6.06	5.56	5.78	5.74	4.74	4.60	4.47	4.61	62.18

Altitude 381-580

Months	J	F	M	A	M	J	J	A	S	O	N	D	Y
Thornthwaite PE	3.82	3.55	4.02	4.68	5.28	5.14	5.29	5.18	4.90	4.95	4.32	4.12	54.96
Correction	1.11	1.10	1.26	1.20	1.08	1.02	1.03	1.04	0.91	0.89	0.97	1.08	
Actual PE	4.24	3.90	5.06	5.61	5.70	5.24	5.45	5.38	4.46	4.40	4.24	4.45	58.13

Altitude 581-880

Months	J	F	M	A	M	J	J	A	S	O	N	D	Y
Thornthwaite PE	3.52	3.28	3.71	4.06	4.95	4.86	4.95	4.86	4.60	4.55	4.03	4.12	51.46
Correction	1.11	1.10	1.26	1.20	1.08	1.02	1.03	1.04	0.91	0.89	0.97	1.08	
Actual PE	3.87	3.62	4.67	4.89	5.35	4.93	5.10	5.05	4.12	4.04	3.92	4.29	53.92

Altitude 881-1115

Months	J	F	M	A	M	J	J	A	S	O	N	D	Y
Thornthwaite PE	3.23	3.00	3.40	3.43	4.62	4.49	4.62	4.84	4.59	4.24	3.74	3.53	47.46
Correction	1.11	1.10	1.26	1.20	1.08	1.02	1.03	1.04	0.91	0.89	0.97	1.08	
Actual PE	3.58	3.30	4.28	4.11	4.99	4.58	4.75	5.04	4.17	3.77	3.62	3.81	50.00

Figure 9(b)

Shaw (26), as a result of daily evidence gathered over a 5 month period in Iowa found that a linear regression between net radiation and solar radiation gave correlations of 0.98 and 0.97 for clear and cloudy days respectively. Since this study shows net radiation and solar radiation to be virtually proportional, it seems safe to assume that solar radiation is a good indicator of available energy over wet soils. Graham and King (7), in a study also based on daily readings, found a correlation of 0.99 between net radiation and the PE of a corn crop at Guelph, Ontario. The author concluded from this evidence that solar radiation, since it is virtually proportional to net radiation, is a valid indicator of PE. Pelton et al. (16) note that the potential evapotranspiration, which by definition excludes large heat transfers, will be nearly in phase with the solar radiation, not only on a monthly basis, but also on an hourly basis.

With the establishment of solar radiation as the best indicator of PE at Waterford, the problem was to apply it in order to establish PE on a regional basis. Now temperature records give the only available evidence in Barbados of decreasing energy potential with increasing altitude. In order to calculate the PE on a regional basis it was necessary to compare the Thornthwaite calculated PE to the PE given by the solar radiation--measured PE regression curve. This allowed monthly correction factors which would bring the two into correspondence to be developed for Waterford, and then to be applied throughout the island. Figure 9(b) gives the Thornthwaite calculated PE, the monthly correction factors, and the final actual PE, for 5 different altitudinal levels in Barbados. This method should give an accurate and reliable calculation of the PE on a regional basis.

GRAPHS OF MOISTURE BALANCE FOR SIX SELECTED STATIONS

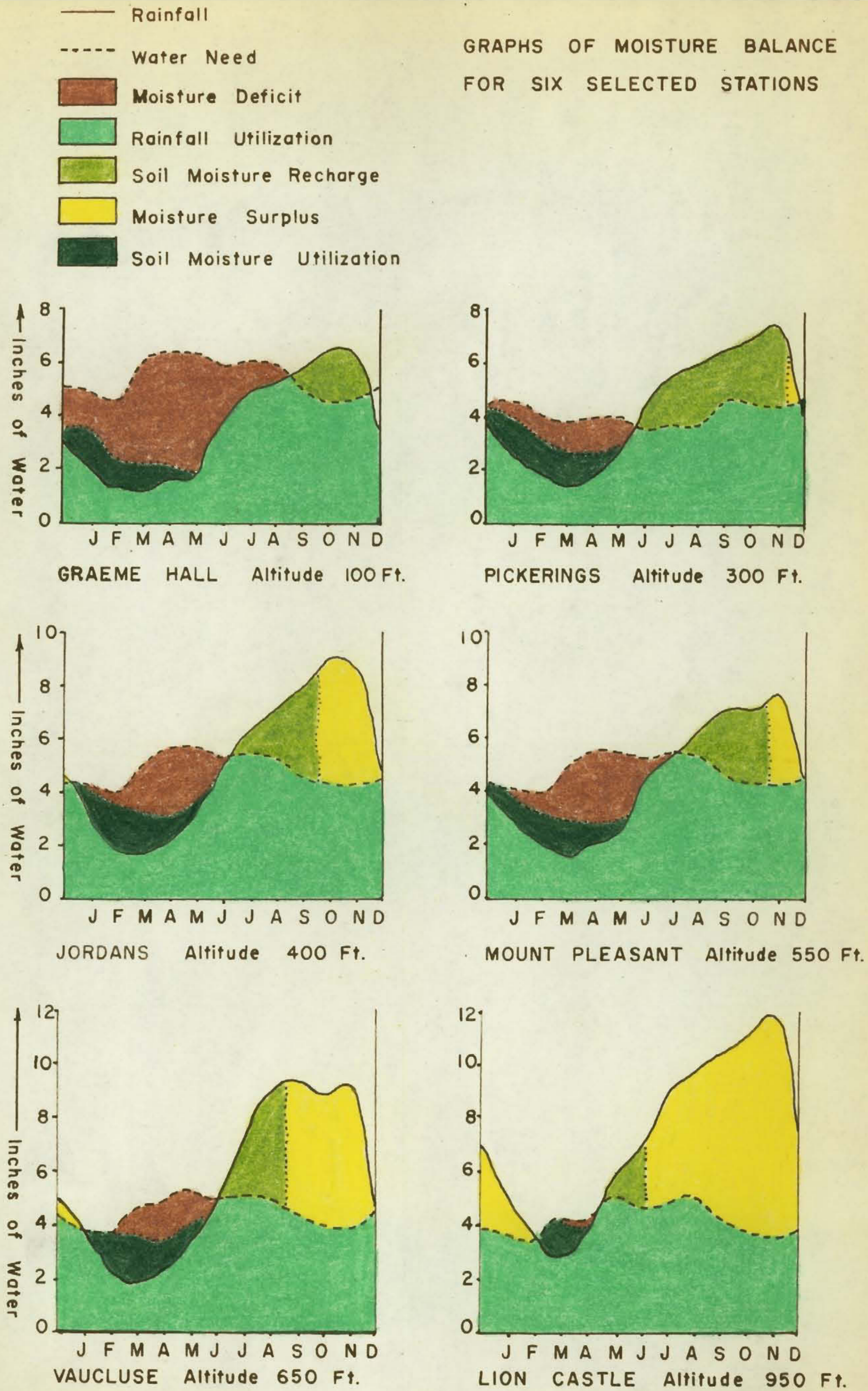

Figure 10

Moisture balance graphs for 6 representative stations in Barbados are given in Figure 10. These computations were carried out for all 58 stations in the island, and maps showing all phases of moisture balance for the island (potential evapotranspiration, actual evapotranspiration, moisture deficit, and moisture surplus) are given in Figure 11(inset in back cover). In the construction of these maps the writer correlated the potential evapotranspiration, moisture deficiency and moisture surplus with altitude for both the leeward and windward exposures by means of linear regression equations. This allowed a more accurate plotting in areas where no datum was available. It should be noted that moisture deficit equals potential evapotranspiration less actual evapotranspiration, and that moisture surplus equals the excess rainfall after soil moisture capacity has been reached. It is therefore possible to have a deficiency and surplus at different times during the year, at any one station.

As would be expected from the change in available energy with altitude, the map of potential evapotranspiration (Fig. (11)), corresponds closely with the topographic configuration of the island. Areas with high potential evapotranspiration (66-70 in.) lie exclusively where heights are under 200 ft. Regions of low water need (46-50 in.) generally are higher than 800 ft. Intermediate potential evapotranspiration similarly occurs in zones between 200 and 800 ft.

The actual evapotranspiration, which interrelates potential evapotranspiration with rainfall and soil moisture capacity, shows a different pattern. Except for north-western St. Lucy and the St. James-St. Peter coastal areas, the actual evapotranspiration is lowest where potential evapotranspiration is highest. These areas are the ones of greatest moisture deficiency and in a narrow zone along the southern coast this deficit exceeds 20 inches/year. Along the western coastal areas, however, a combination of higher rainfall and soils of greater moisture-holding capacity has given this region the highest actual evapotranspiration for the whole island, and the available moisture more nearly approaches the water requirements of the vegetation. As can be seen from the map, there is little or no moisture deficiency over a significant amount of the higher parts of the island.

Application of Thornthwaite's 1948 climatic classification (29), shows a variation from humid megathermal areas with little water deficiency ($B_3A'r$); to moist subhumid, megathermal zones with no water surplus ($C_1A'd$); (Fig. 12).

It is interesting to speculate on what the present day moisture balance would allow in the way of natural vegetation in Barbados. A crude attempt at this has been made in Figure 13. This map is based on a study by Rosayro (20), in Ceylon, which relates natural vegetation to Thornthwaite's classes. It can be seen that if general conditions in Barbados parallel those of Ceylon, and if the present day moisture balance has been similar in the past, that much of Barbados should have been covered by a forest. Such a forest would have ranged from wet to dry tropical evergreen, with a thorny open, scrub-woodland in the drier areas. That this was probably the situation is supported by reference to a heavy tropical forest at the time of initial European settlement, which were discovered by Watts[1] while pursuing archival research in London and Paris.

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1. Private correspondence.

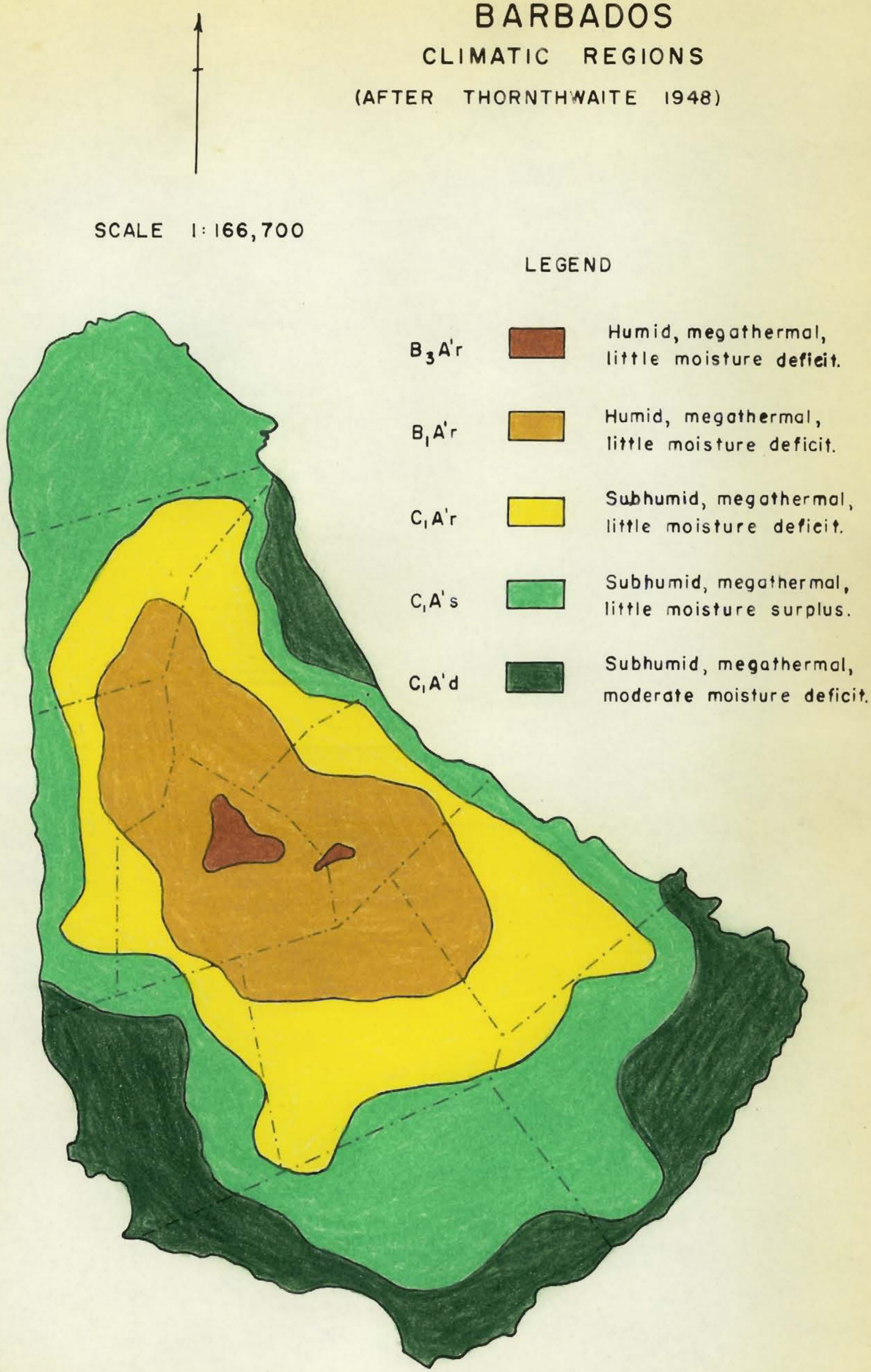
BARBADOS
CLIMATIC REGIONS
(AFTER THORNTHWAITE 1948)
SCALE 1:166,700
LEGEND
$B_3A'r$
Humid, megathermal, little moisture deficit.
$B_1A'r$
Humid, megathermal, little moisture deficit.
$C_1A'r$
Subhumid, megathermal, little moisture deficit.
$C_1A's$
Subhumid, megathermal, little moisture surplus.
$C_1A'd$
Subhumid, megathermal, moderate moisture deficit.

FIGURE 12

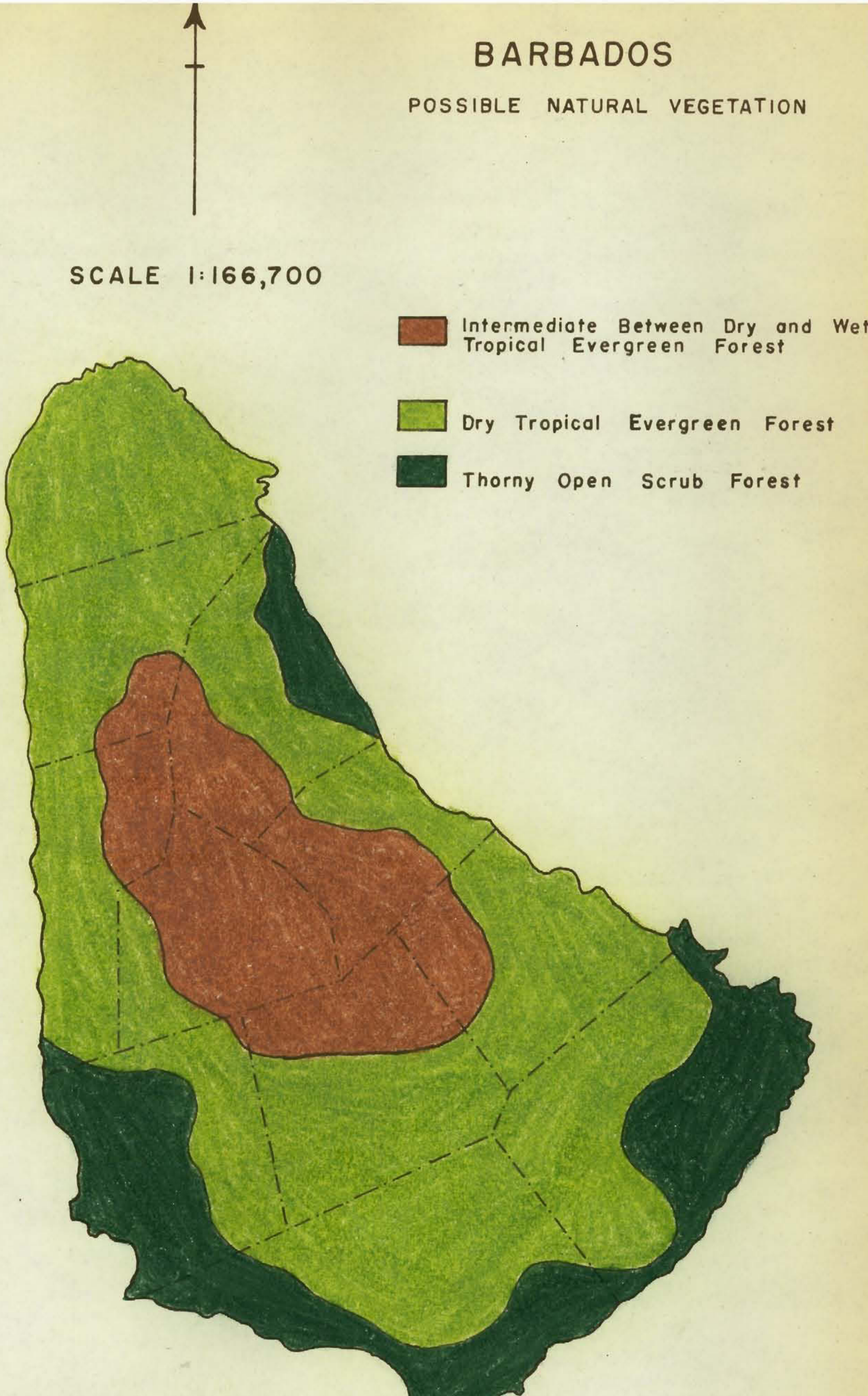
BARBADOS
POSSIBLE NATURAL VEGETATION
SCALE 1:166,700
Intermediate Between Dry and Wet Tropical Evergreen Forest
Dry Tropical Evergreen Forest
Thorny Open Scrub Forest

Figure 13

Since one of the aims of this paper is to show the relationships between moisture balance and sugar cane yields, it is necessary to consider the physiology of the sugar cane plant in relation to moisture; its ecological manifestations with regard to climate; the actual crop yields; and the nonclimatic increases in yield caused by new cane varieties and and the increased use of fertilizer.

The Morphology and Physiology of the Sugar Cane Plant

The sugar cane plant closely resembles corn in external morphology. It varies from 1.2 to 1.8 M. in height and has a stem thickness from 2 to 5 cm. The aerial part of the plant contains from 10 to 40 internodes. Both length and thickness reflect growth conditions, particularly the moisture environment.

The stem tissue consists of thin-walled parenchyma cells, and unlike other grasses, except corn and sorghum, there is an intercellular substance (juice). It is this juice which is most important in the production of sugar. Pith development in the stem is very rare, and there is no secondary thickening so that all increase in girth must be accomplished by stretching of the primary parenchyma cells.

The leaf includes a basal sheath which encircles the stem in tubular fashion and the actual blade which varies in length from 1 to 2 M. and from 2 to 6 cm. in width. The leaf margin is finely serrated. Both conduction and rigidity are achieved by means of a large medial vein. Increase in age leaves the bottom leaves functionless, and they die away and are discarded. All root development is secondary.

The storing of sucrose in the stem proceeds from the base toward the top with increasing maturity. Full maturity is determined by a maximum sucrose content.

Ecological Manifestations With Regard to Climate

Muller (14) outlines the climatic ecology of cane as found in studies in the Dutch East Indies. He claims that the optimum temperatures for cane lie between 77 and 99°F. The mature sugar plant will evapotranspire 0.88 imperial gallons of water/day, and daily evapotranspiration from an acre of cane reaches 21,120 gallons. The desirable rainfall ranges from 70 to 98 inches/annum. Cane will thrive in the rainiest spots on earth (eg. The Khasi Hills along the southern edge of the Brahmaputra Valley where the annual rainfall reaches as high as 474 in.), and the xerophytic leaf structure allows the withstanding of moderate water deficiencies. Severe drought, however, causes a drying up of the leaf about its longitudinal axis. Sugar cane thrives best in bright sunlight, and constant cloudiness combined with high relative air humidity, leaves the plant soft and susceptible to insect pests and fungus infection.

The planting season is chosen so as to protect the young plants against damage by heavy rain, while at the same time allowing them to obtain full benefit of the main heavy rains at the end of 6 months of development and to mature during the dry season. Sugar cane is propagated exclusively by a vegetative process using pieces of stem.

From the discussion of Barbados' agriculture in the introduction, it can be seen that the cropping regime closely conforms to the general desirable pattern outlined by Muller. McIntosh (12), in discussing the growth characteristics of sugar cane in Barbados, points to the importance of climatic impetus. He states that the time and extent of tillering[1] is largely governed by the amount and distribution of rainfall. The

1. Tillers are the stems which grow from the vegetative propagate.

dry season exerts a limiting effect on tillering during the early stages of growth, but since cane length-increments are negligible, McIntosh surmises that what growth energy is provided by moisture is devoted to the production of tillers. Whether the number of tillers influences subsequent crop yields seems to be a moot point in agricultural research. Growth increments (ie. increase in length and girth), are generally high from July to October, and in spite of high rainfall are negligible after this period. McIntosh states that rainfall is of greatest importance during the early rainy season (May, June and July) insofar as subsequent crop tonnages are concerned. He continues that the grand period of growth may be hastened or retarded according to the rainfall amount and distribution.

Cane Yields in Barbados

Sugar yield in Barbados is expressed in tons of cane harvested/acre (tons/acre), for the whole island; for low, intermediate and high rainfall areas; for each parish; and for individual plantations. Yields are also broken into plant cane yields, ratoon yields, and the yields for each variety. The actual tonnage of sugar produced from the harvest, which is the economically important quantity, is only given for the whole island. Fortunately, however, the actual tonnage of sugar is quite closely a direct function of the tons of cane harvested. Figure 14 gives the linear regression between tons/acre and sugar produced, which shows a correlation coefficient of 0.94. The relationship is given by the equation:

$$Y = 6X - 40$$

where $\underline{Y}$ is tons sugar x 10^3
and $\underline{X}$ is tons cane/acre

LINEAR REGRESSION OF TONS OF SUGAR PRODUCED WITH TONS CANE HARVESTED/ACRE

$Y = 6X - 40$

$r = 0.94$

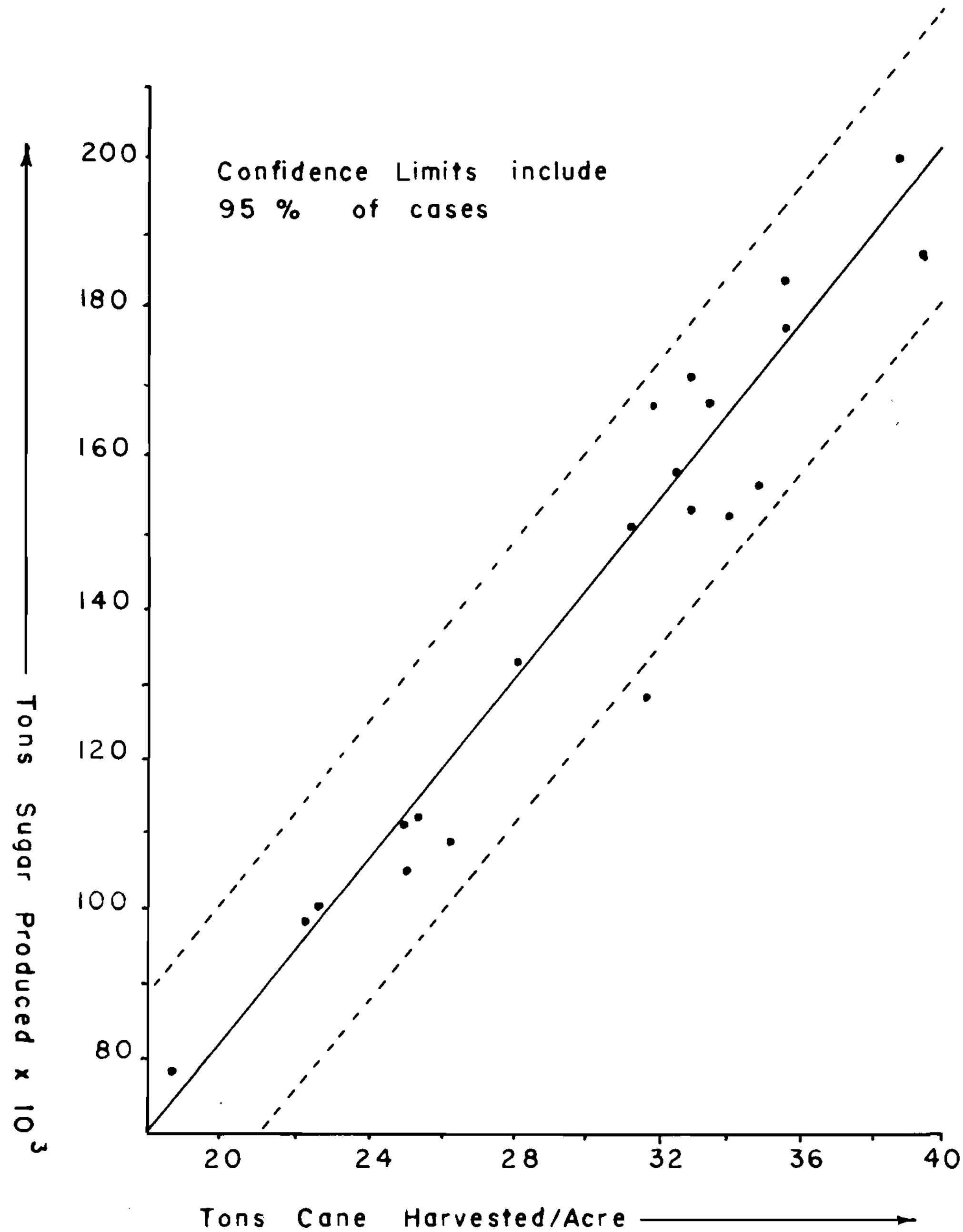

Figure 14

Since sugar produced is to a large extent a direct function of the cane harvested, it allows the use of cane harvested/acre for which there is adequate data, as a measure of success for both the harvested cane and the refined sugar.

The yield of sugar on a world-wide scale varies between 20 and 80 tons/acre. It can be seen that Barbados with yields ranging between 20 and 50 tons/acre is not a high yielding area. In addition to the various average yields, the author was able to augment his knowledge by obtaining data (1955-61) from 6 representative plantations for which rainfall figures were also available, and the moisture balance could, therefore, be calculated. These plantations fall in different moisture zones and their areal distribution is shown in Figure 15.

Nonclimatic Influences on Yield

Climate is not alone in influencing crop yields, and the use of fertilizer and new varieties must both be considered, before a thorough appreciation of the effects of the changing moisture balance on cane yield can be achieved.

It is not known when fertilizer was first used, but it can be surmised that animal manures were applied quite early. It is known that artificial fertilizer was in general use prior to the last war; that the supply was drastically cut during the war years; and that after 1945 application of 1 ton of potash for every 12 acres was general. Fertilizer application was stepped up to 1 ton/8 acres around 1957. Saint (21) writes that mulching with cane trash or sour grass before the dry season increases plant cane yields by 4 to 6 tons/acre, and that potash not only gives greater yields but allows more extensive ratooning. Mulching and ratooning have both been general practices since 1945 and since yield-climatic relationships for the individual plantations are only considered

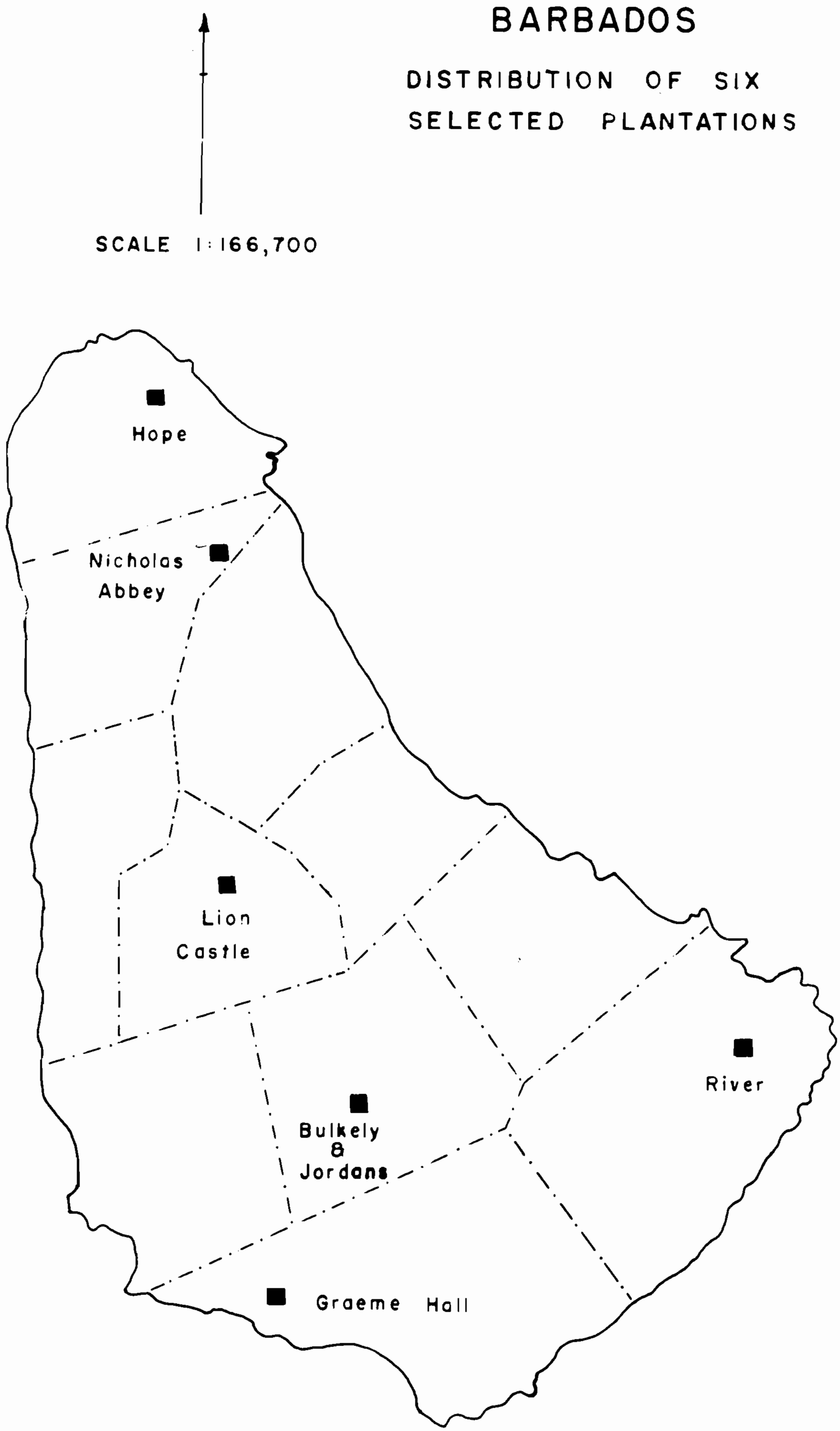
BARBADOS
DISTRIBUTION OF SIX
SELECTED PLANTATIONS
SCALE 1:166,700
Hope
Nicholas
Abbey
Lion
Castle
River
Bulkely
&
Jordans
Graeme Hall

FIGURE 15

from 1955 to 1961, it is possible to accept these factors as constant for this period. Since 1957, however, the increased use of fertilizer may have influenced cane yield, and although this is a variable which cannot be expressed quantitatively, its possible effect on yield should be appreciated.

The influence of changing cane varieties on yield presents a more difficult problem. Saint states that between 1935 and 1939 variety B2935 was grown on over 40% of the crop land and that this raised sugar production 15% in low rainfall areas and 9% in intermediate rainfall zones. It should be appreciated that different varieties are dominant in different areas according to their potential under certain moisture conditions. From 1945 to 1956 the use of B37161 was dominant in all rainfall areas, covering from 55 to 80% of total acreage. After this period it was steadily superseded by four other major varieties until in 1960 it was grown on only 5% of cane land (Foster (6)). Of the replacement varieties, B41211 was most important in low rainfall areas; B41211 and B4744 in intermediate rainfall regions; and B4744 and B45155 in high rainfall zones. It is difficult to assess accurately the quantitative role played by new varieties in changing the cane yields, but it must be supposed that the new varieties which gain dominance do increase sugar production.

Intangibles which have affected production to a greater or lesser extent, are three-fold. They include the development of a better soil tilth due to deep cultivation by modern machinery; cane fires which differentially affect yields from year to year and from plantation to plantation; and the competence of management.

CHAPTER IV RAINFALL AND MOISTURE BALANCE RELATIONSHIPS TO SUGAR YIELD

Rainfall and Cane Yield

It was realized early that rainfall somehow influenced cane yields, and various attempts have been made to express this influence mathematically.

Rawson (18), who was much concerned with rainfall influence on sugar yields wrote in 1874:

> "It is believed that any marked excess of rain during the first six months of the year is injurious both to the crop which is to be reaped and that which is to follow. The cane plant during the early stages of its growth is very hardy and requires but little moisture;.........With light showers during the first 6 months the young canes make no marked progress, but the roots are increasing in length before the end of August and during September and October the rains usually come to their aid at the critical time. They then grow with extreme rapidity, are extremely tender and succulent, and a short spell of dry weather at that time usually does severe mischief. If, however, the first 6 months of the year are wet, and the young canes are excited to an abnormal rapidity of growth, they are liable to be seriously affected by any interval of dry weather in the middle of the year. Moreover, rainy weather in the reaping season retards the manufacture (of sugar) and causes a great loss from the rotting of the canes at their roots."

In what today seems a crude analysis but which at the time was a significant pioneer attempt, Rawson (19) proposed to predict the crop yield (in hogsheads) by multiplying each inch of rainfall during the preceding calendar year by 800.

In 1929, Leake (11), published the following regression formula for predicting sugar yields in Barbados.

$$\text{Yield} = 0.026\,\underline{P} + 0.055\,\underline{D} + 0.540\,\underline{G} + 4.12$$

where $\underline{P}$ is rainfall in the wet season prior to planting

$\underline{D}$ is rainfall in the dry season following planting

$\underline{G}$ is rainfall in the wet season during the period of grand growth.

Leake's calculations for the years 1911 to 1926 inclusive show that it was possible, using his equation, to estimate in the December prior to harvest the probable yield with an even chance of being within 3 tons/acre of the actual. However the author found that the application of Leake's method to individual stations for random years between 1955 and 1961, gave an average error of 32% and maximum and minimum errors of 53% and 13% respectively.

Halais (8), in 1954 developed an empirical method for predicting cane yield/unit area and the sugar manufactured as a percent of the cane for Mauritius. His method involved simple and multiple linear regressions between certain critical rainfall distribution data. He postulated that because sugar production was quite successful in Mauritius, the normal monthly rainfall distribution for the island must necessarily fit the monthly water requirements of sugar cane. The plant cane in Mauritius reaches maturity in 12 months and a division is made into an 8 month vegetative period from November to June inclusive and a 4 month maturation period from July to October inclusive. During the vegetative period any monthly rainfall which fell short of the normal was considered deficient by Halais and detrimental to growth, but he maintained that rainfall in excess would do no damage in freely-draining soils. Conversely, excess moisture would be detrimental during maturation, as it would be held in the soil and used by the plant for further growth, which would delay maturity. Drought was measured numerical by the sum of monthly rainfall deficits between November and June. The drought (D) affects final cane tonnage. Excess moisture (E) is measured numerically by the sum of monthly rainfall excesses between July and October. Over 78 years of records Halais found no correlation between November to June deficits and July to October excesses in Mauritius. Halais' linear regression equation for cane tonnage/crop year is:

$$\text{Yield} = \text{Normal } \underline{TCA} + \underline{k}_1(15-\underline{D})$$

where $\underline{TCA}$ is tons cane/arpent[1].
$\underline{k}_1$ is a regression coefficient which varies for different areas of the island.
$\underline{D}$ is the moisture deficiency during the vegetative period.

The equation to give sugar manufactured as a percent of cane is:

$$\text{Sugar manufactured} = \text{Normal } \underline{SMC} - \underline{k}_2(15-\underline{D}) + \underline{k}_3(2.5-\underline{E})$$

where $\underline{SMC}$ is sugar manufactured as percent of cane.

$\underline{k}_2$ and $\underline{k}_3$ are regression coefficients which vary throughout the island.
$\underline{E}$ is the excess moisture during the maturation period.

Halais method allows the determination of more than 80% of the annual fluctuations in sugar production for years free from cyclonic disturbances in Mauritius.

Both Leake's and Halais' methods have virtues and shortcomings. They both use a relatively simple quantitative expression based on rainfall which is the most available and comprehensive climatic parameter for most parts of the world. Halais' method has the advantages that it differentiates areally and also allows a calculation of the sugar produced as well as the cane reaped. The major disadvantages are that both methods are merely empirical expressions and do not explain why the yield is influenced in a certain way; moreover they express only the rainfall factor in the moisture balance cycle. Halais' basic assumption is that because sugar is successful in Mauritius then the normal rainfall regime must suit the water requirements of sugar cane. It is agreed that there is normally enough rain to insure growth, but it does not follow that the water requirements for sugar are satisfied or that maximum yields are achieved under "normal" conditions.

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1. 1 Arpent x 1.043 = 1 Acre

The writer feels that a more explanatory and scientifically sound approach is to consider crop yields in relation to moisture balance. This treats the function of the plant, the temperature, the total radiation, and the soil, as well as the rainfall, in the growth cycle. It should allow a determination of what moisture balance will achieve a maximum yield or constitute a drought, and also give information on what irrigation will be necessary at any given time and place in order to insure maximum yields, information which is generally lacking in Barbados at present. It will be necessary in such a consideration, to differentiate between plant cane growth and ratoon growth, since each covers a different time period in its life cycle.

Moisture Balance and Cane Yields

The only reliable yield data which separates plant cane and ratoon yields for the individual plantations is available for a 7 year period (1955-61 inclusive). This period fortunately shows a marked variety both in moisture balance and cane yield, and is considered ideal for a detailed exploration into the relationships between moisture balance and cane yield.

A detailed moisture balance covering the 7 year period has been calculated by the author for each of the 6 representative plantations shown in Figure 15. These are: Graeme Hall which lies in the driest part of Barbados; Lion Castle which records the highest rainfall in the island; the combined plantation of Bulkely and Jordans in an intermediate moisture area; River in the most easterly part of the island; and Nicholas Abbey and Hope toward the north.

A number of tentative hypotheses were postulated and tested and of these only two resulted in a significant correlation. These hypotheses are outlined below, and each consists of two parts, the first concerning plant cane yields and the second ratoon yields.

<u>Hypothesis</u> I(a) - Plant cane yield increases linearly as actual evapotranspiration (AE) approaches potential evapotranspiration (PE) over the 17 month growing period from November to March.

The linear regression curve (Fig. 16(a)) becomes:

$$Y = 0.56\,X - 4.81$$

where $\underline{Y}$ is plant cane yield
and $\underline{X}$ is AE/PE x 100

and gives a correlation coefficient $r = 0.78$ for the 6 stations. Hence the ratio of AE/PE accounts for 60% of the change in plant cane yield.

I(b) - Ratoon yield increases linearly as AE approaches PE over the 12 month growing period from April to March.

The linear regression gives the curve:

$$Y = 0.39\,X + 0.24$$

where $\underline{Y}$ is ratoon yield
and $\underline{X}$ is AE/PE x 100

and an r value of 0.73 (Fig. 16(b)). Only 53% of ratoon yield changes are accountable to changing AE/PE.

<u>Hypothesis</u> II(a) - Plant cane yields increase linearly as the moisture deficit decreases during the period of grand growth from June to October inclusive.

This linear relationship is expressed by the curve

$$Y = 43.0 - 1.34\,X$$

where $\underline{Y}$ is plant cane yield
and $\underline{X}$ is moisture deficit

which is shown in Figure 17(a). The correlation coefficient is -0.70

LINEAR REGRESSION OF PLANT CANE YIELD WITH (AE/PE x 100 %) DURING THE 17 MONTH GROWING SEASON

$Y = 0.56X - 4.81$

$r = 0.78$

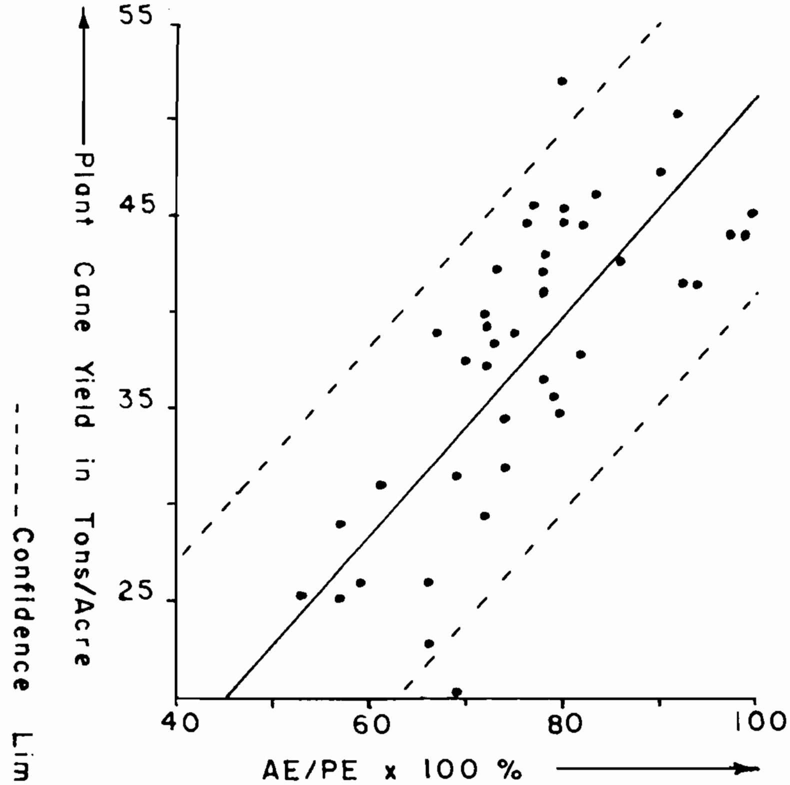

Figure 16 (b)

LINEAR REGRESSION OF RATOON YIELD WITH (AE/PE x 100 %) DURING THE 16 MONTH GROWING SEASON

$Y = 0.39X + 0.24$

$r = 0.73$

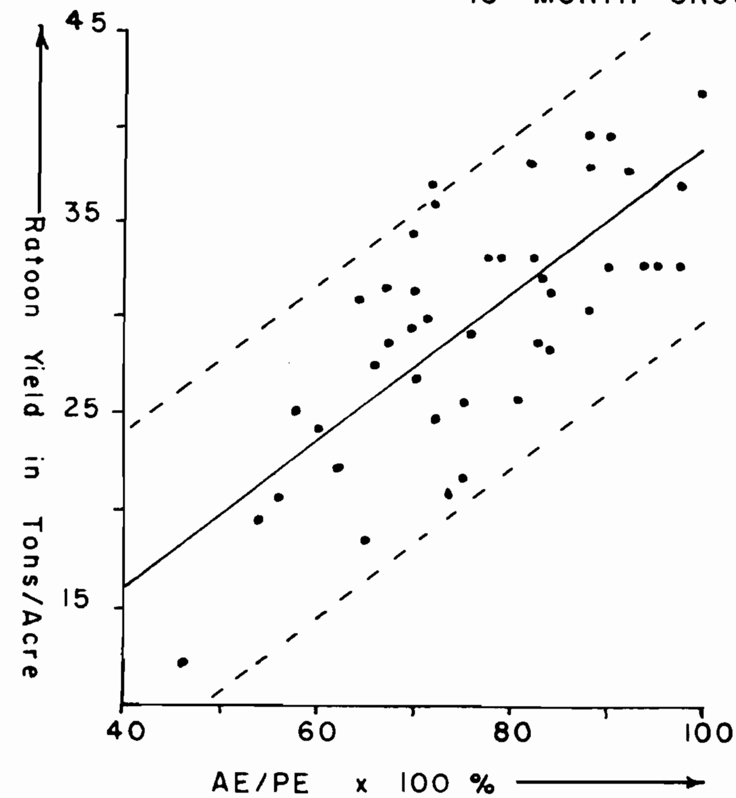

Figure 16 (b)

LINEAR REGRESSION OF PLANT CANE YIELD WITH MOISTURE DEFICIT DURING THE WET SEASON FROM JUNE-OCTOBER

Y = 43.0 - 1.34 X

r = -0.70

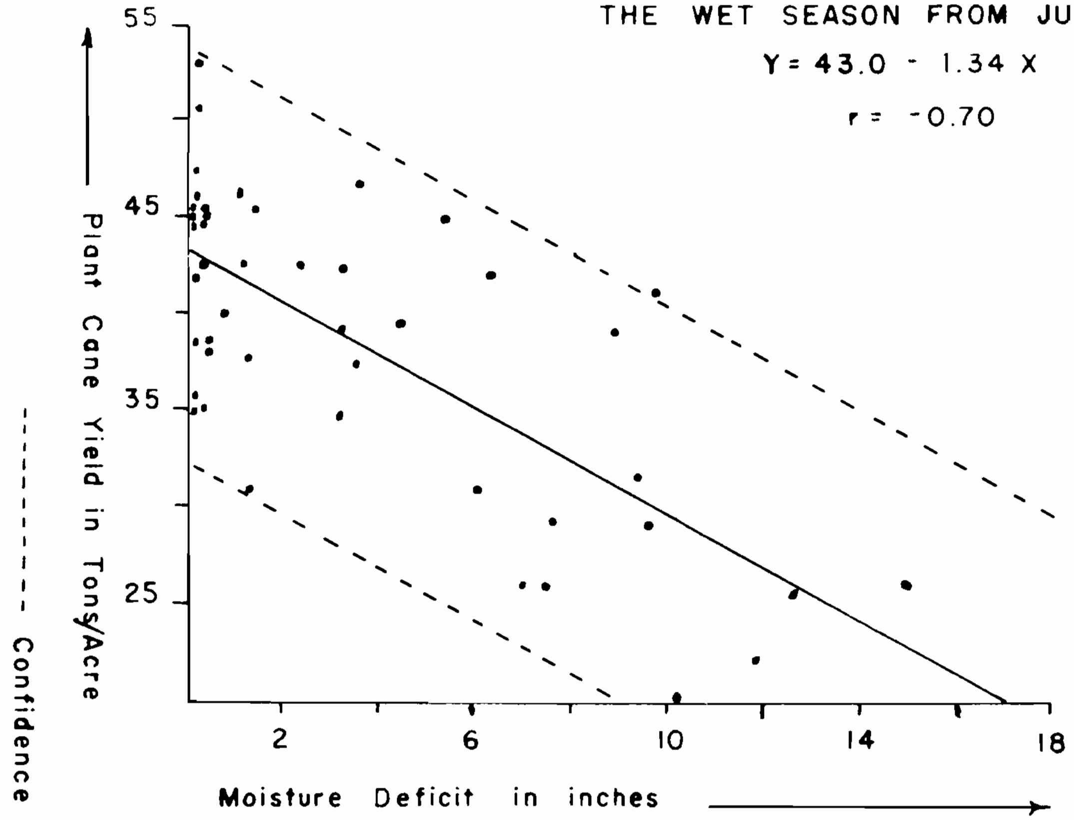

Figure 17 (a)

LINEAR REGRESSION OF RATOON YIELD WITH MOISTURE DEFICIT DURING THE WET SEASON FROM JUNE-OCTOBER

Y = 32.9 - 0.82 X

r = -0.48

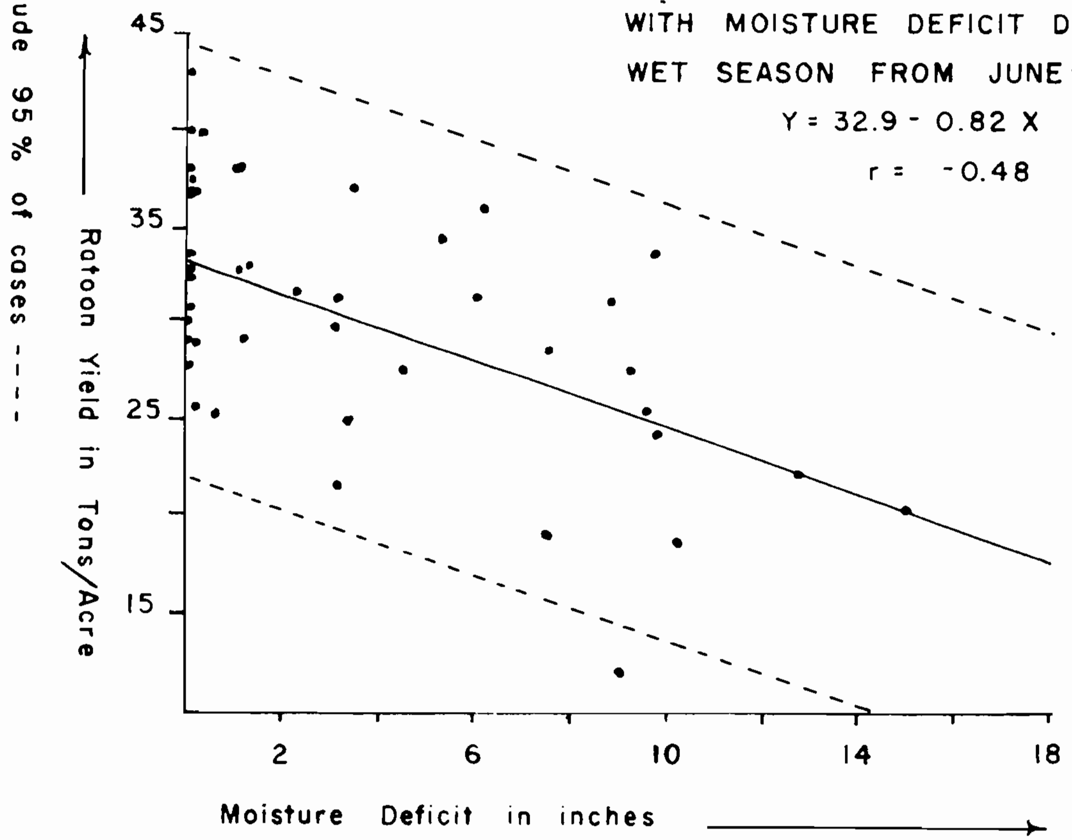

Figure 17 (b)

(ie. as moisture deficit increases, the yield decreases). Changing moisture deficit during the period of grand growth explains only 49% of changing plant cane yield.

It was noted by the writer that Lion Castle rarely experiences a moisture deficit during the period of grand growth and yet the yields are not as high as would be expected. A correlation of 0.85 was achieved by omitting the Lion Castle data, giving an explained variance of 72%.

II(b) - Ratoon yield increases linearly as the moisture deficit decreases during the period of grand growth from June to October.

The correlation coefficient of 0.52 for the curve

$$Y = 32.0 - 0.82\ X$$

where <u>Y</u> is ratoon yield
and <u>X</u> is moisture deficit

is very low and not really of much significance (Fig. 17(b)). This case differs from that of the plant cane yields, as the omission of the Lion Castle data does not increase the relationship ($r = 0.48$).

It is difficult to draw definite conclusions from the foregoing statistical analysis, but certain facts seem evident.

The moisture balance throughout the 17 month growing period of the plant canes is significant in determining the final yield. The moisture deficit during the period of grand growth is of considerable importance to the success of the plant cane yield except in the very moist areas (eg. Lion Castle). This latter anomaly probably occurs because during the period of grand growth which corresponds to the rainy season, the heavy cloud cover in the very moist areas results in a lowered energy supply from the sun, thus inhibiting photosynthetic activity and plant growth. The importance of total radiation in determining final yield has been substantiated by Smith[1].

---

1. Uncompleted PhD thesis.

Ratoon yield seems to depend far less on moisture factors than does the plant cane yield. Again the overall moisture balance is most indicative of crop success, but to a far smaller degree. The moisture deficit during the period of grand growth plays little part in influencing the final yield.

From the confidence limits of the curves (Fig. 16 (a)&(b)), it can be safely stated that if the actual evapotranspiration equals the potential, then plant cane and ratoon yields will rarely fall below 40 and 30 tons/acre respectively.

Irrigation

It is evident from the foregoing analysis that the moisture balance does not exert an absolute control on sugar yield in Barbados. As found above, however, if AE = PE, relatively high yields can nearly always be assured. Hence if irrigation water is applied so that AE always equals PE, the plant cane and ratoon yields will rarely fall below 40 and 30 tons/acre respectively. Figure 18 is based on the assumption that if rainfall equals PE, then AE will most likely equal PE. For the years when the rainfall falls below this amount, irrigation will be necessary and in Figure 18 the number of water deficient years in every 10 is expressed. It is necessary at this time to consider Smith's work entitled "The Irrigation Needs Of Barbados"(27). Smith worked out potential evapotranspiration using Thornthwaite's method. Temperature data was taken from Bridgetown and a 1°F temperature decrease for every 320 feet of altitude was allowed. With rainfall data from 45 stations, he took the difference between rainfall and potential evapotranspiration as denoting irrigation need and produced a series of rough maps showing irrigation requirements for each month of the year. Smith then calculated the num-

BARBADOS

NUMBER OF YEARS IN TEN WHEN IRRIGATION WILL BE NEEDED TO MAKE AE = PE

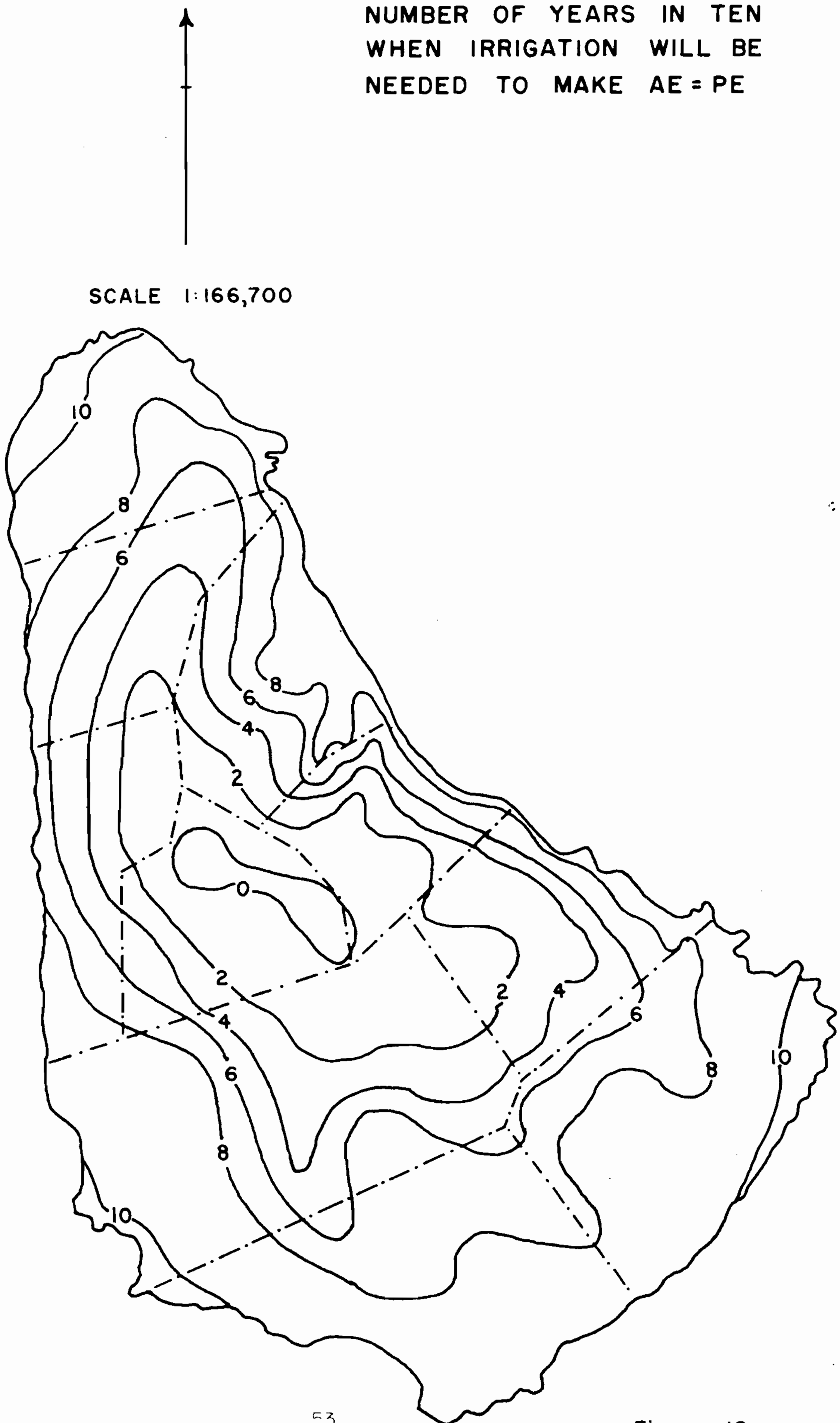

Figure 18

ber of years in 10 when irrigation would be needed in any given month. His results do not agree well with Figure 18. Smith finds that even in the highest rainfall areas (eg. Lion Castle) that irrigation will be needed 1 year in 10 in November, and 8 years in 10 in March. Much of the difference is probably due to his use of a fewer number of stations, and to the different technique which was employed to calculate moisture balance.

Figure 19 combines a knowledge of irrigation needs with Senn's calculations on available ground water resources. It is assumed by the writer that where two or less years in every ten has a rainfall deficit, irrigation will not be economically worthwhile. Hence about one-sixth of the total area of Barbados needs no irrigation. Other areas are excluded from profitable irrigation because of insufficient ground water resources. These include the coastal areas where the ground water is brackish; the Scotland district and Codrington College catchment basin (Fig. 3), where ground water sources are insignificant; and the Bridgetown area where domestic consumption is high and no cane is grown in any case. It can be seen from Figure 19, that approximately one-half of the cane lands of Barbados could be profitably irrigated.

BARBADOS

AREAS WHERE IRRIGATION FROM GROUND WATER SOURCES MAY BE MOST PROFITABLY EXPLOITED

SCALE 1:166,700

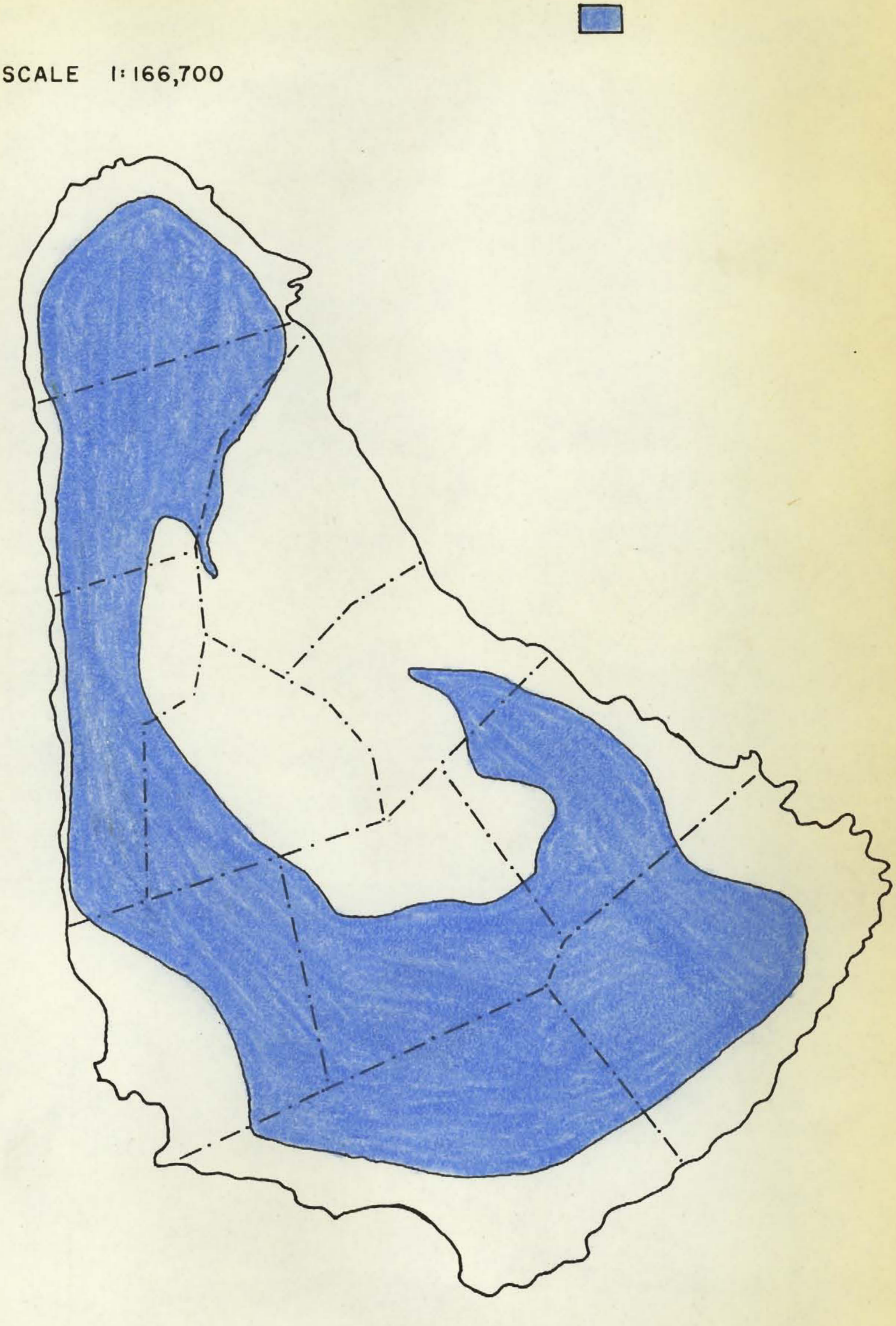

Figure 19

CHAPTER V SUMMARY AND CONCLUSIONS

Summary

Data from the recently established climatic station at Waterford, Barbados, combined with comprehensive records on regional rainfall, are sufficient to allow a detailed investigation into the island's moisture balance. In turn the moisture balance can be exploited to help explain climatic controls over sugar cane growth.

Sugar has been the mainstay of Barbados' economy since 1650, and at present occupies most of the island's arable land. It is harvested in two forms; a plant cane crop which grows throughout a 17 month period, and ratoon crops which mature in 12 months. Yields vary greatly both areally and with time.

The various influences on cane growth include the moisture regime; the energy balance; topography, soils and drainage; and farm management. Thornthwaite's method of estimating the moisture balance from temperature, rainfall, and soil moisture data was employed for Barbados. It was found, however, that the calculation of PE using temperature as a measure of available energy did not agree well with the measured PE at Waterford. PE seemed instead to be a direct function of solar radiation, which agrees with other investigations. It was necessary to develop a correction so that estimated PE agreed more closely with measured PE at Waterford, and then to apply it to the rest of the island. As an interesting sidelight, it was postulated that the present day moisture balance would favour a natural vegetation varying from wet tropical evergreen forest in the wettest areas, to an open thorn scrub in the driest.

The cane plant is a member of the grass family, and like other members of the family develops only primary tissue. Unlike most other grasses, however, it forms an intercellular juice known as sucrose, which increases in amount with maturation, and is refined to make sugar. During growth, particularly the phase of grand growth, the cane plant transpires a large amount of water. Optimum rainfall lies between 70 and 98 inches, but the plant can survive moderate moisture deficits, and grows in areas where rainfall is excessive. Bright sunshine is advantageous, and constant cloudiness reduces the plants' resistance to disease. The amount of sugar extractable from the mature cane correlates highly with the weight of the vegetative growth before refining. This relationship is useful since data on the latter are much more comprehensive.

Sugar cane yield does not vary absolutely with changing moisture balance. Although various formulae to predict cane yields from rainfall have been developed, they use only one parameter in the moisture balance cycle, and are not based on a knowledge of physiological process. A statistical assessment of the influence of changing moisture balance on cane yield shows that the plant cane yields are more responsive to moisture balance factors, than are ratoon yields. The only two moisture influences which give high correlations with yield are the AE/PE ratio throughout the growing period of both plant cane and ratoon crops, and the moisture deficit during the period of grand growth of plant canes. If AE=PE throughout their growing periods, plant cane and ratoon crops are virtually assured of relatively high yields. From a knowledge of cane moisture needs and ground water resources, the author calculated that irrigation would be economically profitable on approximately one-half the cane lands of Barbados.

Conclusions

Topographic configuration and prevailing wind direction are the dominant influences in Barbados' rainfall distribution. Rainfall due to surface heating, which is particularly important during the rainy season, influences this distribution along the western and south-western coastal areas.

The soil moisture retention at field capacity varies with the different soil types. With the present state of knowledge, however, the assignment of absolute values for field capacity represents only an educated guess.

Total incoming solar radiation gives a more reliable measure of the available energy for evapotranspiration than does air temperature. The latter, however, allows an estimate of changing energy potential with altitude.

During the dry season more heat energy is radiated from the earth's surface than in the wet season when it escapes in the form of latent heat of vapourization. This leads to a higher lapse rate in the dry season.

In Barbados, the correlation of rainfall, potential evapotranspiration, moisture deficit, and moisture surplus with altitude, for both windward and leeward exposures, is an excellent mapping technique, for it allows extrapolation where no data are available.

On a regional scale, 60% of the variance in plant cane yield and 53% of ratoon yield variance can be explained in terms of changing moisture balance.

Barring catastrophic influences, it is virtually certain that plant cane and ratoon yields will be high, if the actual evapotranspiration always equals the potential throughout the growing period of each.

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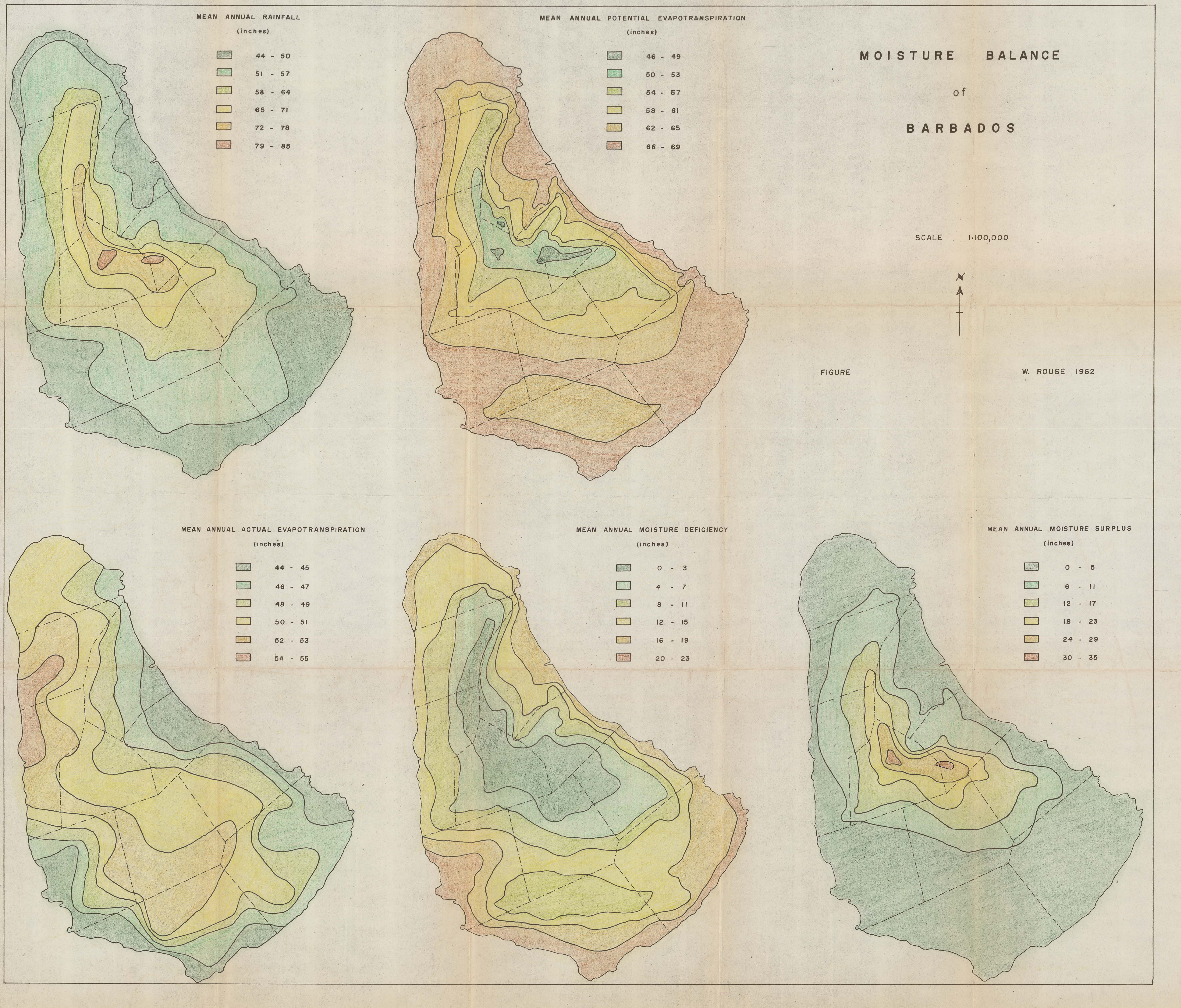
MOISTURE BALANCE
of
BARBADOS
SCALE 1:100,000
N
FIGURE
W. ROUSE 1962
MEAN ANNUAL RAINFALL
(inches)
44 - 50
51 - 57
58 - 64
65 - 71
72 - 78
79 - 85
MEAN ANNUAL POTENTIAL EVAPOTRANSPIRATION
(inches)
46 - 49
50 - 53
54 - 57
58 - 61
62 - 65
66 - 69
MEAN ANNUAL ACTUAL EVAPOTRANSPIRATION
(inches)
44 - 45
46 - 47
48 - 49
50 - 51
52 - 53
54 - 55
MEAN ANNUAL MOISTURE DEFICIENCY
(inches)
0 - 3
4 - 7
8 - 11
12 - 15
16 - 19
20 - 23
MEAN ANNUAL MOISTURE SURPLUS
(inches)
0 - 5
6 - 11
12 - 17
18 - 23
24 - 29
30 - 35