WATER BALANCE STUDIES IN RELATION TO TEA YIELDS IN THE BROOKE BOND LIEBIG ESTATES, KERICHO, KENYA

by

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This thesis is my original work and has not been presented for a degree in any other University.

E.K.M.

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PREFACE

Tea is an important cash crop in East Africa and is grown in areas contrasting substantially in their physiographic and climatic conditions. The mode of production in Kenya varies from large commercial estates managed by commercial companies to small production units owned by small holder farmers.

Previous researches on tea productivity in East Africa endorse the fact that climate and soils are the major physical factors controlling tea growth. Whereas climate is the product of large scale atmospheric circulation features over which man has little control, under good management practices, the deficiencies in soils can be identified and rectified. Thus the only factor inhibiting or encouraging tea growth is climate. It is proposed, therefore, that knowledge of the relationship between tea production and climate is essential in the evolution of land management policies and the development of tea varieties concomitant with increased tea productivity. It is against this background that this thesis attempts to examine the role of climate in the production of tea in Kericho, Kenya.

An evaluation of the role of climate in tea production must of necessity take into consideration the interaction of climate with other non-climatic factors in affecting tea productivity. Thus in a bid to gauge realistically the influence of climate on tea production, an attempt has been made to eliminate as much as possible certain agronomic aspects of tea cultivation which interact with weather to confuse the interrelationships between tea yield and weather parameters. The effect of these factors which were identified as soil fertility, age of the tea bush, plucking aspects and prunning cycles was minimised by a logical and suitable sampling design.

The broad range of climatic variables that affect tea growth make it difficult to isolate and specify the actual influence of any single climatic element upon tea productivity. However, by formulating agroclimatological/agrometeorological indices that have a bearing on tea growth, it is possible to quantify the influence of climate on tea yields. For the purpose of this investigation, the water balance model has been used as a basis for formulating agroclimatological indices related to tea growth. The adoption of the water balance approach was decided upon after a careful and meticulous evaluation of the suitability of other alternative approaches. For example, past approaches in studies of climate-plant relationships have tended to measure the impact of climate on plant growth and production by correlating individual climatic parameters such as Stevenson's screen air temperature or rainfall with crop yields. The limited success of such approaches is obvious since air temperature or rainfall are not sufficiently representative parameters of the tea crop environment or any other crop for that matter. Also analysis of the relations between individual climatic elements and plant production lacks recognition of the multivariate nature of plant-climate relationships.

Some aspects of the structure and content of this thesis deserve comment. The introductory chapters 1 and 2 serve to identify the problem, the need and justification of the present investigation into tea-climatic relationships in the study environment. A review of the existing literature on plant-water relations with particular reference to tea production occurs in Chapter 2. Chapter 3 discusses the objectives of the present investigation in the light of existing knowledge on tea-climate relations and pertinent methodology used in realising the identified objectives and testing of hypotheses. The scope and suitability of the data required for this investigation is discussed in chapter 4.

Chapter 5 discusses the results of the analysis concerning tea-climate interactions in the study area. Simple correlation coefficients and linear regression analysis were used in establishing and gauging the role of climate on tea production.

A summary of the major findings arising from this investigation and conclusions drawn is the subject of chapter 6. The implications of the findings of this study upon present tea production management practices are spelt out. Future research needs to enhance our stock of knowledge on tea-climate relations are also identified.

It is hoped that the results of this study will not only be of value to the tea industry in the limited area of study but should appeal to a wide audience interested in matters relating to plant-environment relationships.

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CHAPTER ONE

INTRODUCTION

INTRODUCTION

Statement of the problem

Tea is a tropical perennial shrub that is grown widely as a cash crop in areas of the World that contrast substantially in their physiographic and climatic conditions (Carr, M.K.V. 1972). Inspite of the fact that tea is a high rainfall crop, the actual climatic and ecological requirements of the crop, particulary in East Africa where the crop thrives well in markedly contrasting ecological environments, have not been succintly quantified (Carr, M.K.V. 1972). In East Africa, tea is grown in areas with a bimodal pattern of rainfall and is a dominant cash crop in the zone of high rainfall, equable temperatures and high humidities (Hanna, L.W. 1971). Hanna, L.W. 1971 reported that so far little pertinent information on the climatic effects has accrued from experimental stations on tea estates because of the short run of the experiments and the limited purpose for which they are designed. It is argued that the continued viability of the tea industry owes much to the "hardiness" of the tea bush which has enabled economic productivity without serious attempts to understand the factors controlling its existence (Brown, L.H. and Cocheme, J. 1973).

Hanna's (Hanna L.W. 1971) work on tea productivity in Uganda authenticate the fact that climate and soils are the major factors controlling tea growth. Whereas climate is the result of large scale atmospheric circulation features over which man has little control, under good management practices, the deficiencies in soils can be identified and rectified. Thus an understanding of the relationship between tea growth and climate is essential in the evolution of land management policies, identification of new tea growing areas for future expansion and the development of varieties concomitant with increased tea productivity.

The broad range of climatic variables that affect tea growth make it difficult to isolate and specify the actual influence of any single climatic element upon tea productivity. However, by formulating agroclimatological indices that have a bearing on tea growth, it is possible to evaluate the influence of climate upon tea yields (Hanna, L.W. 1971). Reported studies in the literature on climate - plant relationships (Laycock, D.H. 1964; Carr, M.K.V. 1969, 1970) have tended to measure the impact of climate upon tea growth by correlating individual climatic parameters such as stevenson's screen air Temperature or rainfall with crop yields. Chang, Jen-Hu (1965) observed that the "customary procedure of correlating yield to air temperature and rainfall is so crude that it contributes little in actual operation and long range planning". Rainfall, for example, can influence plant growth only indirectly through soil moisture. It is thus reasonable to consider that rainfall is not a sufficiently representative parameter of the soil moisture environment. Soil moisture status depends among other things on the evaporative demand of the atmosphere which is in turn influenced by solar energy, wind velocity, atmospheric relative humidity, plant characteristics such as leaf colour and on the amount and rate of waterinput through precipitation. Thus Chang Jen-Hu (1965) suggested that it is only the application of the water balance model and other sophisticated concepts that can permit a realistic quantitative assessment of the effect of climate on yields. Against the background of Chang's suggestion, it is the plan of this study to use the concept of "water balance" as a basis for the formulation of climatological indices to be related to tea yield as a function of tea production. The water balance model adopted in the present study has three main components. These are: precipitation, available water and water output. Evapotranspiration is the major component of water output from plants and was designated as E_T. Under conditions of unrestricted water supply, the evapotranspiration rate is maintained at the potential level and is usually termed as potential evapotranspiration. Similarly, under limited supplies of water, evapotranspiration must proceed at a rate below the potential level. According to Thornthwaite, C.W. (1948) and as used by Hanna, L.W. (1969), actual evapotranspiration is computed as a function of precipitation and soil moisture storage change. When precipitation (P) is greater than daily E_T, actual evapotranspiration (AE) is regarded as being equal to E_T. However, if $P \angle E_T$, AE is computed as the sum of rainfall and soil moisture storage change. Available water is defined as the amount of water held between field capacity (soil particles completely saturated with water and deep drainage has ceased) and permanent wilting point (point at which a wilted plant can no longer recover turgidity even when it is placed in a saturated atmosphere). In agriculture and soil science, water tensions equivalent to - 0.3 bar and - 15.0 bars are taken to represent field capacity and permanent wilting point respectively. Further development and detailed description of the water balance concept occurs in chapter 4. In this study, tea yield was considered as a useful response parameter to be correlated with climatic parameters. Tea yield was defined as that quantity of the dry matter constituting the harvestable portion of the vegetative part of mature tea expressed in Kg/ha of processed tea.

It is recognized that the water factor in climate, particularly soil water availability as related to atmospheric evaporative demand and the internal water status of the plant constitutes one of the most important climatological variables limiting plant growth and survival. The transfer of water, hence energy, through the soil-plant-atmosphere continuum is not only subject to physical forces of the environment but is also influenced by physiological control. The regulation of the movements of the stomatal pores through which water escapes to the atmosphere by transpiration is such a physiological control. As such, the evaportranspiration component of the water balance model is an important physiological phenomenon intimately linking the plant to the physical environment (Brown, R.W. 1977).

Although a number of studies on the influence of climate on crop production have been carried out in Eastern Africa (see Chapter 2) no comprehensive work exists on the climatic effects on tea production in Kenya. It was therefore felt that an inquiry into the mode of the responses of the tea plant to climate in Kenya was required. The major objective was to quantify the influence of climate on tea yield with reference to evaporation, solar radiation, evapotranspiration and soil moisture supply. It was decided to carry out this investigation in Kericho, Kenya (Kericho map 1). The methodology chosen is developed in chapter 3.

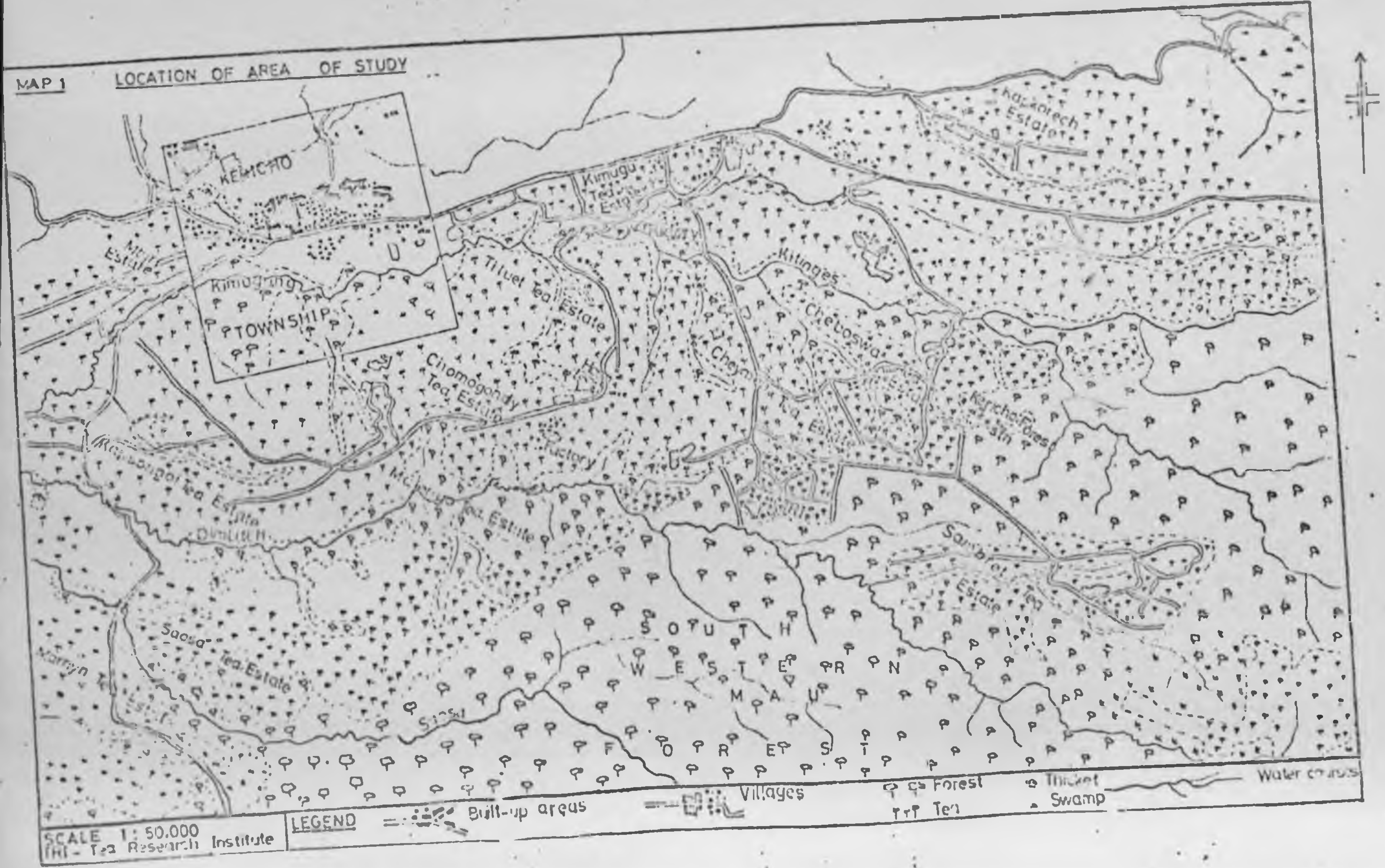
Reasons for selecting study area and crop

In order to realistically gauge the impact of climate on tea production, it was necessary to minimize the influence of non-weather variables on tea growth. It is in this regard that an area and crop were selected. Since the estate practice of tea production under commercial companies is characterised by high quality tea husbandry leading to consistency in fertilizer application, control of weeds, pruning, plucking and labour input, it was felt that yield data from Brooke Bond Liebig estates in Kericho would be reasonably free of variations caused by changes in agrotechnical practices. A preliminary investigation of the estate records in relation to fertilizer application, weed control, pruning and plucking revealed a consistency in tea husbandry that justified the hypothesis that the effect of extraneous variables upon tea growth was sufficiently constant. The presence of a climate station within close proximity of the study estates was another important requirement. In Kericho, the opportunity to use long term climate data from the Tea Research Institute of East Africa Meteorological station was apparent. The Brooke Bond Liebig company manages a number of tea estates with several tea fields in close proximity. Fields which are near together were considered important since these were bound to have similar characteristics with respect to antecedent soil fertility and microclimatic variability.

Scope and limitations of study

Most of the data used in this investigation is secondary data accruing from the estate tea yield records and the agrometeorological station maintained by the tea Research Institute of East Africa. The nature of the temporal and spatial variation in the aspect of tea-yield climatic responses cannot be investigated for periods smaller than one month because of limitations in tea-yield data. Tea yield data was available within the time frame of one month. Short periods have some physiological significance in tea productivity. For example, diurnal soil moisture deficits have significant influences upon the physiological processes of growth discussed in chapter 2.

MAP 1 LOCATION OF AREA OF STUDY



CHAPTER 2

LITERATURE REVIEW

CHAPTER 2

LITERATURE REVIEW

PHYSIOLOGICAL SIGNIFICANCE OF PLANT WATER RELATIONS TO YIELD

The quantity and quality of plant growth is the product of a complicated wave of interactions involving the plant and its environment.

Although the growth and development of any plant would depend on its hereditary potentialities, the importance of water as a medium for the physiological process of plant growth cannot be overemphasized. Water is required as a medium for nutrient absorption, synthesis of metabolites and structural materials, transport of assimilates etcetera, all important processes of plant growth and development. A correct internal water balance is essential to the proper running and development of the plant system. Although the total water potential is not the only "property" to which plants respond, it is nonetheless an important property governing direction of "source-sink" reactions in the plant system.

Assuming that water, in and around a plant cell, is close enough to equilibrium, the following equation of water potential (ψ) can be written:

$$\psi_W = \psi_{cell} = \psi_{vacP} + \psi_{vac\phi}$$

where W = cell wall

vac = vacuole

P, ϕ = pressure and osmotic components respectively

When the water potential of the cell tissue or organ of a plant is zero (at zero it would be at equilibrium with pure free water) the individual cells are said to be turgid. However, if the water potential drops below the zero level, the turgor pressure of the cells also drops giving rise to flaccidity. The condition of flaccidity is well shown by wilted leaves (Slatyer, R.O. 1969).

Two main factors govern the turgidity or flaccidity of cells depending in which direction they offset the level of plant water potential. These are first, the level of the soil water potential and second, the diurnal lag of absorption behind transpiration. These factors are also influenced by both physiological and environmental factors.

Absorption of water by the plant occurs because the suction at the leaves (or the water potential at any point in the plant system) is greater than the soil water potential near the roots. As the plant loses water through transpiration, the leaf water potential drops. If this water is not regained by absorption (i.e. if absorption lags behind transpiration), the leaf water potential will be progressively reduced. The cell turgor pressure declines rapidly as the leaf water content and leaf water potential are reduced and depending on the cell volume/turgor pressure relationships and the structural characteristics of the leaves concerned, they will gradually become wilted (Slatyer, R.O. 1969).

Slatyer, R.O. (1957a), proposed that at the point where ψ leaf had dropped to a stage at which cell turgor pressure was zero, and when ψ leaf= ψ root = ψ soil, the plant would be in a state of permanent wilting and the soil water content would be equivalent to that in which the soil -

water suction is - 15 bars.

EFFECTS OF WATER IMBALANCE ON PLANT PROCESSES GROWTH AND DEVELOPMENT

Primordial Initiation

Amongst the most sensitive parts of the plant to the conditions of water stress are the vegetative and productive primordia in the apical meristems. Moderate bouts of water stress suspend the initiation of primordials (Gates, C.T. 1968).

Cell Division

Multiplication of plant cells has been shown to be at least suspended in cases where water stress has existed. Gardner, W.R. and Nieman R.H. (1964) report instances in which cell division has continued to take place though at a reduced rate in plants subjected to stress.

Cell Enlargement and Differentiation

Stunted vegetation clearly manifests the effect of water stress upon cell enlargement. It is evident from the literature that in some species cell enlargement is so sensitive to water stress that stem elongation or leaf enlargement can be inhibited by small diurnal amounts of water tension that occur in plants normally enjoying plentiful water supplies in days of high radiation incidence.

Lack of cell enlargement leads to poor organ development. Vegetative plants show signs of poor leaf development characterised by small surface area and therefore reduced photosynthetic activity and often limited net assimilation rate. This is indeed the first sign of indirect effects of soil water status on physiological processes having a key implication to final biological yield.

In mature tissues, stress brings about migration of phosphorous from older leaves to the stems and meristematic tissue (Williams R.F. and Shapter R.E. 1955), and protein hydrolysis leading to the breakdown of normal cell function.

Fordham Effect

In an attempt to explain the annual tea yield distribution in Malawi, Fordham, R., (1970) contended that yield is not necessarily a function of growth rate. He postulated that plucking itself would bring about uneven crop distribution. He pointed out that since shoot elongation is more sensitive to physiological drought than the initiation of primordial buds, buds are produced at a more constant rate than pluckable shoots.

So long as drought is not severe enough to limit bud initiation, buds will continue to form and accumulate until the stress conditions are alleviated. Abrupt cessation of water stress conditions would be accompanied by the expansion and elongation of buds giving rise to a peak crop. In periods of water stress, however, few buds will develop into pluckable shoots and yield will be depressed.

Root Development

The relationship between water stress and root development is not clear. Some authors suggest that root development is enhanced relative to shoot development by water stress (Troughton,A. 1962; Salim, M.; et al, 1965).

There is reason to expect that water stress would reduce elongation of roots due to a reduction in rates of meristematic activity directly associated with the level of internal water stress (Newman, E.L. 1966; Salim,M; et al, op. cit.).

Transport

Under conditions of plentiful water supply, only small leaf water gradients would be required to transport water to the transpiring surface. Since the stomata remain open, and therefore the diffusive resistance due to stomatal impendance remains small, evapotranspiration is determined by environmental factors, in particular those factors influencing air turbulence near the crop surface, and solar energy.

As the leaf water content declines (due to dessication or increased transpiration, so that leaf water potential is less than soil water potential in the root range), a level of leaf water potential is reached at which the stomata close. Boyer, J.S. (1970) found in sunflowers that a level of leaf water potential equivalent to - 8 bars would cause stomatal closure. The events associated with stomatal closure include the restriction of photosynthesis and the increase of leaf temperature due to greater disposition of the absorbed energy into sensible heat transfer rather than evaporation. If this condition is protracted, lack of leaf turgidity would inhibit cell enlargement and subsequent growth. Furthermore, diurnal increase in leaf temperature may induce midday closure by increasing the respiration rate and the level of intercellular CO_2 concentration (Slatyer, R.O. 1969).

Nutrient.Uptake

The relationship between nutrient availability and plant water status is not a straight forward one. For example, nutrient uptake is not directly related to water uptake (Russel,R.S. and Barber, D.A. 1960), neither is nutrient availability a function of soil water imbalance (Fawcett, R.G., and Quirk, J.P. 1962).

Gates, C.T. (1957) has shown that the effect of senescence upon nitrogen and phosphorus levels in the leaves of tomato plants (*Lycopersicum esculentum*, mill.) is confused with that of water stress. In an investigation, he observed that the nitrogen and phosphorous levels in leaves decreased with the increased water stress. However, in considering young and old individual leaves, supplied with adequate water, he noted that the nitrogen and phosphorous levels decreased with leaf age, with the earliest and greatest reductions shown by the younger leaves.

From the above trend of events, it seems that an imbalance in nutrient supply arising from water stress does have a limiting effect upon certain aspects of plant growth and development. This imbalance should easily show up in the final crop yield.

Protein Synthesis and Nitrogen Metabolism

It is clear from the literature that a close association obtains between growth rate and protein synthesis. There is also a correspondence between protein synthesis and protoplasmic ingredients such as ribonucleic acid (RNA) content and between RNA and deoxyribonucleic acid (DNA) (Williams,R.F. and Rijven, A.H.G.C., 1965). Because of the well known effects of plant water stress upon plant growth, it is certain that water imbalance would have a limiting effect upon transamination and subsequent protein manufacture. Kessler,B., and Monselise, S.P. (1964); Ben-Zioni, A., Itai, C. and Vaadia, Y., (1967) have shown that water stress induces proteolysis.

A reduction in the rate of increase of DNA with imposition of slight stress levels has been observed in radish leaves (Gardner, W.R., and Nieman, R.H. 1964). Shah C.B., and Loomis, R.S. (1965) have also confirmed that slight degradation of already formed RNA.

Since nitrogen and phosphorus are integral components of the pyrimidine ring structures that constitute the nucleotide parts of DNA and RNA molecules, the suspension of primordial initiation can probably be explained by inhibition of DNA and RNA synthesis imposed by water stress. Slatyer, R.O., (1969) has suggested that in older leaves, hydrolytic breakdown processes tend to occur.

Plant Hormones

Osborne D.J. (1965) has reported that the introduction of cytokinins to the leaves of a number of annual plants produced a retarding effect upon chlorophyll degradation and promoted transamination and protein manufacture.

However, the presence of kinetin in stressed tobacco leaves - (-4 bars water potential) did not have a similar effect upon the incorporation of L-leucine into protein. A reduction in the ability of the leaves to incorporate L-leucine into protein molecules was observed with the younger leaves being the most sensitive. Humpries, E.G. (1968) has reported that 2 chloroethyltrimethylammonium chloride promotes root growth relative to shoot growth, thus delaying the onset of stress and reducing its severity. Slatyer, R.O. (1969) points out that since the introduction of kinin to the shoot retards the rate of senescence, "kinin supply to the shoot is important in the maintenance of active protein synthesis.... studies of root development and metabolism in relation to hormone balance may provide important insights into aspects of stress physiology"

Photosynthesis and Carbohydrates Metabolism

When evapotranspiration demand exceeds water uptake, a condition of negative leaf hydrostatic pressure develops. A reduction of leaf turgor pressure induces stomatal closure. This creates a restriction in the supply of CO_2 necessary for photosynthesis. Severe stress may also affect photosynthesis through the dehydration of the photosynthetic apparatus. These observations have been confirmed by Troughton, J.H. (1969) who found that the reduction in net photosynthesis in cotton leaves. (*Gossypium hirsutum*) was due to closure of stomata caused by water stress. He noted that cotton leaves wilted at relative water contents of around 80-85%.

There is evidence to demonstrate that stomatal closure is the primary cause of the first stages of photosynthetic response to water stress. Santarius, K.A., et al (1967) have shown that CO_2 related photosynthetic reactions (such as ATP synthesis, NAD synthesis et cetera) are affected at water stress levels higher than those responsible for stomatal closure. In their experiments, they found that this high stress levels correspond to relative water contents of less than 50% probably corresponding to water potentials below - 25 bars (Slatyer, R.O., 1969).

The relationship between photorespiration or dark respiration and water stress is not clear, partly due to the difficulties in studying these two processes. There is evidence, however, indicating that dark respiration is relatively unaffected by water stress until moderate water stress occurs (Greenway, H. and Hiller, R.G., 1967).

Iljin, W.S. (1957) found that water stress enhanced conversion of starch into sucrose. There are also reports of reduced polysaccharide levels not being accompanied by an increase in sucrose content (Woodhams, D.H., and Kozlowski, T.T., 1954).

This water stress may inhibit plant growth through its influence on a variety of physiological processes that go on within the plant. Although some of these processes within the plant have not been specifically investigated in relation to water stress, it is surmised that on the analogy of the plants that have been investigated, they hold true of the tea plant also.

BIOCLIMATIC STUDIES IN EAST AFRICA

The available literature on studies of crop-weather relations in East Africa indicate that most of the studies have been broad in scope, and were designed to provide the information necessary for zoning or classifying the East African landmass into various landuse categories, rather than to explain specific levels of crop yield. Examples include the work of Sansom,H.W. (1955) who attempted an agroclimatological classification of East Africa based on Thornwaite's, C.W. (1948) empirical formulae. Sansom's results, however, are of limited value due to the inadequacy of the formulae in estimating evaporative demand in areas with a high humidity content (Hanna,L.W. 1971).

Dagg,M. (1965) combined Penman's (Penman, H.L. 1948) and Thornwaite's (Thornwaite, C.W. 1948) approach in an attempt to zone the Rangelands of Kenya on the basis of their moisture deficits. Although Dagg's contribution is an improvement over Sansom's work, such general classifications are less useful than crop water use studies in attempting to explain yield.

Whyte, R.O. (1966) attempted to divide East Africa into zones of humidity gradients. Arid and semi-arid zones were delimited on the basis of the probability of receiving a certain critical rainfall amount. Such studies are useful on exploratory or preliminary basis; however, probability statements cannot tell us whether the rainfall will exceed the critical value in any particular year. Also that since every crop has its own particular water requirements, both in terms of amount and distribution, the significance of critical rainfall amounts is limited without reference to other important elements of the water balance such as evaporation or runoff.

Pratt, D.J. Greenway, P.J. and Gwynne, M.D. (1966) have classified East Africa into six main eco-climatic zones on the basis of edaphic characteristics, land potential plant indicators and climatic parameters. Like other landuse classifications their study did not deal with the climatic requirements of any specific crop.

Annual rainfall and its reliability can be used to indicate broad patterns, but it is now generally recognized that it is the distribution of rainfall throughout the year and not its amount alone that is relevant for agriculture (Kenworthy, J.M. 1964; Hanna, L.W. 1975).

Obasi, G.O.P. and Kiangi, P.M.R. 1975 used Thornwaite's (Thornwaite, C.W. 1948) water budget method and Woodhead's (Woodhead, T. 1968) and Brown et al (Brown, L.H. and Cocheme, J. 1973) data but in effect substituting Penman potential evapotranspiration expression (Penman, H.L. 1956b) to that of Thornwaite's own for computing the water balance in Kenya. In their paper, they used an expression in which plant water use was equated to 76% of open water evaporation. This water use index is, however, too general to apply to any specific crop since the relationship expressed by the ratio of potential evapotranspiration to open water evaporation depends on such factors as aerodynamic roughness of the crop, the amount of ground cover achieved and the phenological stage of growth.

The broad range of variables that affect the metabolic activities of plants makes it difficult to isolate and quantify the actual influence of any single climatic parameter upon plant growth. For example, Evans (Evans, L.T.

1963 p. 437) pointed out that plants may react to more environmental variables than have yet been delineated. Hanna, L.W. (1969) noted that there is no way of knowing if climatic effects are direct, indirect or delayed.

It is apparent therefore that studies of plant-water relations must be carried out against the background of those phenological aspects known to govern the crops response to water. In this way, confidence can be attached to relationships obtained.

The use of a few gross measures of the climatic environment may not provide significant correlations. This problem was expressed by Chang Jen-Hu (1965) when he pointed out that "the customary procedure of correlating yield to temperature and rainfall is so crude that it contributes little in actual operation and long-range planning". Chang Jen-Hu (1965) suggested that it is only the application of the water balance model and other sophisticated concepts that can permit the effect of climate on yield to be expressed in exact quantitative terms. It can be further argued that since the exchange of energy between the plant and its soil -

atmospheric environment is facilitated by the linkage provided by soil water and solar energy, it is possible to formulate a single climatic index incorporating water and solar energy transfer to explain yield. This appears to be the most fruitful approach at present for dealing with the problem of the climatic effect on crop yields.

CLIMATIC EFFECTS ON TEA IN EASTERN AFRICA AND ELSEWHERE

Previous climatic studies on tea in Uganda (Hanna, L.W. 1969), Mufindi in Tanzania (Carr, M.K.V. 1969) and Malawi (Forcham, R. 1970) confirm that the availability of soil moisture supply is the most important climatic factor governing the overall crop distribution in these countries. According to Dutta, S.K. and Sharma, M.A. (1967), cool seasons of high altitudes are periods of very slow growth but similar low temperatures do not inhibit tea growth in high altitude equatorial regions though Carr, M.K.V. (1970) found at Mufindi, Tanzania that cool season yields are lower and related to soil temperature. Hanna, L.W. (1971) reported that solar energy and supply of nutrients may set the upper limit of production whenever soil water is not limiting. Eden, T. (1958) found that high maximum temperatures in excess of 29.5°C damaged tea. Hadfield, W. (1968) also reported that excessive leaf temperatures limited productivity in north-east India. Carr, M.K.V. (1970) and Hanna, L.W. (1971) demonstrated that while growth should increase with high radiation, high potential evapotranspiration rates can cause partial midday stomatal closure even with ample water supply.

The effects of solar radiation and temperature cannot be easily separated from the associated factors of humidity and water supply. Hanna, L.W. (1971) for example found that in Kampala area, high solar radiation is partly coincident with the wet seasons, when tea yields are also high. Dry seasons are, however, characterised by depressed yields. According to Pierre, H.C. et al (1965) the decrease in soil moisture owing to lack of sufficient rainfall will affect growth rates. In Malawi, the heaviest pluck is about three weeks after the arrival of the rains (Tea Research Foundation of Central Africa, 1962/1963) though these high levels are not maintained and tea bushes have been observed to go dormant after a few weeks irrespective of the persistence of adequate moisture Carr, M.K.V. (1970 p. 290). Hanna's (Hanna, L.W. 1969) investigations in Uganda indicate that the exceptional rate of growth triggered by wet conditions after a dry period are characteristic of the yield curve in all estates in Uganda. Willatt's (Willatt, S.T. 1969, 1970 and 1971) work in Malawi showed that consumptive use of water by mature tea remains constant ($E_T = 0.85E_o$)

until a soil moisture deficit of 200-250mm was reached, that is, when 40% of the total available moisture in the rooting zone was used. He further reported that the level of water extraction from different depths was a variable in any growth season; 90% of the moisture used from profiles at yield capacity came from the top 1.2m. Willatt also found that inspite of the effect of other environmental factors on tea yield in the hot dry season, the low yields in the months of September, October and November had significant correlation with soil moisture deficits at the beginning of those months.

According to Carr, M.K.V. (1971), Eden, T. (1965), Hasan, K.A. et al (1965) and Harler, C.R. (1966), the minimum annual rainfall necessary for the successful cultivation of tea is of the order of 1150-1400 mm. Eden, T. (op.cit) pointed out that monthly rainfall of less than 50mm persisting for several months will affect crop production severely. Such threshold rainfall values are, however, meaningless without a statement of distribution of rainfall particularly in relation to the evaporative demand of the air.

In Ceylon, Portsmouth, G.B. (1957) found that among the various climatic parameters studied in relation to clonal tea plants of one variety, rainfall recorded one, two and three months prior to plucking gave a strong positive correlation with yield, the highest correlations being obtained for rainfall 2¼ months before plucking. However, the variations in yield appeared to be caused by changes in leaf size and shoot length, rather than the number of shoots. Except during drought, the numbers of flush shoots harvested were independent of climatic conditions.

Laycock, D.H. (1958) failed to obtain any significant correlations between annual or monthly rainfall and annual yield in Malawi. However, on dividing the year into three distinct periods, Laycock was able to fit a highly significant multiple regression on rainfall of the form:

$$Y = 0.0909B + 0.0472K - 0.0600L + 1.7923$$

where Y = the yield of made tea in 100kg/ha

B = the early rains (November -December)

K = the main rains (January-May)

L = the period when the soil profile was drying (June-October)

Early rain was found to increase yields more significantly than the main rains. Dry season rain had a depressive effect on yield. Laycock considered that both the early and main rains extended the growing season, but the dry season rain was inadequate to maintain the growth which it may have stimulated.

Hasan, K.A. et al (1965) obtained a significant positive correlation between rainfall, mean temperature and yields in Pakistan; however, a negative correlation was obtained with mean range of temperature. Analysing yield data from six estates they found the following multiple regression equation:

$$Y = -3.6746 + 0.301\ Rf + 0.0591T - 0.0049Rt$$

where

Y = Estimated yield

Rf = Inches of rainfall in previous two months

T = Mean temperature (^{o}C) for previous month

Rt = Mean range of temperature(^{o}C) for previous month

They observed that mean monthly temperatures less than 18°C and greater than 30°C were unfavourable for tea in Pakistan. A difference in the range of temperature exceeding 11°C was unfavourable unless the monthly mean was favourable.

Against the background of the present literature review, it is obvious that although a number of studies have been carried out in Eastern Africa, no comprehensive work exists on the clomatic effect on tea production in Kenya. Hanna's classical (Hanna, L.W. 1971) work on climate - tea yield interactions was conducted in Uganda whereas Etherington's (Etherington, D.M. 1973) works on tea in Kenya was an econometric investigation into smallholder tea production. The need to bridge the apparent gap justified the present study which attempted to quantify the impact of climate on tea production in Kenya.

CHAPTER 3

OBJECTIVES AND METHODOLOGY

As indicated briefly in Chapter 1 (p 4), there is a definite need for a quantitative assessment of the effect of climate on tea production in Kenya. This need is urgent since no comprehensive work on the climatic effects of a major commercial crop in the country as tea production is available in Kenya.

As discussed in chapter two, the application of the water balance model and its simplicity and ease of transferability can permit the effect of climate on yield to be evaluated in exact quantitative terms. It was also argued that since the exchange of energy between the plant and its soil - atmospheric environment is facilitated by the linkage provided by soil water and solar energy through plant related processes such as evapotranspiration, it is possible to formulate precise tea plant - climatic indexes to explain yield. This appears to be the most fruitful approach at present for dealing with the problem of climatic effects on crop production.

In the light of the above discussion and that in the previous chapters, the objectives of this study are:

1. To evaluate quantitatively the effects of climate upon tea yields in a representative tea growing area in Kenya (see map 1) with particular reference to evaporation, solar radiation, evapotranspiration and soil moisture supply.

2. To establish the relationship between solar radiation, soil moisture supply and the tea-yield distribution curve for Kericho.

In attempting to study the impact of weather upon tea productivity, it is necessary to recognize the influence of non-weather variables upon tea growth, development or yield. These factors would include the genetic potential or tea variety, agrotechnological practices in tea-husbandry namely; tea plucking pattern, pruning cycles, soil fertilization, pest and weed control.

Since the estate practice of tea production under commercial companies is characterised by high quality tea husbandry leading to consistency in fertilizer application, control of weeds, pruning, plucking and labour input, it was considered that yield data from Brooke Bond Liebig estates in Kericho would be reasonably free of variations caused by changes in agrotechnical practices. A preliminary investigation of the estate records in relation to fertilizer application, weed control, pruning and plucking rounds revealed a consistency in tea husbandry that justified the hypothesis that the effect of agrotechnical variables upon tea growth was sufficiently constant.

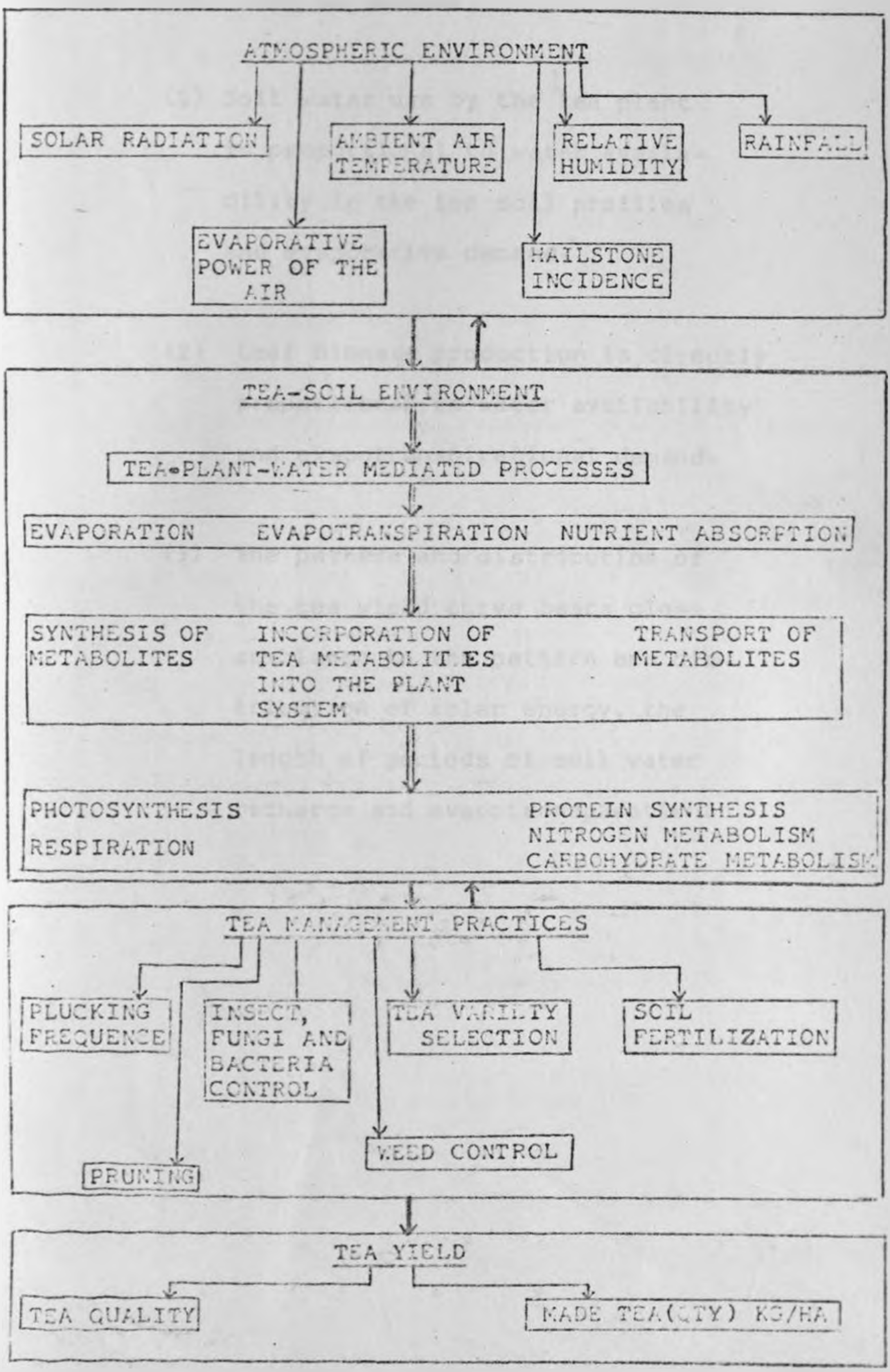
In addition to non-weather variables mentioned above, there is sufficient indication from literature (Hanna, L.W. 1971; Carr, M.K.V. 1971; Fordham, R. 1970) to suggest that the age of the tea bush has an important bearing on its physiological capability and dry matter formation. It is for instance pointed out that the response of tea plant to its environmental conditions declines gradually as senescence is approached. In this respect, the effect of age must be considered together with the extraneous variables in the tea-climate response function.

In order to understand the tea plant and its interactions with the climatic environment, the following model (Fig. 3.1) is suggested.

The model shows how quantity and quality of plant growth is controlled by hereditary and soil-water environmental factors operating through the internal processes and conditions of the plant.

In view of the known facts regarding the significance of the eco-climatic effects of tea upon the tea yield distribution curve and the physiological basis of the role of soil water and plant water on total plant growth and development, the following

FIG. 3.1 SUGGESTED SIMPLIFIED TEA PRODUCTION - ENVIRONMENTAL RESPONSE MODEL



hypotheses will be tested:

(1) Soil water use by the tea plant is proportional to water availability in the top soil profiles and evaporative demand.

(2) Leaf biomass production is directly proportional to water availability and evapotranspirational demand.

(3) The pattern and distribution of the tea yield curve bears close semblance to the pattern and distribution of solar energy, the length of periods of soil water recharge and evapotranspiration.

It was noted in the earlier chapters that the transfer of energy and water through the soil-plant-atmosphere continuum provides an important survival link between the plant and its physical environment (Brown, R.W. 1977). Climatic analysis revealed marked variations in the solar energy and soil moisture distribution curves for Kericho. The extent and manner in which these variations related to the tea yield distribution curve were studied by simple correlation analysis using simple correlation coefficients and simple regression analysis (Snedecor, G.W. and Cochran, W.G., 1967)

Denoting tea yields by Y and climatic parameter(s) by X, the correlation coefficient r between X and Y is defined as:

$$r_{xy} = \frac{\overline{xy}}{SxSy} \quad \text{----------(1)}$$

where $\overline{xy}$ is the mean product of corresponding X and Y deviations; also called the covariance of, or between X and Y

SX is the standard deviation of X

Sy is the standard deviation of Y

The relationship between soil moisture supply (expressed in the form of water balance indices) and the tea yield distribution curve was examined variously by means of simple regression analysis. Hanna, L.W. (1971) suggested that the tea yield - soil moisture responce curve could be divided into three parts on the basis of known facts regarding general plant's responses to differential levels of soil water availability. These compartments of the soil moisture response curve are:

(i) Relief of soil water stress
(ii) Periods of field capacity
(iii) Periods of increasing soil water stress

On the basis of the compartments of the soil moisture response curve, four regression models to evaluate the relationships between tea yields and water balance indices were formulated as follows:

(i) Relief of soil water stress (Days ($P>E_T$)

Denoting Days ($P>E_T$) by X_o and letting Y = kg/ha of made tea, the regression equation describing the relationship between tea yields and the duration within a month that the top soil profiles are being filled will be of the form

$$\hat{Y} = a_o + b_o X_o \quad \text{------------} \quad (2)$$

where P = precipitation

E_T = evapotranspiration

$\hat{Y}$ = estimated yield (kg/ha) made tea

a_o = regression constant

X_o = Days ($P>E_T$)

b_o = regression coefficient

(ii) Periods of field capacity (Days AW = 140mm)

Denoting Days (AW= 140mm) by X_1 and letting Y = kg/ha of made tea.

The regression equation describing the relationship between tea yields and duration of unlimited supply of water will be of the form:

$$\hat{Y} = a_1 + b_1 X_1 \quad \text{----------} \quad (3)$$

where $\hat{Y}$ = estimated yield (kg/ha made tea)

a_1 = regression constant

b_1 = regression coefficient

X_1 = Days AW = 140 mm

(iii) Periods of increasing soil water stress (Days ($P > E_T < 15$)

The regression equation describing the relationship between tea yields and duration of soil water stress will be of the form:

$$\hat{Y} = a_2 + b_2 X_2 \quad \text{-----------} \quad (4)$$

where $\hat{Y}$ = estimated yield (kg/ha made tea)

a_2 = regression constant

b_2 = regression coefficient

X_2 = Day ($P > E_T < 15$

iv. Relief of soil water stress and field capacity conditions in the top 80 cm of soil surface

I_o = Days (AW = 140mm) + Days ($P > E_T$)

The relationship between the tea yield distribution curve and combined effect of field capacity conditions and duration of soil moisture recharge will be assessed by the regression equation of the form:

$$\hat{Y} = a_3 + b_3 X_3 \quad \ldots \quad \ldots \quad (5)$$

where $\hat{Y}$ = estimated yield (kg/ha made tea)

a_3 = regression constant

b_3 = regression coefficient

X_3 = I_o = Days (AW = 140mm) + Days ($P > E_T$)

AW = available water

Agroclimatological Model:

Equation (5) was considered as an important model describing the joint effects of unlimited water availability (field capacity conditions) and duration of soil moisture recharge. It was hypothesized that constant unlimited supply of soil moisture to the surface layers where the tea-plant's root distribution density is highest considered together with duration of moisture recharge should explain most of the variability in the tea yield distribution curve. According to Robinson, J.B.D. and Gacoka, P (1962) and Wilson, K.C., (1969), it is in the surface layers where most of the tea nutrients are concentrated. Because nutrient availability would also depend on the correct balance between various soil mineral elements in the soil and on the rate of water use by the plant, there is reason to believe that any variations in moisture use from these surface layers will have important implications upon tea growth and subsequent yields.

All the analysis done on the data as described in this chapter was possible by means of the computer facilities at the Institute of Computer Science, University of Nairobi. The computation of the correlation coefficients and regressions discussed was done by resorting to the XDS 3 program in the I.C.S. library.

Assumptions and Limitations in Linear Regression and Correlation Analysis

It should be emphasized that regression models are adaptible to use both for predictive and explanation purposes. In prediction exercises, the main objective is to derive an estimating equation in which the amount of variation in the dependent variable accounted for by the independent variables is maximised. This is often accomplished at the expense of relatively insignificant regression coefficients. Hauser, 1972 has pointed out that "explanatory" equations typically give low R^2 values. Others argue that one can predict without necessarily explaining; intercorrelation amongst the independent variables may be ignored (Hanushek, 1977).

If the intention to use a regression model is to explain the amount of variation in the dependent variable accounted for by the independent variables then the emphasis must be on individual regression coefficients and on establishing significant relationships. Here then the objective is to maximise R^2 subject to significant β'S. This objective may be realised by a stepwise procedure in which the important independent variables (that is those showing strong relationships with the dependent variable) are selected on the basis of their partial correlations or t-tests. This procedure, sometimes called stepwise regression by forward selection (occasionally backward elimination), poses a number of interrelated difficulties. First, forward and backward selection procedures often give different answers, and neither may be the optimum (see for example Garside, 1965). Second, results depend on the order in which variables are introduced into the regression set, since once included, variables are dropped from the set only if their partial correlations fall below a given significance level (Hauser 1972).

It may be argued that a strict consideration of significance levels in a stepwise regression procedure which is at best regarded as explanatory is of little relevance, since the objective of such a procedure is to identify the most important variables in a regression set. Hauser, 1972 has warned that rigorous concern with Type 1 errors (incorrectly rejecting the null hypothesis) and high significance levels is out of place in exploratory studies since the chance is increased of rejecting as insignificant differences which actually do exist (see also Gould, 1970 P.445). It is suggested that in data search procedures, relatively low significant levels, say 0.01 to 0.30, which will tend to minimise Type

II errors, should be used (Hauser, 1972).

Since the main objective in the present study is to evaluate the significance of soil moisture indices upon tea productivity, it appears justified to use stepwise regression as an explanatory technique in this respect. Thus on the assumption that the independent variables entering the regression set at significance levels between 0.01 and 0.15 are reasonably significant, it is possible to obtain regression coefficients accounting for significant differences in tea productivity.

CHAPTER 4

DATA REQUIREMENTS OF THE INVESTIGATION

The present study was conducted on three tea estates namely KIMUGU, CHEBOSWA and CHEYMEN all under the management of Brooke Bond Liebig Company (B.B.L.C). These estates are in the neighbourhood of Kericho town (map 1), Rift Valley Province of Kenya and close to the Tea Research Institute of East Africa (T.R.I.E.A.). T.R.I.E.A. is located at latitude 0° 22's and longitude 35° 21'E and at an altitude of 2178m above sea level.

In order to investigate the impact of weather upon tea productivity, it was necessary to minimise the effect of non-weather variables upon tea growth. These extraneous variables were identified as follows:

(a) plucking rounds
(b) pruning cycles
(c) herbicides and fertilizers
(d) soil fertility

Since the estate practice of tea production under commercial companies is characterised by high quality tea husbandry leading to consistency in fertilizer application, control of weeds, pruning, plucking and labour input, it was felt that yield data from Brooke Bond Liebig estates in Kericho would be reasonably free of variations caused by changes in agrotechnical practices. A preliminary investigation of the estate records in relation to fertilizer application, weed control, pruning and plucking rounds revealed a consistency in tea husbandry that justified the hypothesis that the effect of extraneous variables upon tea growth was sufficiently constant.

In addition to the extraneous variables mentioned above, it is also necessary to select data from fields located near to the climate station. Hopefully, fields which are near together will also have similar characteristics with respect to antecedent soil fertility and microclimatic variability.

There is sufficient indication from literature (see for example Hanna,L.W., 1969; Carr, M.K.V. 1971, and Fordham, R. 1970) to suggest that the age of the tea bush has an important bearing on its physiological capability and dry matter formation. It is for instance pointed out that the response of the tea plant to its environmental conditions declines gradually as senescence is approached. In this respect the effect of age must be considered together with the extraneous variables in the tea-soil moisture response function.

ESTATE YIELD DATA

DATA SPECIFICATIONS

In a bid to obtain realistic relationships between climatic parameters and tea growth attributes, the effect of non-weather variables had to be minimised as much as possible. Tea yield was defined as that quantity of the dry matter constituting the harvestable portion of the vegetative part of mature tea expressed in kg/ha of processed tea. To minimise the effect of the extraneous variables on the tea yield function, a sampling design taking into account the role of both the agrotechnical tea practices and physiological aspects was formulated. The agrotechnical tea practices and physiological aspects considered in the selection of estates for tea yield data included:

(i) Age of the tea bush
(ii) plucking rounds
(iii) pruning cycles
(iv) soil fertility
(v) Herbicides and fertilizers

AGE OF THE TEA BUSH

Brooke Bond Liebig Company (BBLC) manages a number of productive tea estates containing tea bushes of varying ages and under different plucking and pruning stages. It was therefore not a difficult matter to select from this spectrum of estates any required number of fields that would provide yield data reasonably free from the effect of non-climatic influences, such as age of the tea bush. According to Hanna, L.W. (1971), "the age of the plant has an important effect on yields as it affects efficiency in the uptake of nutrients". Hanna, L.W. (1971) observed that tea at Kitoma, Uganda, which was 3-4 years old showed greater sensitivity to climatic variations than the more mature tea at Kiko. Rapid tea responses to climatic changes appeared to show clearly during the first eight years from planting with the response stablizing at an age of 15 years. Thereafter, tea yields were observed to be independent of maturity.

The estates selected for tea yield data contain tea plants varying in age between 20 and 50 years. Hopefully, because this is mature tea, bush size, root development and the efficiency of nutrient uptake can be expected to have varied little over the period of analysis.

The names of the estates and the ages of fields that provided the data are shown below.

TABLE 4.1

ESTATE	FIELD NUMBER	DATE PLANTED
CHEYMEN	23	1928
	24	1957
KIMUGU	12	1931
	13	1956
CHEBOSWA	10	1930
	14	1957

Source: Brooke Bond Liebig Tech. Dept.

PLUCKING ROUNDS

Commercial tea under BBLC is plucked at intervals of 10-14 days, thus giving 2-3 plucking rounds in a month. Fields that have been previously pruned and still recovering from the residual effects of pruning may not be ready for plucking after 10 days. Such fields were not considered for yield data.

PRUNING CYCLES

Mature tea is pruned after it has been in production for 4 years. After that it requires about six months during which the crop recovers from pruning effects, before it comes into full production again. Evidence shows that during the recovery period, the tea bush is less sensitive to climatic changes (Hanna, L.W. 1971). The shoots may be dormant for sometime in unfavourable weather, however, production may be induced if few shoots are plucked. Eden, T. (1976) has suggested that the number of dormant buds increases with time after pruning. Other evidence suggests that the dormant state is the natural response to adverse conditions.

Thus dormant or tea recovering from pruning effects may exhibit yield data variations that are independent of climatic influences. In order to minimise the effects of such non-climatic factors, yield must be carefully adjusted. In the present study, care was taken to minimise this effect by taking data from fields that had fully recovered from pruning (at least six months after pruning).

SOIL FERTILITY. FERTILIZERS AND HERBICIDES

The work done on soils by the Tea Research Institute of East Africa (T.R.I.E.A.) at Kericho in collaboration with the Brooke Bond Liebig Company Technical Department and my own field inquiries indicates that the soils in the Kericho tea areas derive from a phonolitic lava material consisting of 65% orthoclase, 25% nepheline, 5% biotite and 5% hornblende.

The phonolitic lava soil derivatives are fairly deep soils. The top soil profiles consist of black moist clay loam. The deeper profiles are characterised by blocky subangular fragments with occasional charcoal fragments (see Table 4.2). It is apparent from Table 4.2 that the percentage size distribution of clay particles (<2mm) increase with depth. This characteristic has an important bearing upon the availability of water to the tea plant. This is because increase in the proportion of clay particles (< 2mm) with depth means that the porosity of the soil at deeper layers also increases appreciably.

TABLE 4.2

Source: Njihia, C.M. (1969) and Mohiddin, S. (1969)

SOIL DATA FOR KERICHO TEA RESEARCH INSTITUTE OF EAST AFRICA (T.R.I.E.A)

DEPTH IN CM	HORIZON	WEIGHT %>2mm	PARTICLE SIZE DISTRIBUTION (mμ) WEIGHT %							
			SAND			SILT				CLAY
			2000-1000	1000-500	500-250	250-100	100-50	50-20	20-2	<2mm
0-8	H11			2			20		39	39
8-26	H12			2			6		38	53
26-41	B21			1			5		30	64
41-69	B22			1			9		21	69
69-93	B23			1			6		18	75
93+	B3			1			7		12	80

During wet periods, therefore, such soils will tend to be waterlogged and poorly aerated. This may in turn affect tea growth. Also the problem of flocculation in such soils tends to interfere with the process of natural humus formation promoted by aerobic soil micro-organisms. Impeded drainage during wet periods may mean that the availability of tea nutrients is limited. Indeed, records on nutrient availability status of soils in Kericho (see Table 4.3) tend to suggest that the amount of exchangeable bases (calcium, magnesium, potassium and sodium) is low. Most of the cations can only be fairly readily exchanged in the top profile (0-8 cm) where the percentage base saturation is high (71%). The level of soil nitrogen is apparently high. The soil reaction fluctuates from strongly to very strongly acid conditions. These conditions tend to suggest that aluminium, manganese or iron should not be supplied in any appreciable quantities otherwise the high solubility of these elements under acid conditions may be toxic to the tea plant.

Soil fertility levels are monitored regularly (by the Brooke Bond Liebig Technical Department) by using soil pH as an indicator

TABLE 4.3

CATION EXCHANGE CAPACITY, PERCENTAGE BASE SATURATION AND PH FOR A TYPICAL CLAY LOAM IN KERICHO

DEPTH IN CM	HORIZON	PH	C %	N	C/N	EXCHANGEABLE CATIONS m Eq/100mg SOIL (Millequivalent/100mg soil)						BASE SATURATION %	ORGANIC MATTER
						Ca^{2+}	Mg^{2+}	K+	Na+	Sum	CEC		
0-8	H11	5.4	13.1	0.9	15	19.8	6.2	0.6	0.2	27.0	38.0	71	22.6
8-26	H12	4.5	4.3			2.5	4.9	0.2	0.1	7.8	22.4	34	7.4
26-41	B21	4.1	3.4			0.4	0.7	0.1	0.1	1.4	19.2	7.0	5.9
41-69	B22	4.1	2.5			0.4	0.7	0.2	TR.	1.5	15.8	8.0	4.2
69-93	B23	4.3	1.1			0.2	0.7	0.1	TR.	1.1	16.0	6.0	1.8
93+	B3	4.4	0.5			0.4	0.9	0.2	0.1	1.7	16.0	10.0	0.8

Source: Njihia, C.M. (1969) and Mohiddin, S. (1969).

of the availability of essential tea elements (NPK, calcium, manganese, zinc and sulphur).

The Brooke Bond Liebig fertilizer application records (for the period 1972-1978 for the fields in the present study) show that the level of NPK application in the form of artificial fertilizers has remained at the ratio of 20:10:10. The dose applied has, however, varied with respect to the specific requirements of each field. The application of zinc oxide either as a powder or spray has been adopted as a means of regulating the acidity of the tea soils and as a source of zinc. Because of insufficient input of sulphur from rain, sulphur is commonly applied as sulphate of ammonia.

In mature tea, weeds such as couch grass and other creeping grasses are variously controlled by derivatives of three basic herbicides:

(i) 2 - chloro, 4,6 bis (ethylamino-s-triazine)
(ii) 2,2, dichloroproprionic acid
(iii) bipyridilium compounds

exemplified in corresponding order by brand-name herbicides SIMAZINE, DALAPON and GAMAXONE.

Thus, there is little doubt that the high standards of tea husbandry maintained throughout the estates (with respect to weed control and control of soil fertility) reduce the number of non-weather variables influencing tea yields in these estates.

SOURCE OF DATA: FORM AND RELIABILITY; YIELD DATA

Although there are 2-3 plucking rounds in a month, the weight of green leaf is not recorded per plucking round. Instead, the tea obtained from the fields is recorded on a monthly basis and is expressed as the amount of processed tea per hectare. The availability of tea yield data within the time frame of a month presents a handicap in the sense that climatic tea yield interactions cannot be examined at a level shorter than a month.

Tea yield records commence with the last completed pruning cycle and apply to those fields which are deemed to be mature.

Careful examination of pruning to pruning monthly tea yield data revealed that tea obtained from pruned fields after six months was reasonably free from effects of pruning. A period of six months recovery was therefore considered adequate for pruned tea estates under study. Hanna, L.W. (1971) also confirmed in Uganda that tea was free from effects of pruning after six months. Monthly tea yields extracted from the estate yield records for each of the six fields 23,12,24, 13,10 and 14 was added for every month and divided by six (6) to obtain a representative monthly value for the three estates, for the period running from 1972-1978. Where a field was recovering from pruning, that month was ignored altogether.

CLIMATIC DATA

The basic climatological data required for the present study was extracted from the T.R.I.E.A. station records in Kericho. T.R.I.E.A. operates a fully instrumented agroclimatological station situated within the institute grounds. Data was extracted on the following parameters for the period running from 1971-1978:

(i) Daily rainfall (mm)
(ii) Daily potential evaporation (class A Evaporation Pan) (mm)
(iii) Daily mean air temperature (°C)
(iv) Daily mean dry bulb temperature (°C)
(v) Daily mean dew point temperature (°C)
(vi) Daily duration of sunshine (hours)
(vii) Daily mean run of wind (miles/day)
(viii) Daily magnitudes of solar radiation ($cal/cm^2/day$)

In instances where radiation measurements as measured by Gunn-Bellani distillometers were unavailable, these were estimated using regression equations available in the station. These were of the form:

$$^{Q}/_{QA} = K + b\ ^{n}/_{N} \qquad \text{.............. (6)}$$

where Q = daily total solar radiation received on a horizontal surface at or near the ground.

QA = the radiation received on a horizontal surface at the upper limit of the atmosphere (see

McCulloch, J.S.G. 1965 for calculation)

$^n/N$ = ratio of hours of bright sunshine to the maximum possible sunshine hours

For Kericho, N = 12.1 hours

K = constant = 50.0

b = regression slope (regression coefficient) = 26.4

According to Brown, R.W. (1977), "one of the most important and complex environmental factors limiting plant growth is the relationship of both soil water availability and atmospheric evaporative demand to the water status of the plant". Thus by formulating an agroclimatological index that has a bearing on plant growth, a rational possibility exists for evaluating the impact of climate upon tea growth.

SOIL WATER BALANCE MODEL

In the context of available climatological data, the water balance approach was adopted as a basis for assessing the impact of climate upon the tea yield response function. The soil water balance model adopted in the present study has three main components. These are: precipitation, available water and water output. These parameters may be expressed algebraically thus:

$$P + WA = WO \quad \ldots\ldots\ldots\ldots \quad (7)$$

where P = Precipitation

WA = Available water

WO = Water output

Because evapotranspiration constitutes the major source of water loss from plants, water output in this study was equated to evapotranspiration.

The water balance model incorporating all the parameters influencing crop growth can be expressed as:

$$P = E_T + DS + 0 \quad \ldots\ldots\ldots\ldots \quad (8)$$

where P = Precipitation

E_T = potential evapotranspiration

DS = infiltration or soil storage change

0 = runoff and deep percolation

In order to appreciate the interrelationship between the parameters of the water balance model, it is necessary to look at each parameter in detail.

PRECIPITATION

The intensity of rainfall influences infiltration rates, subsequently determining the water stored in the soil. A study of the incidence of rain days and daily amounts is therefore necessary in determing a time interval to be adopted in a soil moisture balance. We must emphasize that such a time interval may not only have a meteorological significance, it must also have a physiological bearing on plant growth. As shown below, the use of monthly rainfall values introduces serious errors and can give an overestimate of soil moisture under conditions of high rainfall intensities.

The temporal and spatial variation of rainfall is also important in studies attempting to formulate realistic agroclimatological indices. For example, a few days of rainfall can raise soil moisture to field capacity within the root range with excess water draining as runoff. On the other hand, rainfall concentrated at the beginning of a month provides more favourable conditions during that month than rainfall coming at the end of a dry month, which apart from the days of precipitation contributes to soil moisture in the following month (Hanna, L.W. 1969). It is therefore apparent that by reducing the time interval on which soil moisture balances may be calculated, accumulated errors can be appreciably minimised. It is against this background that the soil moisture balance for tea used in this study is worked out both on the daily and ten-day basis.

Such short periods have also some physiological significance in tea productivity. For example, diurnal soil moisture deficits have significant influences upon the physiological processes of growth discussed in chapter two. There is reason, therefore, to expect that soil moisture stress at the daily level may have an important bearing on final tea yields.

POTENTIAL EVAPORATION (Eo)

Evaporation either from a plant surface (transpiration) or soil surface is a diffusive process which is partly molecular and partly turbulent. Analogous to molecular and other well known transfer mechanisms, the basic equation of vertical flux of water vapour, E, (Rijtema, P.E. 1968) can be written as:

$$E = -\rho KV \frac{dq}{dz}$$

where ρ = air density in gcm^{-3}

q = specific humidity in grammes of water vapour per gram of moist air

KV = eddy transfer factor of water vapour

Z = height

It is evident from the above equation of vertical flux of water that upward transport depends upon the vertical gradients of vapour pressure and the rate of mixing. The rate of mixing is a function of air turbulence also influenced by the aerodynamic roughness of a crop. Although evaporation and transpiration from a soil/crop surface are essentially governed by similar physical principles (both processes being characterised by molecular and turbulent properties) the process of evaporation is not subject to diffusive resistances brought about by internal geometry, size and shape of stomata and cuticular apertures. The transpiration rate of actively photosynthesizing plants is determined by the available energy. Progressive development of soil water tensions often leads to closure of stomata and hence a reduction of transpiration. Because of the higher albedo of the vegetation, the closure of stomata at night, and the diffusion impendance of the stomata, potential evapotranspiration of a short crop is less than open water evaporation. On the basis of turbulent theory, Neumann, J.R. (1953) has argued that evapotranspiration (E_T) of a short crop is approximately 75% of the open water evaporation.

Inspite of the significance of daily water balances, certain data derivation problems have sometimes caused deviation from strict adherence to the approach. This has been the case where evaporation data as measured by class A evaporimeters was not available. In such instances, calculation of potential evaporation for periods longer or equal to ten days has followed the approach devised by Penman, H.L. (1948).

The reliability of the Penman formulae for estimating Eo for periods greater than one week has been sufficiently substantiated by catchment research in East Africa (see for example Wang'ati F.J. and Blackie, J.R. (1971) and Dagg, M. (1968a)).

According to Dagg,M. (1968a), evaporation values (as obtained from class A evaporimeters) in Kericho are reasonably accurate for application in crop water use studies apart from small underestimations or overestimations (during certain periods of the year) arising from turbulence caused by the rim of the pan. Other factors affecting the reliability of the pan data include effects of rainfall splashes, interference by animals and birds, pan size, exposure, colour and shape of pan.

The mathematical expression of Penman's H.L. (1948) formulae used in the computation of ten-day and monthly Eo values, as modified by McCulloch, J.S.G. (1965) (to allow for altitudinal effects) for use in East Africa is of the form:

$$
\begin{aligned}
Eo = {} & \frac{\Delta}{\Delta + \varphi} \left\{ Ra(1-r)\ (0.29 \cos\theta + 0.52\, {}^{n}/N) \right\} \\
- {} & \frac{\Delta}{\Delta + \varphi} \left\{ \sigma Ta^{4} (0.10 - 0.90\, {}^{n}/N)(0.56 - 0.08 \sqrt{ed}) \right\} \\
+ {} & \frac{\varphi}{\Delta + \varphi} \left\{ 0.26 (1 + {}^{h}/20{,}000)(1 + {}^{u}/100)(e_a - ed) \right\}
\end{aligned}
$$

where Eo = total evaporation over a given period in mm/day,

e_a and e_d = duration of vapour pressure at air temperature (mb.) and duration vapour pressure at dew point (mb.)

h = altitude in metres

Δ mb/°C is the slope of the saturation vapour pressure/temperature curve from List, R.J., 1966, Smithsonian Table 103 p. 372,

φ mb/°C = CpP/EL where Cp= specific heat of dry air at constant pressure, P= atmospheric pressure, L= latent heat of vapourization of water (585 cal/g)

Cp = 0.00042/°C (Slatyer, R.O. and McIlroy, I.C. 1961),

ϵ = ratio of density of water vapour to that of dry air at the same temperature pressure

Ra = radiation at the outer limit of the earth's atmosphere, from List, R.J 1966, Smithsonian Table 132, p. 418.

Rc = Ra $(0.29 \cos\theta + 0.52^{n}/N)$ is the Glover, J. and McCulloch, J.S.G. (1958) form of the Angstrom equation where θ is latitude. Rc = incoming radiation in cal/cm^2/day

σTa^4 = black body radiation (Tanner G.B. and Robinson, S.M. 1959), 0.26 (1+h/20,000) times saturation deficity in millibars is approximately equal to Penman's 0.35 (1.465-0.465 P/Po) times saturation deficit in mm mercury, over the range of altitude 0-3000 metres.

Ten-day and monthly mean evaporation values have been computed using McCulloch tables (McCulloch, J.S.G. 1965)

POTENTIAL EVAPOTRANSPIRATION (ET)

Evapotranspiration is the combined evaporation from all the surfaces and the transpiration of plants (Chang, J.H. 1968). Not all the water that is absorbed by root hairs is transpired from the leaves. A small amount is incorporated into the plant's protoplasmic system.

It is necessary to recognize that evapotranspiration may take place under conditions of unlimited water supply or in situations where the available water is less than the maximum possible. According to Penman,H.L. (1956b) evapotranspiration under unlimited supplies of soil water may be defined as the "amount of water transpired in unit time by a short green crop, completely shading the ground and of uniform height".

Although Penman did not specify the type of "short green crop" nor its height, the importance of horizontal homogeneity in the computation of ET using the energy balance and aerodynamic methods has nevertheless been recognized.

The aerodynamic roughness and height of a crop has an important bearing upon advection which in turn greatly influences crop water use. There is evidence that the causes of advection under the crop canopy can be quite different from those above the canopy (Kalma, J.D. 1970). For instance, wind profiles taken within extensive areas of closed canopy orchards often show a great variation in wind velocity from place to place beneath the canopy - often referred to as trunk-space phenomenon. Kalma,J.D. (1970), investigating the advection phenomenon in a mature orange tree plantation attributed the trunk-space phenomenon to horizontal advection originating within the plantation through the roadways and missing tree-gaps.

Chang,J.H. (1968) suggested that broad leaves being aerodynamically rougher than grasses, are capable of extracting more energy from the air, and hence, have higher evapotranspiration rates.

It is apparent that Penman's definition of a complete ground cover is imprecise. Ideally, a vegetation cover may be said to be completely covering the ground if it intercepts all the incident radiant energy. However, in actual fact, even a tall dense crop with a high leaf area index can only rarely absorb as much as 95% of the available radiation (Chang,J.H. 1968).

In a study of the comparison between lysimeter and catchment water balance estimates of evapotranspiration from a tea crop in Kericho, Wang'ati F.J. and Blakie, J.R. (1971) demonstrated that an average tea ground cover of 65% transpired at a rate equal to 85% of open water evaporation. This rate has been shown to be consistently constant for tea except for periods following pruning (Tea Association 1962/1963), Dagg, M. (1968), Pereira, H.C. (1962). This factor of consumptive use of tea, that is, ET/Eo = 0.85 has been used in the present study for the purpose of calculating the water balance for tea.

ACTUAL EVAPO-TRANSPIRATION (AE)

Under conditions of unrestricted water supply, the evapotranspiration rate is maintained at the potential level. In this instance, ET may be equated to AE. However, as the soil profile dries, AE will fall below ET. When this happens, the availability of water to plants will not only be determined by weather factors but also by soil factors. The concept of "soil water availability" while never clearly defined in physical terms, has for many years excited controversy. Veihmeyer, F.J. and Hendrickson,A.H. (1955) claimed that soil water is equally available throughout a definable range of soil wetness, from an upper limit (field capacity) to lower limit (the permanent wilting point). In other words, evapotranspiration continued at the potential rate between these two limits. They contended that the "equal availability of water" between field capacity and permanent wilting point is explained in terms of the extremely small amounts of energy required to extract a gram of water at the permanent wilting point and transport it to the transpiring surface.

The theory of equal availability of water has been questioned by many workers (Hillel, D, 1971, Brown L.H. 1977). There is now evidence to show that soil water is not equally available between field capacity and wilting point.

More recent work on the relationship between evapotranspiration and soil moisture tension have shown that a number of factors control soil moisture status (Chang, J.H. 1968). These factors include soil texture, moisture tension characteristics, hydraulic conductivity, rooting density and weather conditions. The most significant of these factors appears to be the weather conditions.

Denmead, O.T. and Shaw, R.H. (1962) found evidence to confirm the effect of meteorological conditions on water uptake and transpiration. They measured evapotranspiration rates of irrigated corn plants placed in containers under varying conditions of atmospheric evaporativity. When evaporative demand attained a magnitude of 3-4 mm/day, AE was observed to fall below ET at an average suction of about 2 bars. When atmospheric evaporativity increased to 6-7 mm/day, the drop of AE occurred at a soil water tension of 0.3 bar. Conversely, when evaporative demand was very low (1.4mm/day), no drop in AE was observed until average soil water suction exceeded 12 bars.

In the present investigation, the calculation of AE follows the approach devised by Thornthwaite, C.W. (1948) and as used by Hanna, L.W. (1969) in a study of tea-water relations in Uganda. According to this approach, when daily precipitation (P) is greater than daily ET, AE is regarded as being equal to ET. In instances where

$P \leq ET$, AE is calculated as the sum of rainfall and soil moisture storage change. Potential water deficit (PWD) or potential water surplus (PWS) was defined as the difference between ET and AE; it is a deficit or surplus of water according to which of these quantities is the greater.

AVAILABLE WATER CAPACITY (AWC)

As already discussed, the availability of water in the soil is dependent on both soil and plant factors. The soil properties such as capillarity, adsorptivity, osmotic potential and gravitational potential together with plant characteristics such as root distribution, in particular the depth of penetration and root density all strongly influence the availability of soil water for crop use.

Obviously, the depth of root penetration must partly determine the soil water reservoir available for plant use. The soil texture and organic matter also have considerable influence on the available water capacity (Pidgeon, J.D. 1972).

In high rainfall areas such as Kericho, where there is a fairly uniform clay loam soil (in terms of texture and structure), there is little doubt that the depth of the root zone of the tea crop is the main factor influencing the available water capacities.

Studies of the rooting behaviour of the tea crop indicate that the tea bush is capable of exploiting the maximum amount of soil water available to it (Kerfoot, O. 1962, p. 24). In Uganda, Hanna, L.W. (1969) has reported that pits excavated in plots of mature tea at Kerita showed abundant roots to depths of 2.4m. It is reckoned that in Kericho with an annual rainfall of 2100mm (spread over 240 rain days) and an annual Eo of 1660mm, the development of substantial soil moisture deficits below two metres is rare, except in extraordinarily dry years (Wang'ati, F.J. and Blackie, J.R., 1971). Dagg, M. (1970) has demonstrated with electrical resistance records that this is indeed the case.

Because of the assumed importance of soil moisture in the top soil layers, where nutrients are readily available, the effect of soil moisture fluctuations (in the top soil layers) on tea growth has to be investigated. In determining the available water capacity, the field capacity and wilting point concepts will be employed. On the basis of the soil moisture data (regarding the available water capacities for the soils in the study area) presented by Pereira H.C. et al (1962), the available soil moisture capacities corresponding to the depths 0.8m, 1.0m and 2.0m represented respectively by 140mm AW, 235mm AW and 340mmAW for BBL estates were calculated.

For each day, the soil water deficit for a soil profile was described by recognizing the highest range in which water was available. Deficits below this range were not considered. This approach although adopted to simplify the description, it would be justified by the decrease in root density with depth, decrease in soil water tensions with depth in view of the dominance of clay-loam texture at deeper soil profiles with higher AW capacities and assumed importance of water in the surface layers.

It has also been possible to check the assumption that soil moisture deficits are rare in Kericho below two metres using the available meteorological data for the period (1971-September, 1978).

ACCUMULATED SOIL WATER AND RUNOFF

Accumulated soil water and runoff components of the soil moisture model have been calculated by accumulating the changes in storage arising from the difference between P and ET upto the appropriate available water capacity. Since each soil depth will be recharged to its appropriate field capacity, the excess rainfall over ET after complete soil moisture recharge drains off as runoff or is available to recharge deeper soil horizons.

DERIVATION OF WATER BALANCE INDICES RELATED TO TEA GROWTH

Studies on the physiological basis of plant-water relations in regard to plant growth and productivity suggest that the tea yield-soil moisture response curve can be divided into three parts:

(i) Relief of soil water stress
(ii) Periods of field capacity
(iii) Periods of increasing soil water stress

Relief of soil water stress (Days $P > E_T$)

Daily soil water balances indicate the timing of relief of stress. It is evident therefore that a desirable criterion for describing the increase in soil water must incorporate a measure of the duration within a month that the top soil profiles are being filled. This can be described by the number of days that available water is present in the surface layers. The condition necessary for this to occur is that precipitation must be greater than evapotranspiration ($P>E_T$). The number of days in a month during which precipitation exceeds evapotranspiration is also a good indicator of solar energy supply. It is a good indicator because rainy days give an indication of cloud cover and therefore incident solar energy supply. The length of time during which the soil profile is filled may influence the order of soil moisture availability in subsequent months.

Periods of field capacity

So long as precipitation received exceeds the evapotranspiration demand (after relief of soil water stress) soils will be recharged to field capacity. At field capacity, water is freely available to the plant. The length of time within a month during which water is freely available to the tea plant has an important bearing upon growth and therefore productivity.

In the present investigation, the number of days in a month that water is freely available in the top 0.8m corresponding to 140mm AW will be used in testing the hypothesis that the water requirement of tea depends on soil water availability. The water requirement of the tea crop during periods of adequate water supply will be equivalent to ET and will be designated ETW. It would be expected that the rate of increase in tea yields diminishes as the period of adequate water increases as production must reach a maximum and thereafter decline.

Periods of increasing soil water stress ($P > E_T$) $<$ 15 days:

Consumptive use (ET) in the course of relief of water stress will gradually exhaust the soil water reserve if no replenishment occurs. The length of time in a month during which soil moisture is inadequate is expected to provide conditions unfavourable for active growth. Prolonged water stress would reduce total tea yields.

Summary of Data needed:

In summary, the basic climatic data required for this study includes rainfall, solar radiation, open water evaporation, air temperature, dry bulb and dew point temperature, duration of sunshine and wind run. This basic climatic data together with data on available water capacities forms the basis for the computation of a water balance model and other climatic indeces related to tea production.

The tea plant response data comprised of monthly tea yields of processed tea.

CHAPTER 5

RESULTS AND DISCUSSION

I. RELATIONSHIP BETWEEN TEA YIELDS. SOLAR RADIATION AND EVAPOTRANSPIRATION (E_T)

(i) SOLAR RADIATION AND TEA YIELDS

The results of previous climatic studies in Uganda (Hanna, L.W., 1969, 1971) and Mufindi in Tanzania (Carr, M.K.V., 1969, 1970) all agree that the direct or indirect effects of solar radiation are important in the growth of tea. High solar radiation intensities are associated with high potential evapotranspiration rates. It may be agreed therefore that while yields should increase with high radiation, high evapotranspiration rates create a condition in which the water absorbed by the roots becomes insignificant to offset the high evapotranspiration losses Denmead, O.T. and Shaw, R.H. 1962 Murtagh, G.J. 1978. If such a condition is protracted, tea growth may be retarded by critical leaf water potentials associated with the development of cell flaccidity and subsequent inhibition of photosynthesis (Boyer, J.S. 1970).

In the present analysis, an investigation of the solar radiation curve (Fig.5.1) revealed that distinct periods of high and low solar radiation values were present. It was also observed that monthly fluctuations of solar radiation were appreciable. The period October to April, 1972-1978 was characterised by relatively high solar radiation values compared to the values recorded during the period May to September, 1972-1978. Because of this apparent pattern in the solar radiation curve, an attempt was made to find out whether this pattern had any correspondence with the tea yield distribution curve. The correlation coefficients showing the relationship between tea yields and different selected solar radiation periods are shown in Table 5.1 .

In general it is clear from Table 5.1 that solar radiation has a positive effect upon tea growth. This means that the solar radiation intensities present in Kericho rarely attain saturation levels that would otherwise influence growth negatively.

Considering monthly solar radiation values and monthly tea yields over the entire period of study (1972-78), (n=79) a positive

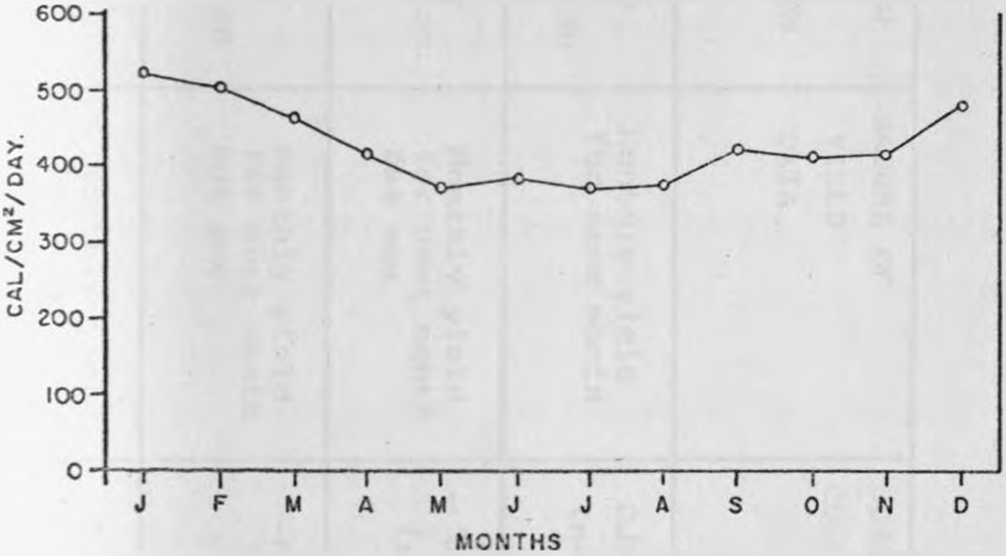


FIG. 5.1 MEAN MONTHLY SOLAR RADIATION AT KERICHO T.R.I.E.A
1972 — 1978

TABLE 5.1

Source: Author's Analysis

CORRELATION COEFFICIENTS SHOWING THE RELATIONSHIP BETWEEN TEA YIELDS AND SOLAR RADIATION

PERIOD	NATURE OF SOLAR RADIATION DATA	NATURE OF YIELD DATA	CORRELATION COEFFICIENT r	COEFFICIENT OF DETERMINATION r^2
January, 1972 to August, 1978	Monthly solar radiation	Monthly yield for same month	0.19 (n=79)	0.04
January, 1972 to August, 1978	Monthly radiation	Monthly yield for next month ~~but one~~	- 0.09 (n=76)	0.01
January, 1972 to August 1978	Monthly solar radiation	Monthly yield for next month but one	-0.10 (n=76)	0.01
Field Capacity (1972-78)	Monthly solar radiation	Monthly yield for same month	0.51 (n=67)	0.26

correlation was obtained. However, this was not significant. On correlating monthly yields with monthly solar radiation values during a wet phase (water readily available in the surface layers 0-0.8m), a significant positive correlation with 67 observations was found (r = +0.51). The significance of this relationship suggests that when water is readily available in the surface layers, solar radiation intensities are responsible for yield changes during this period. Thus solar radiation accounts for 26% of the variations observed in the yield distribution curve.

Considering that there may be delayed effects in the response of tea to monthly fluctuations of solar radiation, an investigation was made into this. Monthly solar radiation was correlated first with monthly yields for next month and second with monthly yields for next month but one. In both of these cases, insignificant negative correlations were obtained (Table 5.1). Further investigation was done first by correlating average solar radiation in the previous two months and actual yield in the second month and then by correlating average solar radiation in the previous three months and yield in the third month. This was done for all months in the study period.. In the first case, a low positive correlation ($r=+0.45$) was obtained with two months averages of solar radiation and second month yields, whereas a correlation coefficient of +0.66 was obtained for three months average of solar radiation and third month yields. These findings appear to confirm the presence of residual effects in the response of tea to solar energy. Thus by taking into account the average effect of solar radiation on the growth of tea in the previous three months we are able to explain 44% of the yield variation.

An examination of the trend of solar radiation over the period 1972-78 (Table 5.2) revealed that the months May to September of every year were characterised by low solar radiation intensities (with majority of cases less than 400 $\text{cal/cm}^2\text{/day}$). On correlating yield with solar radiation in the period May to September, a correlation coefficient of +0.61 with 28 observations was found. In other words, about 37% of the variation in yields may be attributed to solar radiation intensities in May to September. However, only a very low

TABLE 5.2:

Source: T.R.I.E.A., Kericho

MEAN MONTHLY SOLAR RADIATION (cal/cm^2 /day),

MAXIMUM AND MINIMUM TEMPERATURE (1972-78)

MONTH	SOLAR RADIATION (cal/cm^2/day	MEAN MAXIMUM TEMPERATURE °C	MEAN MINIMUM TEMPERATURE °C
JANUARY	521	24.3	8.1
FEBRUARY	502	24.7	8.9
MARCH	465	24.7	9.3
APRIL	418	23.3	9.5
MAY	374	21.0	9.3
JUNE	388	21.4	8.8
JULY	370	20.8	8.8
AUGUST	376	21.0	8.7
SEPTEMBER	424	22.3	8.1
OCTOBER	413	23.0	8.4
NOVEMBER	414	22.6	8.8
DECEMBER	487	21.6	8.4

TABLE 5·1 contd.

January, 1972 to August, 1978	Average for two months	Second month yield	0.45 (n=39)	0.20
January,1972 to August, 1978	Average for three months	third month yield	0.66 (n=23)	0.44
May to September, 1972-1978	Monthly radiation	Monthly yield	0.61 (n=28)	0.37
October to April 1972-1978	Monthly radiation	Monthly yield	-0.11 (n=46)	0.01

correlation of r = -0.11 was obtained for the relationship between yield and solar radiation in the period October to April. It should be noted that the period October to April was characterised by relatively higher solar radiation values than those observed in the periods May to September. Thus the negative relationship between yields and solar radiation intensities during this phase suggests that monthly solar radiation values above 400 cal/cm^2/day are not favourable for plant growth. It should be emphasized, however, that the relationship between tea yields and solar radiation in the period May to September may not be straightforward. The period of low solar radiation values corresponds with more than half of the number of ten-days field capacity periods in any year over the study period. Thus the period of low solar radiation values is also the period when deep percolation is prevalent causing leaching of tea nutrients. It may be therefore that the low tea yields recorded in May to September is due to low solar radiation intensities, nutrient deficiencies in the top soil layers or because there is no water stress. The question of the association between leaching and nutrient availability in the surface layers, however, calls for further investigation.

In summary, it is clear from the present findings that solar radiation is not the dominant factor influencing the tea yield distribution curve in all months. However, its importance in wet months (May to September) should be emphasized. It is noted that during wet months, solar radiation explains 37% of the variation in the tea yield distribution curve.

The presence of residual effects in the response of tea to the solar radiation is also indicated. It appears that under the environmental conditions of the area of study, solar radiation conditions in the previous three months have a positive and significant effect upon tea growth.

(ii) POTENTIAL EVAPOTRANSPIRATION ($ET=0.85E_o$) AND TEA YIELDS

The amount of water passing through the plant system via the roots, the stems and finally transpired via the leaves is a function of the stage of development of the crop, its aerodynamic roughness and the prevailing soil moisture conditions. The role of these factors in the consumptive use of crops was discussed in chapter two. It was also pointed out that under plentiful supplies of water, a mature tea bush transpires at a constant rate equal to 85% of open water evaporation (E_o) Wan'gati, F.J. and Blackie, J.R. 1971.

There is evidence to suggest that maximum production of dry matter is only possible in a given environment when its true evapotranspiration is the same as the potential evapotranspiration at all times (Wangati, F.J. and Blackie, J.R. 1971).

An examination of the temporal trend of ET over the study period showed that monthly fluctuations of Et are relatively small compared to those of monthly solar radiation over the same period. No clear cut patterns are present in the E_T curve (Fig 5.2), although it is clear that relatively higher values occur in January to March and October to December. However, it was of interest to

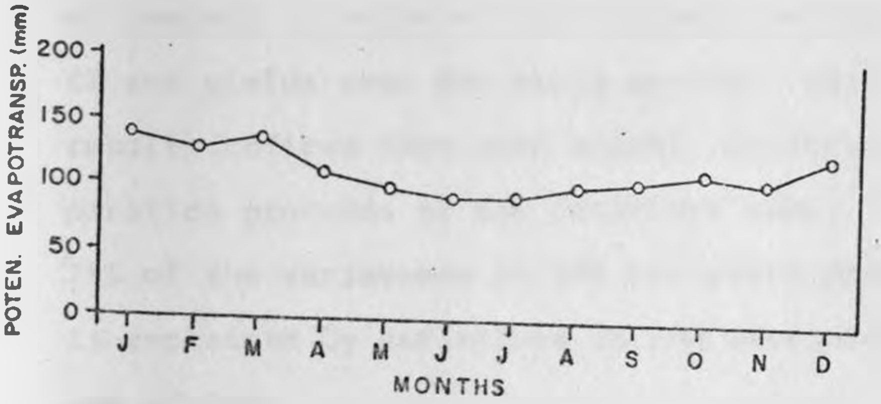


FIG. 5.2 MEAN MONTHLY POTENTIAL EVAPOTRANSPIRATION FOR BBL TEA ESTATES 1972 – 1978.

examine the relationship between ET and yields in months when maximum production of dry matter was possible. For this purpose, 67 observations of monthly yield were correlated with corresponding values of ET when there were plentiful supplies of moisture in the top 80 cm of the soil surface. A low positive correlation coefficient of 0.54 was obtained. This can be compared with an overall r value of 0.21 between monthly ET and yields over the study period. This result confirms that when actual evapotranspiration proceeds at the potential rate, 29% of the variations in the tea yield curve is explained by variations in the consumptive use of tea.

In order to allow for possible time lags in the response of tea to variations in evaporative demand, tea yield was correlated with ET in the previous three months. In this case, the average ET values for the previous three months was correlated with actual yields in the third month. This operation yielded a highly significant positive correlation with $r = 0.72$. Thus 52% of the yield variations in the third month are explained by the rate of ET over the previous three months.

It is interesting to note at this stage that whereas it is clear from the previous section that solar radiation is an important factor governing the tea yield distribution curve, the relationship between ET and yield on one hand and solar radiation and yield on the other hand for same periods must be stressed (Table 5.3). For example, it is noticed that the correlations for the relationships between ET and yield and solar radiation and yield considering all months, wet months and previous three months are very similar. Furthermore, it is apparent that ET shows a relatively stronger relationship with yield than solar radiation. A plausible interpretation for this relationship is that solar radiation is an important factor influencing evaporative demand and therefore an important component of ET in the study area. One may conclude that in the overall monthly potential evapotranspiration rates explain only a small variation of the tea yield distribution curve, in particular the

TABLE 5.3

Source: Author's Survey

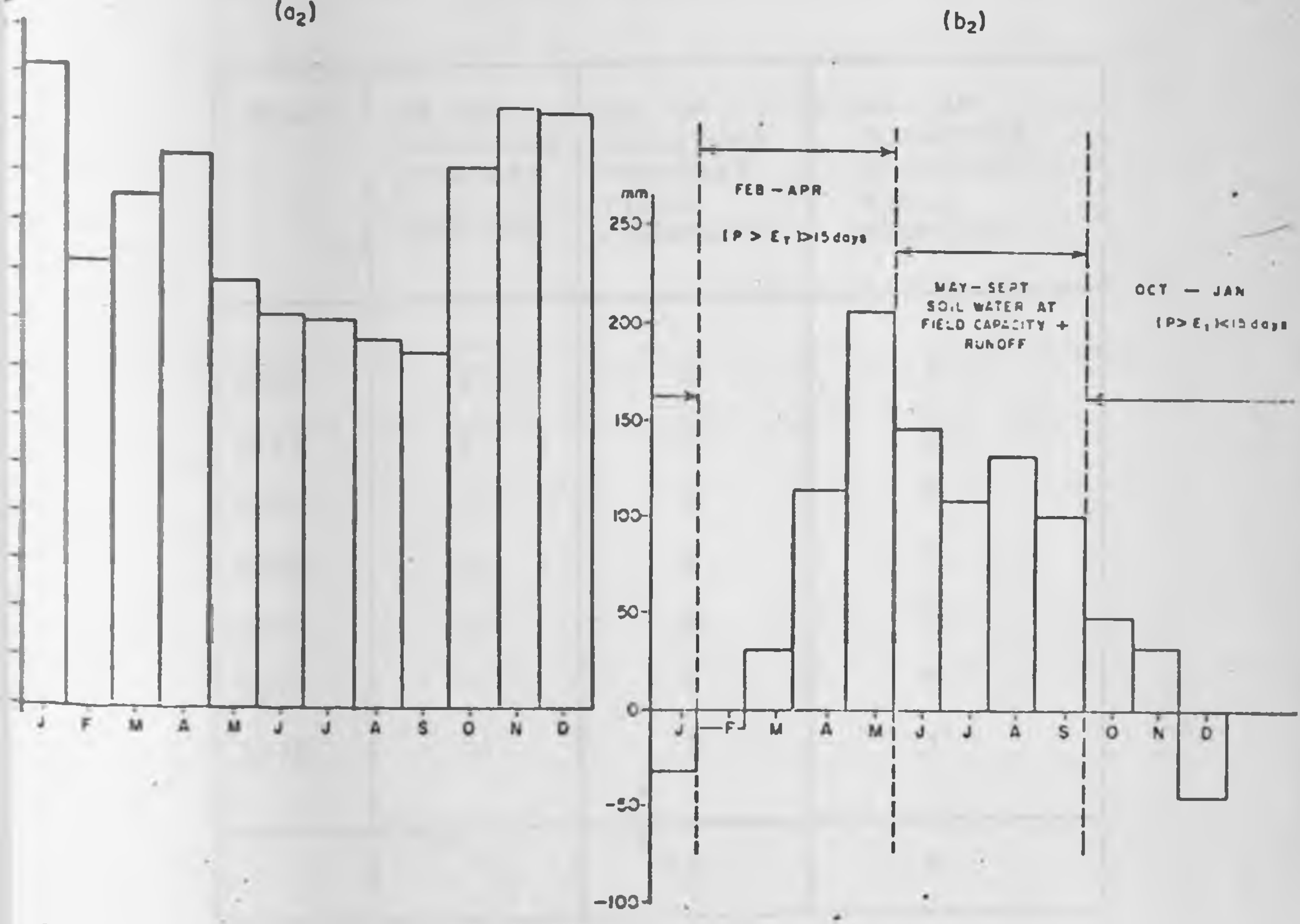
CORRELATION COEFFICIENTS SHOWING THE RELATIONSHIP BETWEEN SOLAR RADIATION, ET AND TEA YIELDS FOR SELECTED PERIODS

PERIOD	NATURE OF SOLAR RADIATION DATA	NATURE OF ET DATA	NATURE OF YIELD DATA	CORRELATION COEFFICIENT FOR SOLAR RADIATION AND YIELD	CORRELATION COEFFICIENT FOR ET AND YIELD
January 1972 to August 1978	Monthly solar radiation	Monthly ET	Monthly yield for same month	+0.19 (n=79)	+0.21 (n=79)
Field capacity months (1972-78)	Monthly solar radiation	Monthly ET	Monthly yield for same month	+0.51 (n=67)	+0.54 (n=67)
January 1972 to August 1978	Average for three	Average for three	third month yield	+0.66 (n = 23)	+0.72 (n=23)

importance of consumptive use (ET) in wet months is apparent. It is also clear that ET rates associated with high solar radiation intensities would inhibit tea growth. This is because the likelihood that the tea bush will experience water stress is increased as low plant water potentials develop with increase in evaporative demand (see Fig. 5.3).

Consideration of the relationship between tea yields and amounts of ET may be further facilitated if we look at the months showing ET values below 100mm and the number of occasions when yields are above and below a figure of 300 kg/ha (Table 5.4).

In general, the results of Table 5.4 suggest that although the tea bush may be transpiring at the potential rate, the amount of water transpired in any month is important in the growth processes of the plant; in other words, maximum or minimum yield must significantly depend upon the rate of evapotranspiration. It is also clear from Table 5.4 that in a majority of cases, yields will remain below a figure of



53 (a_2. b_2) MEAN MONTHLY YIELD OF MADE TEA (kg/ha), MEAN MONTHLY ($P - E_T$) WITH SOIL-MOISTURE RESPONSE SEASONS AT BBLC ESTATES, KERICHO 1972 – 1978.

TABLE 5.4

Source: Author's Survey

NUMBER OF OCCASIONS (MONTHS) WHEN ET <100mm AND TEA YIELDS <300 AND >300KG/HA

YEAR	NO. OF OCCASIONS (MONTHS) ET<100mm	NO. OF OCCASIONS (MONTHS) YIELD <300KG/HA	NO. OF OCCASIONS (MONTHS) YIELD >300KG/HA
1972	6	3	3
1973	6	5	1
1974	3	0	3
1975	1	1	0
1976	1	1	0
1977	2	1	1
1978	2	1	1
		12	9

300 kg/ha whenever the amount of potential evapotranspiration is below 100mm.

Table 5.5 confirms that yields above 300kg/ha may be anticipated so long as E_T remains above 100mm. It appears reasonable to suggest, therefore, that under conditions of plentiful supplies of soil moisture in the top soil layers, yields will continue to increase with increase in E_T until such a time that high E_T rates create a condition in which the water absorbed by the roots becomes insufficient to offset the high evapotranspiration losses. A condition of water stress may thus set in and the result may be a decline of yields.

Table 5.5

. Source: Author's Survey

NUMBER OF OCCASIONS (MONTHS) WHEN $E_T > 100$mm AND TEA YIELD < 300 AND > 300 KG/HA

YEAR	NO. OF OCCASIONS (MONTHS) $E_T > 100$ mm	NO. OF OCCASIONS (MONTHS) YIELD > 300KG/HA	NO. OF OCCASIONS (MONTHS) YIELD < 300KG/HA
1972	6	5	1
1973	6	6	0
1974	5	5	0
1975	6	5	1
1976	6	3	3
1977	9	5	4
1978	6	5	1
		34	10

It would be of interest to note that the highest yield value over the study period was obtained in March, 1977 (607 kg/ha); E_T was 136mm. The lowest yield was recorded in August, 1973 (172 kg/ha). The corresponding E_T value was 92mm (see also Table 5.6 and 5.7 Appendix A).

II RELATIONSHIP BETWEEN WATER BALANCE INDICES AND TEA YIELDS

(i) RELIEF OF SOIL WATER STRESS (DAYS $P>E_T$

The number of days in a month during which precipitation exceeds evapotranspiration (days $P>E_T$) is a good indicator of the rate of soil moisture recharge since this represents the duration of time when water is actually added into the soil profile. This index also indicates the timing of relief of stress (Hanna, L.W. 1971). In the present study, an investigation into the relationship between the duration of soil profile wetting in months when water was readily available in the surface layers and tea yields suggested that protracted soil wetting inhibits tea growth.

A regression relationship between tea yields and days $P>E_T$ was

$$\hat{Y} = 497.52 - 9.71\,Xo \quad .... \quad (9)$$

$(r = -0.50,\ n = 67)$

where

$\hat{Y}$ = tea yield in kg/ha,

Xo = duration of soil profile wetting

The limiting effect of the duration of soil profile wetting suggested by the significant negative correlation coefficient may be recognized if it is considered that in April, 1972, there were 15 days during the month with $P > E_T$, 9 days during which the rainfall received was nil and 14 days with rainfall greater than 5mm. The yield recorded in this month was 425 kg/ha. In May, 1972, when we had a yield value of 311 kg/ha, there were 18 days with rainfall greater than 5mm, 4 days with no rainfall, 24 days with $P > E_T$ and a reduction of solar radiation from 449 cal/cm^2/day (April, 1972) to 362 cal/cm^2/day (May, 1972). There was no change in the soil profile wetness as these months experienced field capacity conditions in the surface layers (top 80 cm of the soil profile). Thus, it appears that whereas the addition of water to profiles already at field capacity reduces yields, the low solar radiation intensities experienced during such periods may be a factor underlying low yields. Hanna, L.W. 1971 reached a similar conclusion when investigating the relationship between soil moisture indices and tea yields in Uganda. He observed that the process of relieving stress is not itself conducive to high productivity, but if conditions permit full advantage to be taken of solar energy, the availability of easily accessible soil water will increase yields greatly. He further reported that if the soil profile is filled rapidly and continuously through the month, yields will be depressed.

(ii) PERIODS OF FIELD CAPACITY (DAYS AW =140mm)

Continuous recharge of the soil profile following relief of stress restores the profile to field capacity. At field capacity, water is freely available to the plant. The length of time within a month during which water is freely available to the tea plant has some bearing upon growth and therefore productivity. To test this hypothesis, the number of days in a month during which water is freely available in the top 80cm of the soil profile corresponding to 140mm AW was correlated with monthly tea yields. This relationship yielded a low insignificant negative correlation coefficient (r=-0.03). This relationship suggested that factors other than water availability influence tea yields during periods when water availability is non-limiting. As noted in the previous section, solar radiation was seen as the dominant factor influencing yields during wet periods. Hanna, L.W. (1971) considered that solar energy and supply of nutrients set the upper limit of production whenever soil water is not limiting.

(iii) PERIODS OF INCREASING SOIL WATER STRESS AND YIELDS DAYS ($P > E_T$) <15

If continuous use of the soil water reservoir by the tea plant is not frequently replenished in the course of relief of water stress, then conditions of inadequate soil moisture would be expected to be unfavourable to active growth. This would depress yields if prolonged for any considerable period. In order to test the hypothesis that declining duration of soil moisture recharge would progressively increase yields so long as the surface profile remains wet and provided other conditions are non-limiting, the relationship between tea yields and days $(P>E_T)<15$ was ascertained.

The regression for this relationship was significant and negative.

$$\hat{Y} = 160.80 - 26.83X_2 \text{ ....} \quad (10)$$

$$(r = -0.58)$$

where Y= tea yield kg/ha

X_2=days $(P>E_T <15)$

The negative relationship between tea yields and duration of soil moisture recharge may be further clarified by examining the association between yields below 300 and above 300 kg/ha when the duration of soil moisture recharge is below 15 and above

15 respectively. Between 1972 and 1978 there were 24 occasions (months) when yields above 300 kg/ha were obtained with days $(P>ET)<15$ and 6 occasions when yields were below 300kg/ha. Similarly, between the same period (1972-78) there were 15 occasions when yields below 300 kg/ha were obtained with days $(P>ET)>15$ days. Thus, it is apparent that relatively high yields are associated with less than 15 days of soil moisture recharge provided other conditions are non-limiting.

(iv) RELATIONSHIP BETWEEN TEA YIELDS AND PERIODS OF ADEQUATE SOIL MOISTURE SUPPLY (FIELD CAPACITY) AND DURATION OF SOIL WATER RECHARGE (DAYS P>ET)

Dry periods of no rain are virtually absent at Kericho (see Fig.5.4 .). Between 1972-1978 the lowest recorded rainfall was obtained in February, 1974 with a monthly total of 15.9mm. Under such conditions, it was proposed that the relationship between duration of soil moisture recharge (days $P>ET$) and duration of time in a month when the surface soil profiles (top 80cm of soil

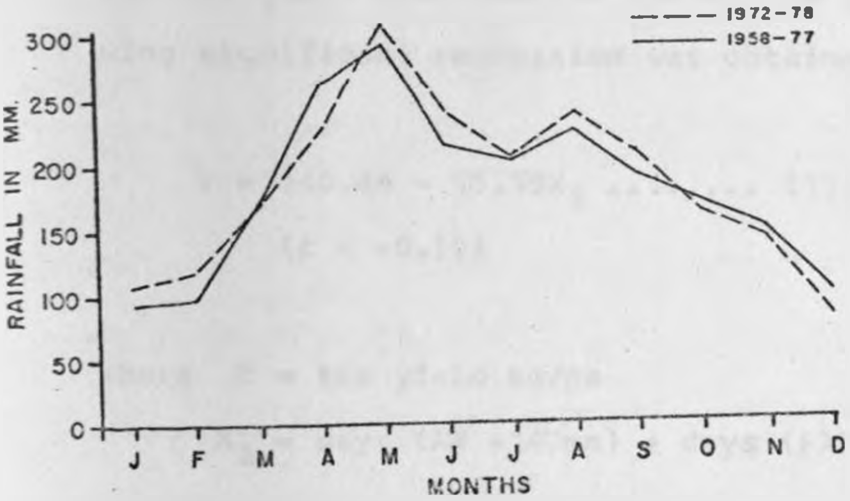


FIG. 5.4 MEAN MONTHLY RAINFALL AT KERICHO T.R.I (E.A) 1958-77 & 1972-78.

surface) is at field capacity is central to any rational explanation of the tea yield distribution curve. This is because the wet months (field capacity months) dominate the soil moisture calendar year at Kericho (see Fig. 5.5). Integrating the effects of duration of field capacity and days P>ET on the tea yield distribution curve, the following significant regression was obtained:

$$Y = 340.44 - 15.79X_3 \text{ .... } (11)$$

$$(r = -0.50)$$

where Y = tea yield kg/ha

X_3 = days (AW =140mm) + days (P>ET)

The strength of the relationship between tea yields and integrated effects of duration of field capacity and days P>ET suggested that continuous moisture addition to soil profiles already at field capacity depressed yields. Hanna, L.W. 1971 also reported that "the wetting of the surface during periods of full profile would explain

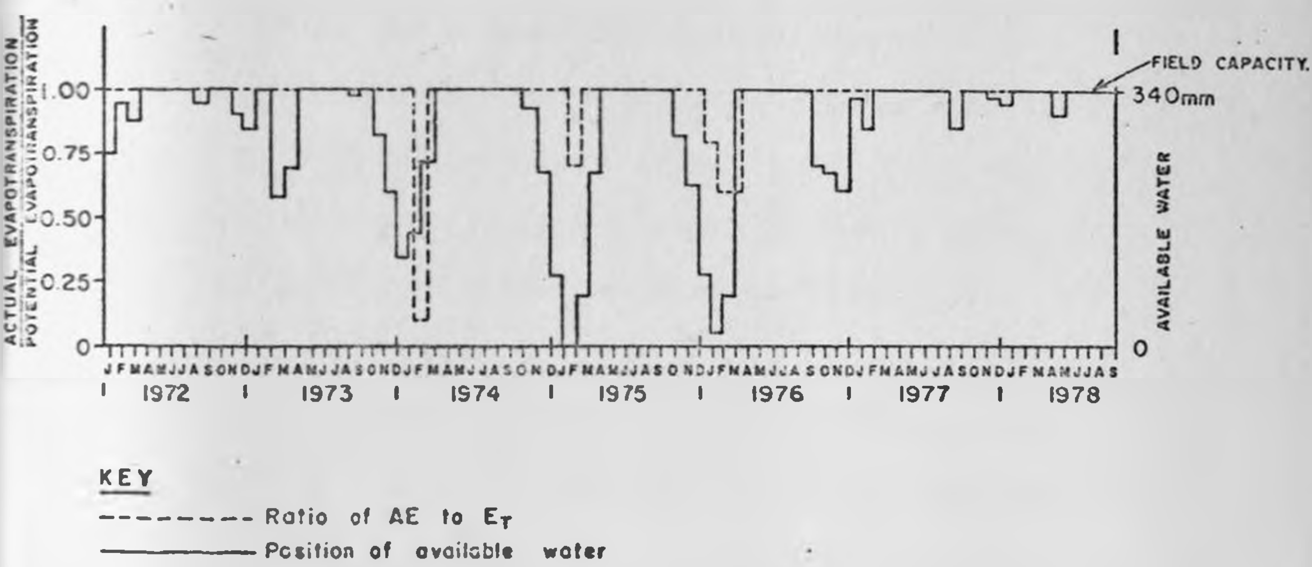


FIG. 5.5 SOIL MOISTURE STORAGE AND DEPLETION FOR B.B.L TEA ESTATE, KERICHO.

the maintenance of growth so that yields bear a relationship with the duration of wetting. Yields are also depressed when the profile is continously wetted".

CHAPTER 6

SUMMARY AND CONCLUSIONS

In the present investigation an attempt has been made to establish the relationship between various climatic parameters and tea productivity in Kericho. By means of a water balance model based on meteorological parameters measured on a daily, ten days and monthly levels, it has been possible to formulate agroclimatological indices related to tea growth.

In the computation of daily, ten days and monthly distribution of soil moisture from meteorological data, consideration has been given to soil moisture retention properties and atmospheric evaporative demand at Kericho.

In order to determine the amount of available soil water storage, the concepts of wilting point and field capacity have been used. The available water was determined as the difference between water held at a suction of 0.3 bar (corresponding to field capacity) and a suction of 15 bars (corresponding to wilting point). The available water in various depths have been calculated.

It has been shown that the first 80cm. of soil depths stores 140mm of available water. Quantities of available water equal to 235mm., 340mm, and 900 mm are held at depths of 100cm, 200cm and 500cm. respectively.

It must be emphasized that the plants' physiological activities that are importantly related to growth and yield are a summation of the effects of climatic conditions, soil fertility status and management practices. Thus a realistic assessment of the impact of climate alone on tea productivity must of necessity allow for the influence of these other factors. In this study, an attempt was made to minimise the influence of non-weather factors on tea growth and yield by ensuring that factors such as soil fertility and cultural factors were at optimum levels.

From the present study, it has been possible to make the following conclusions:

(1) Solar radiation and tea yields are positively related in wet periods of any year (that is when field capacity conditions exist in the top soil layers). In this study a positive correlation between monthly tea yields and solar radiation was

obtained (r=+0.51, n=67).

(2) Tea exhibits a delayed response to monthly fluctuations of solar radiation. A positive correlation was obtained between tea yields and solar radiation in the previous three months (r=+0.66, n= 23).

(3) The amount of water transpired by a tea bush under plentiful supplies of water determine the expected maximum or minimum yield (so long as other factors are not limiting such as nutritional factors, disease and so on). A positive correlation was obtained between potential evapotranspiration (E_T) during wet months and monthly tea yields. (r = +0.54, n = 67).

(4) Empirical evidence in the present analysis reveals that in most cases monthly yields will remain below a

figure of 300kg/ha if E_T during wet months remain at 100mm. or below.

(5) Tea shows a time lag in its response to variations in evaporative demand. Monthly tea yields correlated with potential evapotranspiration (0.85Eo) in the previous three months yielded a positive correlation ($r = +0.72$, $n = 23$).

(6) When soil moisture is readily available in the top soil layers, subsequent profile filling depresses tea yields. The regression equation for the relationship between duration of soil profile wetting during wet months was significant, with a negative correlation coefficient.

$$Y = 497.52 - 9.71\ Xo$$

$$r = -0.50,\ n = 67.$$

where Y = tea yield in kg/ha

Xo = days ($P > E_T$) in wet months

= duration of soil profile wetting.

It was borne out in this analysis that so long as the top 80cm. of soil surface remains at field capacity, continuous subsequent filling equal to or exceeding 15 days has a critical depressing effect on tea yields.

(7) So long as the top soil profiles remain at field capacity, meaning that the soil moisture depletion rate or infilling rate are minimal, factors other than water availability influence tea yields. Low solar radiation loads during field capacity months appear to explain some proportion of yield variation in the yield distribution curve. This conclusion concurs with Hanna's (Hanna, L.W. 1971) observation that solar energy and supply of nutrients set the upper limit of production whenever soil water is non-limiting. A low insignificant correlation coefficient (r = - 0.03) was obtained for the relationship between duration of adequate

water supplies (water availability equal to 140mm.) and monthly tea yields.

(8) Tea yields would remain high so long as field capacity conditions in the top soil layers are maintained and provided continuous addition of moisture thereafter proceeds at a rate of less than 15 days (that is days $P > E_T < 15$) in any month. A regression equation established for the relationship between days $(P > E_T) < 15$ and tea yields was significant.

$$\hat{Y} = 160.80 - 26.83 X2$$

$$(r = -0.58)$$

where

Y = tea yields

X_2 = days $(P > E_T) < 15$

(9) It is apparent in this study that a significant proportion of the variations in the tea yield distribution curve are variously

explained during different times by solar energy supply, water transpired by the tea plant (evapotranspiration) and duration of soil profile wetting.

(10) On average the seasonal trend in tea yields at Kericho are as follows: The highest yield occur in October to January, drop sharply in February but increase steadily thereafter until April. Yields drop again sharply thereafter and continue until September. These yields relate to the climatic parameters in the manner discussed above.

RECOMMENDATIONS

The results of this study have important implications on the agronomic practices of tea husbandry, planning of tea collecting centres, factories and not the least the allocation and distribution of labour force within the estates.

On the aspects of tea husbandry, it may be suggested that a closer watch on the status of tea nutrients in wet periods is important. This is because there may be appreciable losses of nutrients due to leaching and prompt measures must be taken to rectify any deficiencies.

Since the period May to September is one of slow growth of tea because of low solar radiation intensities, severe prunning is not advisable as low rate of recovery may increase chances of root rotting due to fungi infestation and other related diseases.

The correlations established for the different environmental factors (selected for this study) and tea yields lend credibility to the suggestion ~~and~~ that solar energy, potential evapotranspiration and duration of soil profile wetting are important surrogates in the determination of potential tea growing areas for further expansion, planning and distribution of factories, collecting centres and labour force management.

SUGGESTIONS FOR FUTURE RESEARCH:

Arising from the above discussion, the following broad areas for further research may be suggested:

1. Experimental field studies are required to ascertain the effects of the interactions between soil moisture supply and other environmental factors including nutrient supply on tea performance. For example, more information is required on the response of tea to various nutrient elements under different soil moisture regimes.

2. Research should be conducted to increase information on the behaviour of root systems under different soil moisture regimes and nutrient availability, and in particular

the relationship between quantity of roots to quantity of shoots.

3. Although recent developments in meteorological physics have provided us with statistical methods for estimating soil moisture, there is need for a simple and rapid method for measuring plant water status. The applicability and usefulness of plant-water status measuring instruments such as the pressure bomb need to be evaluated for tea. There is now evidence to suggest that the method of determining suction pressure by the immersion of leaf tissue in sucrose solution of various concentrations to find the isotopic solution may not apply adequately for all plants.

4. The effect of soil moisture stress on the quality of tea is still largely unknown; a better understanding would make it easier to assess the need for a compromise between quantity and quality; a continuing problem in tea production management.

APPENDIX A

TABLE 5.6. PRECIPITATION (P), POTENTIAL EVAPOTRANSPIRATION ($E_T = 0.85E_o$), AVAILABLE WATER BETWEEN SURFACE AND 2.0 M OF SOIL DEPTH (AW) AND DEEP DRAINAGE LOSSES (DD) FOR TRI (EA), KERICHO, 1972 – 1978

		JAN.			FEB.			MAR.			APR.			MAY			JUNE			JULY			AUG.			SEPT.			OCT.			NOV.			DEC.		
		I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
1972	P	255	7.9	24.8	701	70.3	41.7	285	58.8	19.0	594	63.7	72.8	149.0	73.2	98.2	74.3	87.0	129.9	74.2	65.1	70.5	41.8	93.8	70.5	52.6	17.2	45.7	31.4	93.5	105.6	85.9	91.5	40.5	11.2	80.0	18.5
	ET	43.6	46.2	52.4	27.4	40.6	35.1	45.4	35.9	50.3	40.3	32.8	31.3	27.5	26.8	32.2	21.4	31.3	23.5	28.1	29.1	32.3	35.5	29.1	33.7	32.0	34.4	35.8	38.5	25.8	26.1	28.2	28.4	32.0	37.0	33.2	51.5
	AW	322	284	256	294	328	335	318	340	309	328	340	340	340	340	340	340	340	340	340	340	340	340	340	340	340	323	333	326	340	340	340	340	340	314	340	307
	DD								0.5			18.7	41.5	121.5	46.4	66.0	45.4	55.7	106.4	46.1	34.0	33.2	6.3	64.2	36.8	20.6				53.4	79.5	57.7	63.1	8.5		21.0	
1973	P	23.1	164.9	0	298	139.1	57.9	4.4	14.8	0	27.9	52.2	81.8	83.3	58.3	120.9	110.6	69.2	83.1	8.8	33.9	71.6	65.8	66.2	59.0	101.8	80.0	27.7	422	44.0	40.0	81.2	14.3	0	11.4	16.8	22.0
	ET	42.3	34.5	54.3	50.7	35.7	30.5	49.8	52.4	55.8	47.2	34.3	34.2	26.5	30.1	29.6	23.3	28.8	29.1	31.1	26.1	34.3	29.1	29.1	33.7	29.7	30.5	32.1	31.4	28.5	38.8	27.3	35.2	38.6	45.4	37.8	43.4
	AW	288	340	286	265	340	340	295	257	201	182	200	245	302	330	340	340	340	340	318	326	340	340	340	340	340	340	336	340	340	340	340	319	281	247	226	204
	DD		78.2			28.2	27.4									81.7	82.3	40.4	54.0			22.8	36.7	37.1	25.3	72.1	49.5		6.2	15.5	1.2	53.9					
1974	P	32.9	19.9	0	0	15.9	0	69.3	49.3	148.8	124.3	55.5	26.5	19.3	79.3	134.0	52.2	58.2	76.2	136.1	58.0	93.5	11.7	17.0	121.9	34.2	107.8	73.9	367	59.7	42.1	52.3	44.6	18.8	5.8	14.7	22.8
	ET	39.9	61.5	54.6	53.5	43.8	42.7	40.4	47.0	27.5	30.9	33.5	45.2	28.3	29.1	33.8	33.3	33.2	26.5	24.0	27.2	27.3	34.3	31.9	34.6	33.1	33.3	33.5	37.7	29.7	38.2	33.4	36.9	37.0	42.4	43.2	45.7
	AW	197	175	121	67	39	0	25	28	147	240	262	244	265	335	340	340	340	340	340	340	340	317	303	340	340	340	340	337	340	340	340	340	320	283	255	229
	DD															95.0	18.9	25.0	49.7	112.1	30.8	66.2			49.8	1.1	74.5	40.4		27.0	3.9	18.9	7.7				
1975	P	16.2	0	0.4	8.1	240.0	13.1	101.0	77.1	28.4	19.9	151.8	106.4	53.4	78.4	166.2	79.3	136.2	32.9	76.6	76.7	51.1	101.6	144.1	157.1	122.0	87.7	113.3	137.1	55.9	63.7	21.5	40.6	2.1	38.9	17.3	1.6
	ET	44.5	47.9	59.2	54.2	57.5	40.9	42.7	47.4	47.9	46.9	33.9	40.5	43.5	33.4	33.9	32.6	32.4	32.1	37.4	29.0	31.7	30.5	33.6	35.6	34.3	35.0	34.4	34.3	40.3	39.4	41.1	39.1	50.4	34.7	40.6	[illegible]
	AW	200	152	94	48	14	0	58	88	69	44	167	230	240	285	340	340	340	340	340	340	340	340	340	340	340	340	340	340	340	340	328	330	281	286	262	215
	DD															57.3	46.7	103.8	0.8	39.2	47.7	19.4	70.7	110.5	121.5	87.7	52.7	78.9	102.8	15.6	24.3						
1976	P	11.5	5.6	0	6.2	32.1	232	5.6	5.0	69.4	429	362	82.3	141.2	177.2	164.4	603	87.8	54.4	49.8	118.9	50.0	20.4	94.2	106.2	56.1	41.1	43.6	7.5	16.8	14.8	14.3	33.5	69.8	8.2	53.3	44.5
	ET	43.0	47.6	49.6	40.6	47.5	43.7	50.0	52.4	50.5	NR	NR	NR	34.8	32.0	31.6	33.0	34.1	31.9	27.5	31.0	39.0	32.4	36.9	39.3	36.6	43.7	40.9	44.0	43.9	54.3	40.5	41.7	37.7	44.3	45.6	40.2
	AW	184	142	92	58	42	22	0	0	19				175	320	340	340	340	340	340	340	340	340	340	340	340	337	340	304	276	237	211	203	235	119	206	211
	DD															112.7	22.3	53.4	22.5	22.3	87.9	11.0		45.3	66.9	19.5		0.1									
1977	P	64.3	21.8	181.0	36.7	14.0	35.6	77.9	13.5	100.4	174.2	21.0	106.2	132.8	56.6	87.7	156	99.4	115.1	136.6	29.0	108.9	117.2	66.2	72.1	139.3	121.3	3.0	49.9	47.4	83.2	84.3	101.8	63.3	13.4	26.0	77.3
	ET	37.1	40.5	43.7	39.9	48.5	31.4	53.4	57.5	45.1	30.9	38.2	32.5	32.4	31.7	38.4	37.3	30.3	31.3	28.4	33.1	37.4	33.3	40.8	33.4	36.8	35.5	44.7	42.2	38.3	38.7	33.4	28.0	32.8	40.1	38.9	41.1
	AW	214	195	332	329	294	299	333	299	340	340	328	340	340	340	340	340	340	340	340	340	340	340	340	340	340	340	298	306	315	340	340	340	340	313	300	337
	DD									14.3	143.3		61.5	100.4	24.9	49.1	23.3	68.6	83.8	102.2		67.6	33.9	25.4	38.7	102.5	85.8					19.6	50.9	73.8	10.5		
1978	P	0	72.9	52.6	1.3	48.2	164.8	125.6	82.2	92.4	176.5	36.7	63.1	150.8	86.4	21.7	49	55.2	112.6	24.8	26.4	82.1	90.8	66.0	92.1	36.4	45.9	106.0									
	ET	46.5	37.0	51.1	52.4	41.1	28.0	37.1	36.4	43.7	38.8	41.1	33.3	35.2	37.3	47.3	37.7	30.2	28.8	29.5	35.0	41.2	33.6	33.6	41.7	38.0	38.8	38.2									
	AW	290	326	328	276	284	340	340	340	340	340	336	340	340	340	314	340	340	340	335	324	340	340	340	340	338	340	340				NR	=	No	Record		
	DD						70.3	101.5	45.8	40.7	137.2		25.4	116.4	47.1			11.5	83.8			24.5	57.2	12.4	50.4		5.5	67.8									

APPENDIX A

TABLE 5.7 DAYS OF FIELD CAPACITY AT DEPTHS 0.8, 1.0M, AND 2.0M CORRESPONDING WITH AVAILABLE WATER CAPACITIES OF 140MM, 235MM, AND 340MM.

YEAR	AVAILABLE WATER CAPACITIES MM	JAN. DAYS	FEB. DAYS	MAR. DAYS	APR. DAYS	MAY DAYS	JUN. DAYS	JUL. DAYS	AUG. DAYS	SEPT. DAYS	OCT. DAYS	NOV. DAYS	DEC. DAYS
1972	140	31	29	31	30	31	30	31	31	30	31	30	31
	235	13	16	23	21	31	30	31	31	30	31	30	31
	340	0	0	0	0	22	11	13	12	6	10	14	0
1973	140	31	28	31	30	31	30	31	31	30	31	30	31
	235	31	29	22	2	30	30	31	31	30	31	30	12
	340	5	5	0	0	5	14	3	14	13	1	7	0
1974	140	28	0	2	30	31	30	31	31	30	31	30	31
	235	0	0	0	23	31	30	31	31	30	31	30	20
	340	0	0	0	0	12	8	17	3	12	11	3	0
1975	140	20	0	0	14	31	30	31	31	30	31	30	31
	235	0	0	0	8	31	30	31	31	30	31	30	31
	340	0	0	0	0	10	12	12	23	16	15	3	0
1976	140	25	0	0	0	23	30	31	31	30	31	30	31
	235	0	0	0	0	16	30	31	31	30	31	21	27
	340	0	0	0	0	8	18	14	11	10	0	0	0
1977	140	31	28	31	30	31	30	31	31	30	31	30	31
	235	31	28	31	30	31	30	31	31	30	31	30	31
	340	3	2	3	17	21	17	15	18	13	7	20	0
1978	140	31	28	31	30	31	30	31	31	30			
	235	31	28	31	30	31	30	31	31	30			
	340	2	5	14	16	16	15	7	18	9			

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