EMPIRICAL MODELS FOR PREDICTING SOIL-CLIMATE AND RELATED PASTURE GRASS PERFORMANCE IN MAUI, HAWAII (AN EVALUATION OF SOIL-CLIMATE CRITERIA OF SOIL TAXONOMY)

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ABSTRACT

Soil Taxonomy requires soil-climate for soil classification and the interpretation of the relationships between soil, climate, and plant. The depth at which soil temperature and soil moisture regimes are currently measured or estimated have been, however, given without presenting any evidence of any particular importance of soil-climate at these depths to soil genesis and/or plant growth. The objectives of this study were to develop mathematical models that can provide first approximations of soil temperatures at different depths and evaluate the depth at which soil temperature and/or soil moisture correlate most to herbage production. Such a knowledge can be used as a criterion for better identification of soil-climate and serve as a basis for the evaluation of the current soil-climate criteria of Soil Taxonomy.

Located on the island of Maui, Hawaii, the area of the study extended along a climosequence with a wide range of ecological zones. The altitudes vary from 36 to 1620 m, the soils from Inceptisols (Andepts) to Mollisols and Oxisols, mean annual air temperatures from 13 to 24 $^{\circ}C$, and total mean annual precipitation from 100 to 872 mm. Computerized automatic weather stations were installed to monitor air and soil-climate environment at 11 sites and pasture grass growth was observed at four of the sites. The measurements

included air temperature, soil temperatures at 0.1- and 0.5-m depths, soil moisture at 0.1- and 0.5-m depths, relative humidity, rainfall, and solar radiation. The dominant grass species were buffel grass, kikuyu grass, and an admixture of fescue, sweet vernal, rattail, Yorkshire fog, and white clover.

Simple linear, multiple, and quadratic regression models were developed to estimate the soil temperatures at 0.1- and 0.5-m depths from air temperature and other environmental factors. All of the models showed a satisfactory coefficient of determination, but the quadratic models were judged to have a greater predictive ability than the others because of their slightly higher R^2 and smaller residual mean squares. In addition, the quadratic models depicted better the curvilinear relationship between the air and soil temperatures.

Soil temperatures predicted by the quadratic models were in better agreement with the measured temperatures than those predicted by the model currently used in Soil Taxonomy. A modification of the Soil Taxonomy model is proposed for soil temperature, that is, to add 2 ^{o}C to the air temperature if the air temperature is less than 22 ^{o}C or to add 4 ^{o}C if the air temperature is equal to or greater than 22 ^{o}C. Such a modification gives a close approximation of the measured soil temperature at 0.5-m depth.

Seasonal fluctuations of herbage production were more correlated to soil-climate at 0.5-m depth than to atmospheric weather or soil-climate at 0.1-m depth. The use of soil-climate properties in Soil Taxonomy is, therefore, justified. The greater impact of soil moisture at 0.5-m depth suggests the location of the soil moisture control section at or below that depth, regardless of soil texture.

It is concluded that if Soil Taxonomy is to be a basis of prognosis of plant response to soil, soil-climate, and other crop production parameters, the diagnostic criteria of soil-climate at 0.5-m depth best serve the purpose.

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CHAPTER I

INTRODUCTION

Soil temperature and soil moisture are important factors not only in soil formation but also for plant growth. They control the rates of weathering, chemical reactions, and transport phenomena in soils (Gerasimov, 1974; Demolon, 1952; Pouquet, 1966; Duchaufour, 1978; Buol et al., 1980; USDA, 1975; France, 1981). They also control the rate of germination, seedling growth as well as plant nutrient uptake (Knoll et al., 1963; McBee et al., 1968; Almarras et al., 1964; Jones and Mederskis, 1963; Moody et al., 1963; McLean and Donavan, 1972; Porter and Moraghan, 1975; Willis et al., 1959; Wijk et al., 1959). The term soil-climate used in this study refers to soil temperature and soil moisture.

Because temperature and moisture can be measured in soil, they are considered to be soil properties in Soil Taxonomy, the U. S. system of soil classification. The difficulties in obtaining soil-climate data are, however, limitations for their use as differentiating criteria (Young, 1976).

In Soil Taxonomy, soil temperature is measured at a depth of 0.5 m where its fluctuation is minimal. Such data are scarce, however, and the common practice is to estimate the mean annual soil temperature by adding 1 ^{o}C or 2 ^{o}F to the mean annual air temperature (USDA, 1975; Smith et al., 1964). The difference between the air and soil temperatures, however, can be greater than indicated, for example, in the colder regions of the world (Smith et al., 1964). A difference of 2 ^{o}C or more is also cited by others to relate these two temperatures (Toy et al., 1978; ICOMMORT, 1979; Uehara and Gillman, 1981). There is a need, therefore, of more constant predictive models that can provide first approximation of soil temperature.

Soil moisture is also important in soil forming processes and plant growth, and it is defined in terms of either the level of ground-water or the presence or absence of water held at a tension of 1.5 megapascal (MPa) in the moisture control section over a specified period of time. Although the depth of the moisture control section is related to factors such as soil texture, little is known about its relation to crop performance.

The objectives of this study are:

(1) to develop predictive mathematical models for soil temperatures at 0.1- and 0.5-m depth, using a minimal set of environmental factors,

(2) to develop functional mathematical equations relating relative pasture grass response to the soil-climate environment as well as to atmospheric weather, and

(3) to evaluate the present soil-climate criteria of Soil

Taxonomy and to propose alternatives, where needed, for a better identification and interpretation of soil-climate in relation to plant growth.

CHAPTER II

LITERATURE REVIEW

2.1 Factors Affecting Soil Temperature

2.1.1 Solar Radiation

Soils receive some heat supply from exothermic chemical reactions within the soil and from the conduction of heat from deeper strata within the earth (Richards et al., 1952). Solar radiation, however, is the main source of energy determining the thermal regime of soils and plant growth. The earth's surface is warmed by radiation from the sun which has an effective temperature of 6000 ^{o}K while the resultant earth temperature is of the order of 300 ^{o}K (Hillel, 1980). Not all of the incoming solar radiation, therefore, reaches the earth's surface. The rate at which radiation is received at the earth's atmosphere is known as solar constant. The value of 1.354 KW/m^2 normal to the direction of the radiation is used in the International Pyrheliometric Scale of 1956 (U. S. Dept. of Commerce, 1978).

Because more than 99 percent of this solar energy is contained in the wavelengths between 0.3 and 4 micra, solar radiation is referred to as short-wave radiation (Chang, 1968). Much of the solar energy is depleted by selective absorption of water vapor and gases, scatter by air molecules and small solid and liquid particles, and reflection outward to space by larger particles and cloud surfaces. The effective net radiation reaching the earth's surface constitutes the global radiation.

This global radiation is further partioned into reflected radiation and absorbed energy which is utilized in heating the soil and the air above the soil (sensible heat) as latent heat of evaporation and effective long-wave radiation (Baver et al., 1972).

2.1.2 Physical Law Governing the Change of Soil Temperature

Law of Heat Conduction--Soil temperature varies continuously with the periodic succession of days and nights and of summers and winters (Hillel, 1980). Soil temperature is influenced by external and internal factors. The external influences include irregular episodic phenomena of cloudiness, cold or warm waves, and rainstorms of periods of drought. The internal factors such as soil properties also influence soil temperature owing to temporal changes in reflectivity and thermal properties due to alternating wetting and drying, and the variation of these properties with depth.

Soil temperature varies horizontally and vertically depending upon the amount of net radiation received. The horizontal variation is small but the vertical variation is appreciable. Smith et al. (1964) estimated the soil temperature fluctuation to be small at 0.5-m depth, while Chang (1958) found that, in the absence of groundwater, seasonal fluctuation of soil temperature at a depth of 20 m in Alaska, 15 m in mid latitudes and 20 m in the tropics.

When heat is supplied to or withdrawn from soil surfaces, the rate at which a soil layer is warming or cooling follows the law of heat conduction where the rate of vertical heat flow per unit cross-sectional area is proportional to temperature gradient (Baver et al., 1972; Hillel, 1980; Priestley, 1959):

$$H/BDxc = -K(dT/dZ)$$

where H = vertical heat flux, BD = bulk density, C = specific heat, dt/dZ = temperature gradient, and K = thermal diffusivity, a property of the medium in question. According to Priestley (1959), air and soil have different thermal diffusivity. The two media compete for the heat received during the day and compete as providers of the heat radiated from the surface at night. The more successful competitor will be the one which is able most readily to conduct heat to or away from the surface. After some mathematical manipulations, the author summarized that the response of the two media follow four rules:

(1) heat flux is proportional to the thermal diffusivity,

(2) heat flow into or out of each medium is related to the ratio of their conductive capacities,

(3) temperature change in the media varies as the total

heat supply (or loss) and inversely as the sum of the two conductive capacities, and

(4) depth varies as the square root of the thermal diffusivity.

Damping Depth and Thermal Diffusivity--According to Hillel (1980), the soil temperature at a given depth (z) and time (t) can be estimated mathematically as follows:

$$T(z,t) = \overline{T} + A_o (\sin(wt - z/d))e^{z/d}$$

where T(z,t) = soil temperature at depth z and time t, $\overline{T}$ = average soil temperature assumed to be constant at infinite depth, A_o = soil surface temperature amplitude fluctuation, w - radial frequency, and d = damping depth. According to the equation, the amplitude of the temperature variation at the depth z is smaller than that of soil surface by a factor $e^{z/d}$ and there is a delay of -z/d in the temperature peak.

The damping depth d is a characteristic depth at which the soil surface amplitude is reduced to e^{-1} = 0.37 time its value. The damping depth is associated with the soil thermal properties and the radial frequency of the temperature fluctuation (w) through the relations:

$$d = (2K/cw) = (2D_T/w)^{1/2}$$

where K - thermal conductivity, c = heat capacity, and D_T = thermal diffusivity. According to these relations, the damping depth is inversely proportional to the radial frequency and hence varies directly with the period of the temperature variation considered. For example, the damping depth is $365^{1/2} = 19$ times larger for the annual variation than for the diunal variation in the same soil (Hillel, 1980).

The damping depth varies, however, with the thermal properties of a soil which in turn vary with soil mineral composition, soil moisture, and aeration. Priestley (1959) recapitulated the values of the thermal properties of different media; these data show the thermal admissivity to be considerable between dry and wet soils. For example, the response of dry sand is more than four times that of wet sand, although the differences vary with factors such as soil compaction and vegetation cover (Priestley, 1959).

Sellers (1972) indicated that the thermal diffusivity of most soils vary from 0.001 to 0.012 cm^2/sec. Based on this value, he estimated the depths of temperature penetration to be 20 to 80 cm for the daily cycle and 5 to 20 m for the annual cycle. He also showed that, for a given thermal diffusivity, the damping depth is smaller for the daily cycle than for the annual cycle. For example, he found that for a thermal diffusivity of 0.004 cm^2/sec, the damping depths were about 0.1 and 2.0 m for the daily and annual cycles, respectively. According to the values listed by Priestley (1959), these values approximate the damping depths for the daily and annual cycles in a sandy clay soil with 15 percent moisture.

In Hawaii, Ekern (1966) found that the thermal diffusivity of the Wahiawa soil (Tropeptic Eutrustox, clayey, kaolinitic, isohyperthermic) varied between 0.002 and 0.0025 cm^2/sec. If these values are assumed to be representative of the thermal diffusivity of the soil in Hawaii, then, the damping depth (d) can be estimated by its relation with soil thermal diffusivity (D_T) and the radial frequency (w). The radial frequencies are 7.27 x 10^{-5}, 2.4 x 10^{-6}, and 2.0 x 10^{-7} rad/sec for the daily, monthly, and annual cycles, respectively. Assuming the value of 0.0022 cm^2/sec as thermal diffusivity, the damping depth will be 7.8, 42.8, and 148.3 cm for the daily, monthly, and annual cycles, respectively.

Hanks et al. (1971) used a numerical approach to solve the partial differential equation that describes soil temperature as a function of time and depth. They found that this physically-based model predicted soil temperature within 1.0 ^{o}C when measured soil thermal properties were used for the computation. The difference between the actual and predicted values was only 0.1 to 0.8 ^{o}C when the thermal diffusivity varied with depth but assumed to be constant with time. Such a difference amounted to 1.5 ^{o}C when the thermal diffusivity was assumed to be constant at 0.2 cm^2/min. The largest difference of 1 to 3.1 ^{o}C was found where the thermal diffusivity was set to 0.45 cm^2/min. This difference was attributed to a large influence of the measured boundary conditions near the surface on the estimated temperature. Improvement of these conditions led to a difference of 2 °C for a three-day periodic measurement. The authors added that this result applied to slowly-drying soils but may not be so for rainy periods or irrigated areas. A reason is that air temperature does not rise above 32.2 to 32.9 °C through contact with well-water terrain (Priestley, 1966).

Hanks et al. (1971) concluded that the difference between the estimated and actual temperatures would have been greater than 2 °C had the soil been bare or dry due to greater variation of temperature at the soil surface. Such findings are in agreement with Gupta et al. (1981) who used the same numerical method and found that the differences were larger when soil temperatures were greater than 28 °C. The authors added that the model would be useful where daily temperature is required and an error of $\pm$ 3 °C could be tolerated.

The model, therefore, is not suitable for the purpose of Soil Taxonomy which requires annual and seasonal temperatures to characterize the soil temperature regime. For example, an error of 3 °C will introduce too much uncertainty for detecting the difference of 5 °C between summer and winter temperatures.

2.1.3 Other Factors Affecting Soil Temperature

Variation in soil temperature is principally due to the amount of solar radiation and the thermal properties of the medium. Thus, any factor affecting that amount and these properties will also influence soil temperature. For example, goegraphic influences such as latititude and exposure directly affect the amount of heat received and the albedo. Large bodies of water also act as a stabilizer of temperature. On the other hand, biophysical factors such as vegetation or any other soil cover prevent excessive heat in soil during the hot season when they intercept a considerable amount of incoming energy. The vegetation can also insulate the soil and reduce the rate of heat loss from the soil during the cool seasons. Soil properties such as soil color changes the absorbity of the ground, while soil texture and porosity influence the thermal conductivity, and soil moisture alters the heat capacity.

Man can do little to change weather conditions at large scale. He can, nevertheless, adjust agricultural practices so as to create the most advantageous conditions for crop production on a small scale. He can (1) mulch to regulate the incoming or outgoing energy, (2) till or drain to decrease the thermal conductivity and thereby increase soil temperature, and (3) irrigate to increase the thermal conductivity and evaporation of water and thereby decrease the soil temperature.

2.2 Effect of Temperature on Plant Growth

Crop and soil scientists have long shown interests in studying the relationship between plant growth and temperature. Air temperature, as distinguished from soil temperature, has traditionally been used, but in recent years, there has been increasing in soil temperature.

In a field experiment on yield response to artificial warming of soil, Rykbost et al. (1975), found that emergence of several crops occurred one to three days earlier in heated plots where vegetative growth was faster and dry matter production was higher than in unheated plots. The authors concluded that soil heating can overcome certain yield limiting factors associated with unheated soils and show response in such soils, but soil heating did not increase yields when optimum growing conditions exist. Because air temperature was not controlled, the authors were not able to correlate yield response to the air temperature, growing degree days, or heat units.

In a greenhouse experiment in which air temperature, relative humidity, and light intensity were controlled, Walker (1969), on the other hand, found the effect of one-degree increments in soil temperatures. He observed changes in the growth and nutritional behavior of maize amounting to an average increase of 20 percent per degree when temperature varied from 12 to 26 ^{o}C. The amount and direction of the change in growth due to change in temperature depend on the temperature selected as the starting point. If the starting point is below the optimum temperature, an increase in soil temperature would result in an increase in growth. On the other hand, if the starting temperature is above the optimum, an increase in temperature would depress growth.

Sprague (1943) studied the effect of temperature on eight grass species including one tropical variety, in a controlled environment using alternating temperature treatments of 4-12, 12-21, 21-29, and 29-38 ^{o}C. The results indicated that the species differed widely in their germination and dry matter production at different temperatures. The emergence and growth of sudan grass, which is known to be a warm climate plant, increased as the temperature increased. Germination of some species such as Kentucky bluegrass, colonial bentgrass, timothy, orchard grass, and Landino clover, however, was severely reduced by the 29 to 38 ^{o}C treatment. Meadow fescue and bromegrass, while germinating fairly at the 29 to 38 ^{o}C, on the other hand, made little growth at that range of temperature. The lowest temperature treatment reduced emergence and growth in all species.

The above results are in agreement with those of many other workers such as Nielsen et al. (1961), and Sosebee and Herbel (1969) who found a significant interaction between species and temperature. Whitney (1974a, 1974b) and Morrow and Power (1979), on the other hand, found that cool-season grasses grew better at low temperature than did warm-season species. Wehner and Watschke (1981) established differential heat tolerance of 22 varieties of pasture grass, while Young et al. (1981) found significant difference in germination response to temperature between eight varieties of grass.

2.3 Location of Soil Moisture Control Section (SMCS)

2.3.1 Factors Influencing Soil Moisture Regimes

On large land areas of the world, much of the agriculture depends on rainfall for their source of water. The moisture content of a soil, however, also depends on landscape positions because the soil may receive water from sources other than rainfall. The soil moisture regime, therefore, is only a partial function of the climate (USDA, 1975).

Although there is a large amount of common knowledge about the soil moisture variations within soils over time, there is only limited literature relating to the determination of soil moisture regime and soil moisture control section, as defined in Soil Taxonomy. Soil moisture content depends primarily on soil texture and soil hydraulic conductivity. The effect of organic matter in soil moisture storage capacity in soils of different textures has also been reported by Jamison and Kroth (1958), Barthelli and Peters (1959), and Foth (1984). In addition, there is a need to consider other factors such as mechanical impedance, drainage, root development, conductivity, temperature gradient, and pore size and distribution (Barthelli and Peters, 1959; Lund, 1959).

In Soil Taxonomy, the total water holding capacity rather than the effective plant available water is considered. Such consideration may be misleading because much of the total water may not be available to the plants. Because the 0.3-bar water may or may not be representative of the field capacity in the various soil textures, Zobeck and Daugherty (1982) have recommended the use of the -50 to -100 cm water content as the value of the field capacity, primarily in medium-textured soils.

2.3.2 Evaluation of Soil Moisture Regime Criteria

A neutron probe was used by Nichols and Stones (1970) to evaluate the soil moisture regimes in previously classified soils. The cumulative days when the soil moisture tension was below 1.5 MPa were counted and found to be closely correlated with the annual precipitation. A noticeable disadvantage in that study was that soil moisture measurements were made at 15-cm depth increments so that a dry section could be counted only when all the 15-cm layers were dry.

In another study of evaluation of soil moisture regime criteria, Thomas et al. (1970) used a combination of vegetation indicators and climate data to differentiate a xeric from a udic zone. Soil moisture tension was inferred from gypsum block inserted into the soil beneath the crown of a tree, and the SMCS was estimated using soil-water release curve. The result of their study based on plant indicators correlated with those based on the soil-moisture criteria of Soil Taxonomy.

Jensen (1984) observed an aridic soil moisture regime within a cryic soil temperature regime, a combination not presently observed in Soil Taxonomy. A new aridic subgroup of Cryoborolls was thus recommended by him to aid in the more accurate classification of Western wildlands.

Jensen (1984) further related grass growth to temperature and moisture regimes. He found that counting the growing period from the day when the soil temperature at 0.5-m depth was more than 5 ^{o}C to be a valuable criterion. He also concluded that owing to the short growing period, it was important that the dates associated with this period to be documented.

Except for the study of Zobeck and Daugherty (1982), most of the work on the soil moisture regime use the criteria as such rather than dealing with the solution to its problems. Except for the report of Jensen (1984), most of the studies also do not relate the criteria to plant growth. For the purpose of soil classification and soil survey interpretation, the differentiating criteria should be based either on its influence on soil genesis or on plant growth. Thus far, most of the evaluation of soil-climate criteria of Soil Taxonomy have failed to address these issues.

2.4 Effect of Soil Moisture Regime on Plant Growth

Much research has been conducted to study the effect of soil moisture on plant growth in controlled and non-controlled environment. Most of these studies reported focus on plant response to some arbitrary soil moisture level and/or time interval, or a specific phenological stage of growth.

In a greenhouse experiment, Herbel and Sosebee (1959) found that emergency of boer lovegrass was reduced unless moisture was available at all times, and survival of emerging black grama was greatly reduced by reduction in moisture at high temperature regime. There was a significant moisture x species x temperature interaction for germination, shoot heights, root length, and average weight per seedling. A reduction in soil moisture a day after planting was more detrimental to survival than a later reduction. These results are in agreement with those reported by Singh and Alderfer (1965) who found that high soil-moisture stress at any stage of growth of vegetable crops led to a reduction of marketable yield. The magnitude of such a reduction was related to the frequency and duration of the stress during certain stages of growth. These results are also in agreement with those reported by Kezer and

Robertson (1927) who found that earlier irrigations of wheat increased the yield of straw to a greater extent than did the later irrigations. Irrigations of small amounts (25 mm) distributed throughout the growing season gave the best results.

Similar results were reported by Denmead and Shaw (1960) and Robins and Domingo (1953) who found that soil moisture depletion to the wilting point by field corn at certain physiologic growth stages markedly depressed grain yields. Water deficit for periods of one to two days during tasseling or pollination periods resulted in a 22 percent reduction. A period of six to eight days gave approximately a 50 percent yield reduction.

A field experiment in a sandy loam soil by Kilmer et al. (1960) has shown that the yield of landino clover was two times higher when soil moisture was 0.67 bar than when it was 8 bars. By contrast, in a simultaneous field and controlled experiment, Hagan et al. (1957) reported that yield of landino clover grown on a clay loam soil was not affected appreciably until the moisture content of the entire root zone approached the permanent wilting point. These authors pointed out that soil moisture-growth relationships depend not only on plant characteristics but also on soil conditions and climatic factors. Such conflicting interpretations are not uncommon in literature. Zobec (as cited by WRCC-50, 1982) distributed a questionnaire to 57 scientists and only 40 percent could agree on any one soil-climate-vegetation relationship interpretation. Weaver (1924), on the other hand, concluded that grass yield was the product of the influence of soil, air, and water.

For the above reasons, therefore, there is a need to study soil temperature and soil moisture regimes together not only because of the effect of the one on the other, but also presumably because of their interaction effect on plant growth.

Soil temperature and soil moisture are essential elements that go together with soil to produce an agro-system. They should not be separated, therefore, in a study of soil-climate-vegetation relationships. In this connection, Ripperton and Hosaka (1949) and Hosaka and Ripperton (1955) defined five vegetation zones in Hawaii on the basis of rainfall and temperature and they attempted to correlate the zones to the categories of the 1938 U. S. soil classification system. These authors found good correlations between the zones and the great soil group but no evidence of correlations at the lower categories.

In contrast, Pendleton and Shiflet (1982) found the relationship between soil classification and vegetation at the great group level or higher categories to be vague. The relationship, however, was more meaningful at the lower categories. In a study of relationships between soil, vegetation and climate on rangeland, Passey et al. (1982) used relict vegetation and climatic factors to determine range site productivity. Their research results indicated that soil subgroups provided the most meaningful level of soil classification for correlation with broad plant association.

2.5 Differences between C3 and C4 Plant Responses to Environment

Green plants process their own food by photosynthesis. In some pasture grasses, the first stable chemical product is a 3-carbon compound and these species are called C3 grasses. In others, the first product is a 4-carbon organic acid and they are called C4 grasses. The dry matter production of C4 plants is generally higher than that of C3 plants, and the differences in the photosynthetic rates of these plants have been associated with differences in leaf anatomy and carbon dioxide reduction, temperature and photorespiration, light intensity, as well as soil water and nutrients.

2.5.1 Leaf Anatomy and Carbon Dioxide Reduction

The leaf anatomy of the C3 plant shows much less distinct bundle sheath and few chloroplast than that of the C4 plants. The enzyme associated with the carbon dioxide fixation in C3 species is ribulose biphosphate carboxylase (RuBP), whereas the carbon dioxide acceptor in C4 plants is phosphenolpyruvate carboxylase (PEPC).

The PEPC has a high affinity for carbon dioxide and is very efficient in harvesting and converting carbon dioxide into organic acid at a much lower carbon dioxide concentration that RuBP in C3 plants. The activity of PEPC is also higher in the mesophyll than in the bundle sheath cells, whereas the activity of RuBP is higher in the bundle sheath than in the mesophyll cells. In addition, oxygen competes with carbon dioxide for reaction with RuBP, resulting in the loss of carbon dioxide uptake at normal oxygen concentration in C3 plants.

The carbon dioxide compensation point varies from 50 to 100 ppm for C3 plants and 0 to 5 ppm for C4 plants (Salisbury and Ross, 1978). The C4 plants, therefore, have an ecological advantage in high temperature zones where carbon dioxide solubility is reduced (Teeri and Stowe, 1976). As an overall result, the leaf anatomy and PEPC activity in C4 species give a higher photosynthetic efficiency than the C3 species with RuBP activity (Brown, 1978; Galston and Satter, 1980; Salisbury and Ross, 1978).

2.5.2 Temperature and Photorespiration

In both C3 and C4 plants, photosynthetic rate increases with increasing air temperature. The cardinal temperatures for most tropical grasses, however, is at least 10 ^{o}C higher than for temperate grasses (McWilliam, 1978). This difference is generally controlled by differences in photorespiration, carbon dioxide solubilization, as well as mesopjyll resistance to carbon dioxide diffusion.

Photosynthesis in C3 plants increases with increasing temperature up to about 25 ^{o}C by speeding up the enzymatic dark reaction. Further increase in temperature, however, also speeds up photorespiration so that photosynthesis may be lower at about 35 ^{o}C than at 25 ^{o}C. In addition, high temperature increases mesophyll resistance to carbon dioxide diffusion in C3 plants and causes low carbon dioxide diffusion in C3 plants and causes low carbon dioxide solubility. This contributes to an increase in the ratio of dissolved oxygen to carbon dioxide and impairs the photosynthetic efficiency of C3 plants because of oxyten competition.

Photosynthesis in C4 plants increases with temperature up to about 35 ^{o}C and there is little, if any, photorespiration. Higher temperature may, however, cause enzyme denaturalization or stomatal closure and thereby decrease photosynthesis (Galston and Satter, 1980).

2.5.3 Light Intensity

In general, a high light intensity is associated with a high photosynthetic rate up to a light saturation of about 0.18 and 0.6 cal/cm^2 min for C3 and C4 plants, respectively. A light intensity above the light saturation point is, however, wasted and a very high light intensity may photobleach plant chlorophyll. The light intensity at which the rate of carbon dioxide output in respiration is known as light compensation point. It varies with the plant species, temperature, and carbon dioxide and oxygen levels. The light compensation point is higher for sun leaves than for shade leaves (Salisbury and Ross, 1978). Tropical grass species, furthermore. have inherently higher photosynthetic rates than temperate grasses. Under shaded conditions, however, photosynthesis is more depressed in C4 plants than in C3 plants.

2.5.4 Water and Nutrients

According to Turner and Begg (1978), water stress affects leaf enlargement, stomatal closure, and photosynthesis. The leaf enlargement, however, is more sensitive to water deficit than stomatal closure or photosynthesis. A marked reduction in leaf area results from small water deficits with a subsequent decrease in photosynthesis. Stomata do not respond to water stress until a certain critical threshold level has been attained. Water stress, therefore, affects photosynthesis even before the stomata close. Moreover, the influence of water deficit on stomatal closure seems to be a somewhat indirect effect. The stomata open as a result of water uptake and the resulting osmotic relationships that cause the guard cells to swell, and they close when the guard cells lose water (Galston and Satter, 1980).

The stomata do not close until 10 to 15 minutes after a water stress has been applied. They, therefore, do not lose water directly in response to water deficit but respond to a messenger, probably abscisic acid (Salisbury and Ross, 1978). The abscisic acid forms in response to stress or unfavorable condition and efficiently controls the guard cell action, because application of extremely low concentrations cause stomata to close (Salisbury and Ross, 1978). Owing to its key position in the pathway for gaseous exchange between the plant and atmosphere, stomata regulate water loss and carbon dioxide uptake. Water deficits that cause stomatal closure, therefore, depress photosynthesis.

Lack of water in plant tissue can also affect the translocation and distribution of assimilates, the loading and unloading of sieve elements, and/or the movement of assimilates in the phloem (Turner and Begg, 1978). For example, "photosynthetic constipation" may occur if photosynthate products are not translocated away and the lack of a sink may slow down the source, and hence, the photosynthetic rate.

The water use can also markedly influence the uptake of soil nutrients and vice versa. Chinene (1983) found that the uptake of N, P, and K by maize was higher under irrigation than under imposed water stress. He added that low N treatments were more affected by drought than the high N treatments. The amount of water extracted by a high

P and high N treatment was greater than that extracted by a low P and high N treatment. Chinene attributed these differences to variation in rooting depth and density and plant vegetative size.

An important difference between C3 and C4 plants is their water use efficiency (WUE), the dry matter produced per unit of water used in evapotranspiration. Turner and Begg (1978) reported that the WUE of C4 grasses is as much as twice that of C3 grasses. Such a difference increases with temperature over the range of 20-33 ^{o}C. The authors attributed the higher WUE of C4 species to (1) higher photosynthesis and growth rates, particularly under high light and temperature and (2) higher stomatal resistance resulting in a relatively greater reduction in transpiration than photosynthesis, particularly under low light conditions.

Another characteristic difference between C3 and C4 grasses is their N use efficiency (NUE), the biomass production per unit of N in the plant. Brown (1976) reported that C4 plants have a greater NUE than do C3 plants. He attributed the presence of the greater NUE of C4 species to (1) the compartmentation of PEPC and RuBP in the mesophyll and bundle sheath tissues, respectively, and (2) the higher relative growth rates of C4 species. As an implication of their higher NUE, C4 plants have an adaptative advantage over C3 plants, particularly in most tropical soils and in arid zones where soil N content is low. Brown (1976) concluded, therefore, that the percentage of C4 grasses tends to increase where the soil N tends to decrease and where the climate becomes warmer and drier.

The C3 and C4 grasses may be found under a diversity of climatic conditions, but C3 grasses are most abundant in cool environments whereas C4 grasses are naturally widespread in hot habitats. Terri and Stowe (1976) found that the relative abundance of C4 grasses in North America was positively correlated with the July minimum temperature and the mean annual degree-day and negatively associated with the length of annual freeze-free period. They concluded that high minimum temperatures were most favorable to the presence of C4 grasses. On a small scale, however, the distribution and growth of C3 and C4 grasses are increasingly influenced by other factors such as the degree of shading (Rhodes and Stern, 1978), rainfall or availability of soil moisture (Turner and Begg, 1978), and soil fertility (Brown, 1978; Andrew and Johnson, 1978).

2.6 Some Considerations on Modeling Procedures

Estimations of yield based on management, soil, and climatic factors have generally been made by use of mathematical models. A mathematical model is a functional relationship between a dependent observable plant response, such as growth, weight, etc., and the pertinent variables influencing the plant. The model serves to identify those variables which need to be evaluated (Walker and Splinter, 1971). A mathematical model can be empirical, mechanistic, or a combination of both (Russo and Dethier, 1978).

2.6.1 Empirical Models

Empirical models are statistical models constructed by use of experimental data and by use of multiple regression techniques. Such models are aimed at the redescription of data and the whole system response, regardless of how it happens. Statistical analysis has long been a useful tool in assessing the effects of climate on vegetal production (Baker and Horrocks, 1973, 1976), and much of the early modeling research on agricultural production systems used this tool as a modeling technique (Curry et al., 1975). As early as 1914, Smith (1914), in studying the effect of weather effect on corn yield, reported a statistical study showing that July precipitation was the critical weather factor in corn yield. Odell and Smith (1940) described the expected yield levels in different soil types while using several levels of management and various combinations of climatic factors. These researchers pointed out the need for assigning production value to the soil and illustrated the relationships between climatic variables and crop yields.

The multiple regression technique has been used by many crop and soil scientists such as Culot (1981), Kourouma (1979), Estrella et al. (1975), Turrent and Laird (1975), Silva (1974), Toy et al. (1978), and Voss et al.

(1970) to establish a functional relationship between a physical or a biological response and some hypothetized independent causal factors. The different technical aspects of model building process has been discussed by Drapper and Smith (1966), Snedecor and Cochran (1980), and Allen and Cady (1982). These authors pointed out some of the most frequent problems encountered in empirical model building process and indicated statistical technique to solve them. Among these are variable selection, multicollinearity between independent variables, use of indicators or dummy variables, and selection of the best predictive model. A general form of an empirical model may be expressed as follows:

$$Y = b_o + a_iW_i + b_iS_i + c_iW_iS_i + d_iZ_i$$

where Y is the response, dependent variable; W_i are the weather variables such air temperature, rainfall, solar radiation, wind speed; S_i are soil properties such as texture, depth, nutrient levels, soil moisture, soil temperature, etc.; W_iS_i are the interactions between weather and soil variables; Z_i are dummy variables that represent qualitative variables such as sites or varieties that do not have continuous values; b_o is the intercept, the expected yield when the input values are zero; and a_i, b_i, and c_i, and d_i are estimated partial regression coefficient. Second order or third order models or models involving square root transformation can be used to express the response. The choice and use of the order must be based on the form of the curve after plotting the original data (Drapper and Smith, 1966; Allen and Cady, 1982).

Of course, potential factors influencing a given system are numerous, of which many may contribute little to improve the prediction in the presence of other variables. Many independent variables may be so highly correlated that their individual effect on the dependent variable are not discernible (Heady and Hexem, 1978). In such a condition, estimated regression coefficients are unrealistic and tend to cause high standard error (Heady and Dillon, 1961; Drapper and Smith, 1966). When two independent variables are highly correlated, only one should be selected as candidate for inclusion in the model. The choice may be on a prior basis and the level of correlation with the dependent variable (Heady and Hexem, 1978; Culot, 1981). Culot (1981) constructed a correlation matrix as a guide to the choice of those variables to be selected as candidate for inclusion in the model.

Several regression procedures have been described for developing empirical models (SAS, 1982a, 1982b; Allen and Cady, 1982; Snedecor and Cochran, 1980; Drapper and Smith, 1966; Heady and Dillon, 1961; Cady and Allen, 1972). Laird and Cady (1969) evaluated three of these procedures, namely, the stepwise backward elimination, and agronomic approach. The authors found that based on the residual sum of squares, the backward elimination model was better than the stepwise, which in turn was better than the agronomic approach. However, if the criterion used was the ability of the model to predict response for new sets of data, measured by the predictive mean square, the agronomic and stepwise models were best.

Despite the existence of statistical techniques that premit the choice of simplest model for a given level of predictive capacility, some workers have felt that statiscal modeling may not be scientifically challenging and may not contribute to the solution of the problem. Laird (1977) pointed out that empirical models are not satisfactory because, among other reasons, (1) the polynomial equation does not adequately reflect the true nature of the response variables to the input variables; (2) all of the site variables are not included in the model; and (3) estimated regression coefficients are biased due to collinearity between independent variables. Baker and Horrock (1976) and Walker and Splinter (1971) added a fourth reason. This was the inability of the investigator to precisely measure the vast number of variable involved and interpret their complex interaction, which have no physiological meaning. Consequently, recent years have witnessed much model building effort toward mechanistic models.

2.6.2 Mechanistic Models

Mechanistic models, also known as simulation models, are based on some existing theory of nature applicable to the phenomenon under study. They are valuable tools for predicting, understanding, and providing insights into the origins and effects of the process involved.

The objectives of simulation models have been extensively examined by Thornley (1976, 1977), while the philosophy and strategy of model building have been studied by Russo and Dethier (1978) and Dent and Blackie (1979). The misconceptions on modeling have described by Passioura (1973), Reynolds (1979), and Sakamoto and LeDuc (1981). Computer modeling has become an increasingly popular technique not only because it provides a synthetic and practical tool for analysis and prediction but also because our knowledge of plant processes and their response to environment involve complex interactions of the soil-plant-atmosphere continuum that are not fully understood (Sakamoto and LeDuc, 1981; Landsberg, 1977). The advent of digital computer gives us a chance to deal with that complexity (Passioura, 1973).

This, however, does not necessarily connote widespread acceptance because many workers remain yet skeptical of simulation modeling and question the aims of modelers and the goals of the models themselves. There is a general acceptance that models may be useful tools in scientific research but, like other tools, they have certain limitations that govern their proper application.

The numerous limitations, misconceptions, misuses, and misapplications of simulation model, the too small a chance of success to obtain an acceptable model, the time and cost required to calibrate the model, and particularly the cumbersome and subjective curve fitting technique used in the model building procedure led Passioura (1973) to the conclusion that "If research is the art of the soluble, crop simulation is at present, the art of the plausible. As such, it is closer to metaphysic than it is to science."

In connection with this, Shannon (1975) pointed out three major limitations of simulation models. They are (1) simulation can appear to reflect accurately a real situation when, in truth, it does not; (2) simulation is imprecise and we cannot measure the degree of imprecision; and (3) simulation results are numerical and there is the danger of attributing a greater degree of validity to the number than is justified. Gordon (1975) concluded that in many instances, the analytical solution is preferable. Unfortunately, complex mechanistic models have still been used where simple empirical models would have sufficed (Reynolds, 1979). The author added that there if often no desire or need to understand actual mechanism responsible for the predicted behavior of the system and that in such a condition empirical models should be used. Sakamoto and

LeDuc (1981) pointed out that empirical models can be used to address the large area crop estimation and provide an overview of the impact of climatic fluctuation. Toy et al. (1978) showed that prediction of soil temperature with reasonable accuracy was possible using simple linear models. The distinction between the various kind of models is the degree to which the process involved are described (Sakamoto and LeDuc, 1981). Reynolds (1979) added that any model represents only one of the many alternatives that could prove equally successful, inasmuch as the relationship between model complexity and predictive capacity and/or enhanced insight is not clear and seems unwarranted at present. Sakamoto and LeDuc (1981) concluded, however, that model development should clearly define the users and objectives of the model.

It follows that mathematical modeling may be a useful valuable approach for problem solving, but neither empirical nor mechanistic models are a panacea for all problems. We must recognize, however, as expressed by Shannon (1975), that the development and use of models are still, to a large extent, an art rather than science; and as such, it is not so much the technique that determines success or failure but rather how the technique is used.

CHAPTER III

MATERIALS AND METHODS

The field work was conducted on the island of Maui, Hawaii, in order to study the relationships between soil temperature and environment on one hand and the relationships between pasture grass performance and soil-climate on the other. The results were further used to evaluate the soil-climate criteria of Soil Taxonomy in relation to plant growth.

3.1 Characteristics of the Area of the Study

3.1.1 General Information

Geographically located between $20^{o}02'$ and $20^{o}35'$ north latitude and $155^{o}59'$ and $156^{o}42'$ west longitude (Fig. 3.1), the island of Maui emerged from the Pacific Ocean as a result of a successive eruptions of two volcanoes, the West Maui volcano and the East Maui volcano or Haleakala (Stearns and Macdonald, 1942). The domes of the volcanoes, now dormant, are connected by a flat isthmus. The topography of the island varies from flat coastal plains where temperatures are high and rainfall scant to steep slopes where temperatures are low and rainfall abundant. The soils, developed from volcanic ash and material weathered from basic igneous rock, vary from relatively young Inceptisols (Andepts) at the higher altitudes to Mollisols and Oxisols at middle and lower altitudes (Table 3.1).

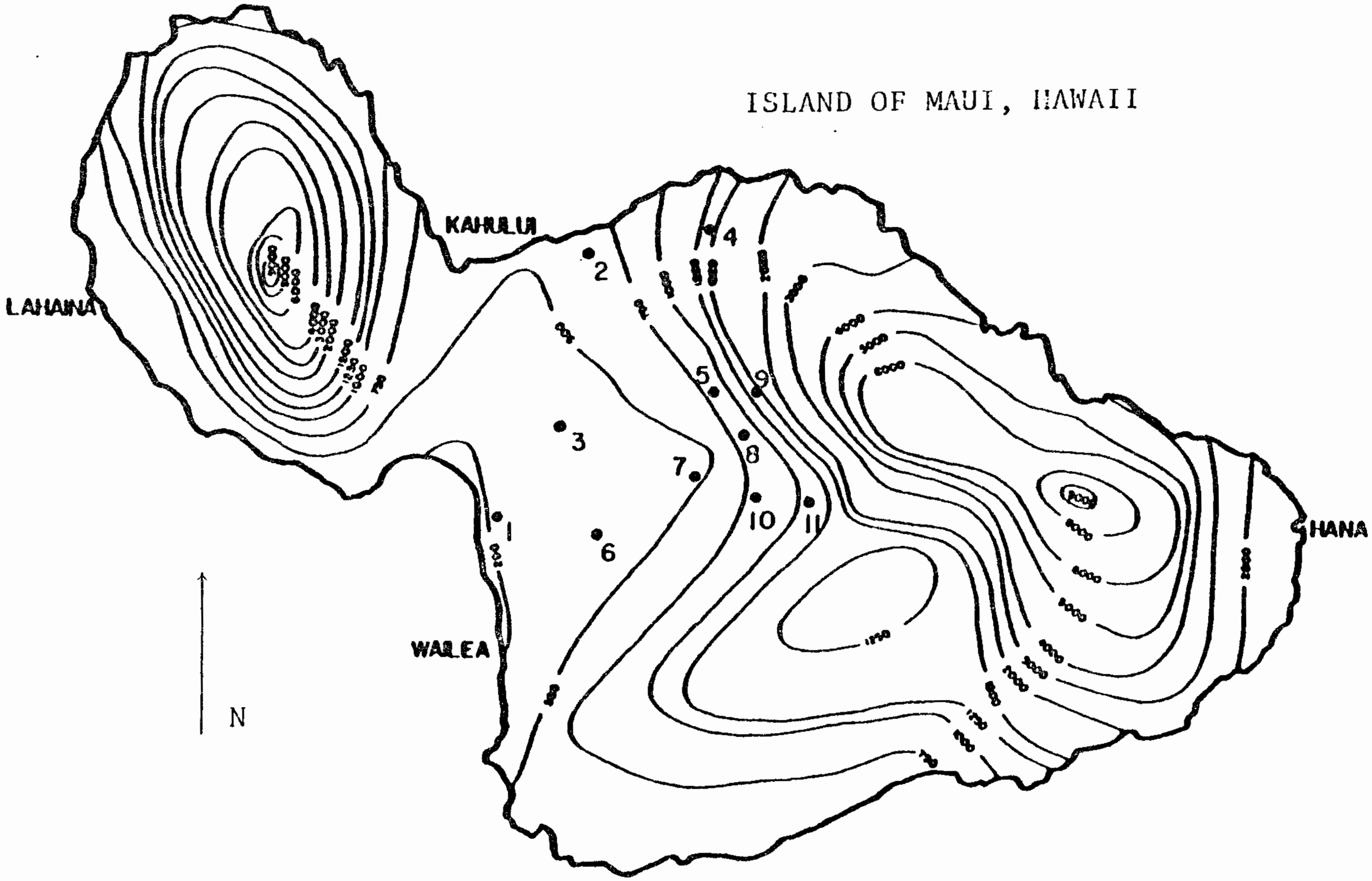


Figure 3.1. Distribution of Rainfall (in mm) and Location of Study Sites.

Remarks: Dots and corresponding numbers refer to weather stations cited in Table 3.1.
Source: Dept. of Land and Natural Resources, State of Hawaii.

Natural vegetation cover varies from xerophytic shrub with few or no trees at the lower elevations to closed and open forests at the higher elevations (Hosaka and Ripperton, 1955), with the understory being a variety of grass communities.

The maximum length and width of the island are about 80 and 43 Km, respectively. The occurrence within such short distances of such a diversity of topography, climate, soils, and subsequent vegetation makes Hawaii a natural laboratory for research on climate and plant response to climate (Britten, 1962).

3.1.2 Climate and Soil Erosion Hazards

The wind flow patterns, temperatures, and rainfall are intimately related to the orography of the study area.

Elevation and Temperature--The altitude varies from sea level to about 1620 m near the summit of Haleakala mountain. The temperature decreases with altitude, and according to Stearns and Macdonald (1942), the temperature decreases about 5 to 6.7 ^{o}C for each 1000 m increase in altitude. These authors found the mean annual air temperature to vary from about 24 ^{o}C at 66-m altitude to 9 ^{o}C at 3220 m.

Ekern and Yoshihara (1977) constructed the sky chart of solar elevation and azimuth with season in Hawaii. Their data show that solar radiation increased progressively from winter to the spring months. For example, the

Table 3.1. Location and Description of the Sites (Soil-Climate Project, 1983).

Location	Elev. (m)	Mean Ann.Rain (mm)	Dominant Vegetation	Soil Family
Kihei (1) *	37	250	Buffel grass,	Torroxic Haplustolls, fine, kaol., isohyperthermic.
Sugar-Paia (2)	61	500-750	Sugarcane	Typic Torrox, clay, kaol., isohyperthermic.
Sugar-Waiakoa (3)	189	250-500	Sugarcane	Torroxic Haplustolls, fine, kaol., isohyperthermic.
Pine-Haliimaile (4)	345	1500	Pineapple	Orthoxic Tropohumults clayey, oxidic, isohyperthermic.
Pine-Pukalani (5)	495	750	Pineapple	Ustoxic Humitropepts fine, kaol., isothermic.
Pasture-Waiakoa (6)*	366	400	Buffel grass, Poa	Torroxic Haplustolls, fine, kaol., isohyperthermic.
Nakamura Farm (7)	720	500	Vegetables	Torroxic Haplustolls, fine, kaol., isohyperthermic.
Pasture-Kekoa (8) *	870	750	Kikuyu, rattail	Oxic Dystrandepts, medial, isothermic.
Forest-Olinda (9)	1110	1300	Slash pine	Entic Dystrandepts, medial, isomesic.
H.Hashimoto Farm(10)	1155	750	Vegetables	Typic Eutrandepts, medial, isothermic.
Pasture-Puu Pahu (11) *	1620	1000	Fescue, Yorkshire fog, sweet vernal, kikuyu, rattail	Typic Dystrandepts, medial, isomesic.

* Pasture grass study sites.
( ) The number between parenthesis is the station location on Figure 3.1.

solar radiation in Maui increased from 364.8 cal/cm^2 day in November to 564.3 in May. Variation in temperature may follow similar trend.

Wind Flow Patterns and Speed--The island of Maui lies in the trajectory of the northeasterly trade winds, which dominate the Hawaiian weather much of the year. They are interrupted in the fall and winter months, however, by southerly winds which last only a few days at a time (Stearns and Macdonald, 1942). The high land elevation at Haleakala is, however, a barrier that alters the northeast tradewinds and causes prevailing southwestly winds up the west slope and easterly winds along its southern coast. The area of study is located on the western slopes. In central Maui, wind velocities average 7.2 m/sec for long term observation and 5.8 m/sec for short term observation in August, period of optimum tradewind conditions (Daniels and Schroeder, 1978). The wind velocity varies, however, with the time of the day (Steven, 1979). Kimberlin et al. (1977) do not include Hawaii as a state with major wind erosion problems. However, wind power, a key to erosion potential is currently exploited for electrical generation and does become a problem in a number of Hawaiian sites.

Rainfall, Soil, and Erosion Hazards--Most of the rainfall is of orographic origin due to the interaction between tradewinds and other winds against the mountains. The amount and distribution of rainfall are determined by elevation, exposure to the prevailing wind and local topography. The windward areas, dominated by the trades during most part of the year, receive heavy rains, whereas the leeward areas receive less precipitation, most of which is irregular (Wentworth, 1955; Britten, 1962). The amount of rainfall, in either case, decreases with decreasing altitude. The isohyet map prepared by the Department of Land and Natural Resources (State of Hawaii) in 1984, shows that the mean annual rainfall varies from 1500 mm at the higher altitudes to 250 mm near the sea level. Rainfall erosion hazard varies accordingly.

The map of rainfall erosion index for Hawaii shows that the erosion index on Maui decreases with decreasing altitude in the study area. These index values vary from 190 at the higher altitudes to 150 at the lower altitudes (USDA, 1978). This is in agreement with data compiled by Langbein and Schuum (1958) who found that sediment yield per unit area increased as effective precipitation increased, up to about 305 mm of effective rain. Above this amount, erosion hazard decreased because of a concomitant increase of vegetation density. The study did not include either topographic or soil factors.

The study area is characterized by abundant rainfall, steep slopes, open forest, and volcanic soils at the high altitudes. Serious soil erosion hazards exist, therefore, in that portion. Erosion hazards exist also at low altitudes because of sparse plant density, particularly at the beginning of the rainy season.

3.2 Experimental Design

3.2.1 Soil-Climate Study

Using existing soil survey maps and with much field work, eleven sites with a wide range of environmental factors were selected along the western slopes of Haleakala mountain in a climosequence extending from low altitude (36 m) to high altitude (1620 m). Campbell Scientific CR21 microloggers were installed at each site to monitor the air and soil-climate environmental factors. The measurements included air temperature at 2.0-m height, soil temperatures at 0.1 and 0.5-m depth, soil moisture at the same depths, relative humidity, rainfall, and solar radiation. Soil temperatures were measured in soils without canopy. The advantages and inconvenience of using such computerized weather stations have been outlined by Fujioka and Fosberg (1981). The accuracy of the data, logistical considerations of the equipment, and the use of the various sensors are discussed by Campbell and Tanner (1981). Although the experiment was initiated during the summer of 1983 and it continues to the present, only one year's weather data were used to describe the regression equation to predict soil temperature from the air temperature, unless otherwise indicated.

3.2.2 Pasture Grass Response to Soil-Climate

Four of the 11 sites listed in Table 3.1 and shown in Figure 3.1 were used to study pasture grass response to soil-climate. These sites were selected because they represented a range of ecological zones in a climosequence with variation in soil temperature and rainfall. At low altitude, at Kihei and Waiakoa, buffel grass (Cenchrus cialaris) was the dominant species representing 98 percent of the grass community. At the middle altitude, at Kekoa, kikuyu grass (Pennisetum clandestinum) accounted for 95 percent of the grass community, while at the high altitude, at Puu Pahu, a mixture of fescue (Festuca sp.), sweet vernal (Anthoxanthum odoratum), rattail (Sporobolus capenses), Yorkshire fog (Holcus lanatus), white clover (Trifolium sp.) as well as kikuyu constituted the grass community. Buffel grass at the low altitude and kikuyu grass at the middle altitude are C4 plants whereas the most dominant species at the high altitude are C3 plants. The corresponding soil at each site is listed in Table 3.1.

At each site, the automatic weather station was installed in the center of an enclosure of 15 m x 15 m to keep the cattle out. Initially nine permanent plots of 0.25 m square were randomly selected by throwing a metal quadrat of 0.5 m x 0.5 m within the fenced area, but the number of plots was increased to 15 after the second harvest. The mean grass biomass for a given season and site was then computed and used in the statistical analysis. The climatic data readings for a given season and site were assumed to be the same for all the plots at the given season and site. The same plots were harvested throughout all the seasons.

A 11-week growing period was used for the first harvest based on the recommendation of Whitney (1974a), but this was adjusted to 13-week periods for subsequent harvests because of the slow growth observed after the first season. These periods were selected in such a way to correspond, as closely as possible, to the duration and variations of the natural seasons.

3.3 Data Collection

3.3.1 Climatic Data Collection

The weather stations were programmed to record the atmospheric and soil-climate variables at 15-minute intervals. Then, daily, monthly, seasonal, and annual values were computed from the initial readings.

3.3.2 Soil Characterization

At each site, a soil profile was described and sampled in collaboration with the Soil Conservation Service, USDA, according to the procedure described in the Soil Survey Manual (1951). These samples were analyzed in the National Soil Survey Laboratory at Lincoln, Nebraska, following the procedure outlined in Soil Survey Investigations Report No. 1 (USDA, 1972). The soil properties included particle size distribution, bulk density, water content at 1/30 and 1.5 MPa, cation exchange capacity, base saturation, organic C, total N, available P, extractable bases (Ca, Mg, Na, K), pH, and mineralogical composition.

3.3.3 Pasture Grass Response to Soil-Climate

The pasture grass was harvested at intervals of 11 to 13 weeks, as mentioned earlier, from July 1983 to February 1985 by clipping the top growth of the grass at ground level. Workers such as Whitney (1974a, 1974b), Beatty et al. (1968), and Stanley et al. (1967) have shown that the best forage regrowth was obtained when the grass was cut 5-cm height or less within 10-week intervals when soil water and nutrients were not limiting.

The harvested grass was brought to the laboratory where it was dried and weighed to obtain the dry-weight biomass. Because the growing period varied somewhat for the different harvests, the growth rate at each site was computed first in terms of Kg/ha day. Then, because of the different species at the different sites (Table 3.1), the relative performance of the site was computed as percent of maximum growth rate of that species and this value was used as the pasture grass response to soil-climate. Although there was a mixture of grass species at the various sites, particularly at the high and middle altitudes, these species were not harvested separately and they were treated as a community.

The nutrient status of the new grass was also determined in the Department of Agronomy and Soil Science plant analysis laboratory. After being ground, the plant samples were analyzed for total N by the Kjeldahl method and for P, K, Ca, Mg, Fe, Mn, Al, Cu, and Zn by the X-ray fluorescence quantometer. Crude protein content in the plant tissue was taken as an index of the quality of the grass and it was estimated as percent N content x 6.25.

3.4 Model-Building Procedures

In order to express the continuous relationship between the physical responses of soil temperature or the biological response of grass variables and the environmental factors, soil temperature and yield functions were established using statistical models that would describe the relation adequately. The data previously collected were first subjected to a visual analysis to judge whether or not it was appropriate to eliminate some variables. Soil texture was excluded because texture data for the Andepts were not reliable. It was assumed that other variables such as bulk density and water retention capability would contain most information related to soil texture. To assess the nature of the relationship between a dependent variable and individual independent variables, a matrix of correlation was constructed, using a SAS computer package, and the dependent variables were plotted against influential independent variables. The correlation matrices were further used as a guide for variable selection whenever multiple regression models were involved. The list, codification, and measurement units used for the variables thought to influence soil temperature and herbage growth are shown in Tables 3.2 and 3.3.

3.4.1 Selection of the Variables and Models

Soil Temperature Prediction--The first objective was to develop empirical models that could be used to estimate soil temperature at a given depth from other environmental factors. The temperature response to environment was estimated by using available data to fit simple, multiple, and second degree polynomial equations. Air temperature was assumed to be the main driving factor. After examining the correlation matrix which was used to eliminate highly correlated variables, three groups of alternatives were examined and the output was compared to select the best model.

The first group of alternatives, using simple and quadratic polynomial, was used to estimate monthly soil temperature as a function of soil properties and monthly weather variables. The general form of such models were expressed as:

$$ST_d = b_o + b_1AT \qquad (3.1)$$

$$ST_d = b_o + b_1AT + b_2AT^2 \qquad (3.2)$$

where ST_d = monthly soil temperature at a given depth d, AT = monthly air temperature, b_i = estimated regression

Table 3.2. Variables Used in Soil Temperature Prediction Models.

FACTOR	Code	Unit
1. Monthly Atmospheric Climate	(AC)	
Air temperature at 2.0 m height	AT	°C
Rainfall (total)	RN	mm
Relative humidity	RH	%
Solar radiation	RAD	$Kcal/m^2$
2. Monthly soil-climate at 0.1 m depth	(SC10)	
Soil temperature	ST10	°C
Initial soil moisture tension	ISM10	MPa
Soil moisture tension	SM10	MPa
3. Monthly soil-climate at 0.5 m depth	(SC50)	
Soil temperature	ST50	°C
Initial soil moisture tension	ISM50	MPa
Soil moisture tension	SM50	MPa
4. Soil Properties	(SOIL)	
Soil reaction (Ph) in solum, and A horizon	PH,PHA	
Cation exchange capacity	CEC,CECA	Meg/100g
Base saturation	BS,BSA	%
Available water capacity	AWP,AWA	%
Organic carbon content	OC,OCA	%
Available water capacity	AWP,AWA	%
Bulk density	BD,BDA	g/cm^3
Rooting depth up to existence of 10 $roots/dm^2$	DEPTH	m

Table 3.3. Variables Used for Modeling Pasture Grass Response.

FACTOR	Code	Unit
1) Atmospheric Climate (MODEL I)	(AC)	
Mean air temperature over the growing period	ATG	°C
Mean max. air temperature	ATG11	°C
Mean min. air temperature	ATG12	°C
Rainfall (total)	RNG	mm
Mean Relative humidity	RHG	%
Mean Solar radiation	RAD	$Kcal/m^2$
2) Soil-climate at 10 cm. depth (MODEL II)	(SC10)	
Mean soil temperature over the growing period	STG10	°C
Mean max. soil temperature	STG11	°C
Mean min. soil temperature	STG12	°C
Mean soil moisture tension	SMG10	MPa
Initial soil moisture tension	ISMG10	MPa
3) Soil-climate at 50 cm. depth (MODEL III)	(SC50)	
Mean soil temperature over the growing period	STG50	°C
Mean max. soil temperature	STG51	°C
Mean min. soil temperature	STG52	°C
Mean soil moisture tension	SMG50	MPa
Initial soil moisture tension	ISMG50	MPa
4) Factor common to all models		
Harvest number	HARV	
Soil Properties (the same as listed in Table 3.4.1.)	(SOIL)	

coefficients, and b_o = intercept, the expected soil temperature when all input values are zero.

The second group of alternatives was concerned with predicting seasonal temperature, using the same technique as for the monthly temperature prediction. The general forms of the equations were as follows:

$$SST_d = b_o + b_1 MSAT \tag{3.3}$$

$$SST_d = b_o + b_1 MSAT + b_2 MSRN \tag{3.4}$$

$$SST_d = b_o + b_1 MSAT + b_2 MSAT^2 \tag{3.5}$$

$$SST_d = b_o + b_1 MSAT + b_2 MSAT^2 + b_3 MSRN + b_4 MSRN^2 \tag{3.6}$$

where SST_d = seasonal soil temperature at a depth d, MSAT = seasonal air temperature, MSRN = seasonal rainfall, b_i = estimated partial regression coefficients, and b_o = intercept, the expected soil temperature when all input values are zero. The seasons were determined according to definitions given by Soil Taxonomy (USDA, 1975) for the northern hemisphere. The four seasons were (1) winter (December, January, and February), (2) spring (March, April, and May), (3) summer (June, July, and August), and (4) autumn (September, October, and November).

Finally, the annual temperatures were computed from the original data, and regression models were constructed to fit simple, multiple, and quadratic polynomial regression models as follows:

$$MAST_d = b_o + b_1MAT \quad (3.7)$$

$$MAST_d = b_o + b_1MAT + b_2MAR + b_3CHR + b_4MAMP \quad (3.8)$$

$$MAST_d = b_o + b_1MAT + b_2MAT^2 \quad (3.9)$$

$$MAST_d = b_o + b_1MAT + b_2MAT^2 + b_3MAR + b_4MAR^2 + b_5CHR + b_6CHR^2 + b_7MAMP + b_8MAMP^2 \quad (3.10)$$

where $MAST_d$ = annual soil temperature at a given depth d, MAT = annual air temperature, MAR = annual rainfall, CHR = chroma, and MAMP = air temperature amplitude, computed as the difference between maximum and mean air temperatures.

The models were compared by examining the coefficient of determination (R^2) and residual mean squares (MSe).

Prediction of Pasture Grass Performance--The second objective was to develop production functions to quantify environmental influences on pasture grass growth. The environment was subdivided into three strata--atmospheric level, soil-climate at 0.1-m depth, and soil-climate at 0.5-m depth, all having a common denominator of soil properties and harvest number (Table 3.3). A production function was then developed using the data from each stratum. For example, the function relating grass growth to atmosphere included atmospheric and soil properties as independent variables but not the soil-climate factors at 0.1 and 0.5-m depth. The resulting model is hereafter called MODEL I. Likewise, the model relating grass performance to soil-climate at 0.1-m depth included the variables pertaining to that stratum and soil properties but not the soil-climate factors at 0.5-m depth. This model is hereafter called MODEL II. The model relating grass response to soil-climate at 0.5-m depth and including the variables related to that stratum and soil properties but excluding any soil-climate factor at 0.1-m depth is MODEL III. Because of its physiological influence on plant growth, solar radiation and its interaction with atmospheric variables were included in all of the models.

The data used for the growing seasons were computed from the daily mean over the growing season. The least square method was then used to fit a second polynomial degree function for each stratum defined above. The general forms of the quadratic polynomial are:

MODEL I: $$\%MGRATE = b_o + b_1AC + b_2AC^2 + b_3SOIL + b_4SOIL^2 + b_5HARV + b_6HARV^2 + c_1(AC \times SOIL) + c_2(AC \times HARV)$$

MODEL II: $$\%MGRATE = b_o + b_1SC10 + b_2SC10^2 + b_3SOIL + b_4SOIL^2 + b_5HARV + b_6HARV^2 + c_1(SC10 \times SOIL) + c_2(SC10 \times HARV) + c_3(RAD \times AC)$$

MODEL III: $$\%MGRATE = b_o + b_1SC50 + b_2SC50^2 + b_3SOIL + b_4SOIL^2 + b_5HARV + b_6HARV^2 + c_1(SC50 \times SOIL) + c_2(SC50 \times HARV) + c_3(RAD \times AC)$$

where %MGRATE = maximum growth rate for each species, b_o = expected response when all input values are zero, b_i and c_i = estimated partial regression coefficients, and the other symbols are individual or subset of variables defined in Table 3.3.

Method of Variable Selection--A major problem in multiple regression analysis is to find a variable or a subset of explanatory variables that are most important in determining the response of interest. Many computer-aided procedures have been developed and described for such a purpose (Snedecor and Cochran, 1980; Allen and Cady, 1982; SAS, 1982). Among these are the FORWARD selection, BACKWARD elimination, PRESS, and STEPWISE regression. The stepwise regression procedure was selected for this study not only because models constructed by stepwise regression have proven to be best for prediction (Laird and Cady, 1969), but also because the procedure fits the objectives of the study most conveniently; that is, the selection of few environmental factors to predict soil temperature or relative performance of grass.

This procedure begins by examining the correlation coefficient correlation between the dependent variable and each of the independent variables. The independent variable that is most correlated to the response is then entered into the model first. The F statistics and partial coefficients of correlations of the other independent variables are then calculated. These variables are introduced into the model one at a time. The F statistic for a variable to be added, however, must be significant at a preset probability level (SLENTRY) and the order of insertion is determined by using the partial correlation coefficient as a measure of the importance of the variable not yet in the model. A unique feature of the procedure is that after a variable is incorporated, the stepwise method reexamines all of the variables previously included in the equation and deletes any variable that does not produce a significant F statistic at a given preset probability level (SLSTAY). The process continues until all of the independent variables outside the model show an unsatisfactory F statistic for entry in the model and every variable in the model is significant at a preset level of significance for stay. In this study, the levels of significance for entry and for stay in the model were set at 15 percent.

3.5 Evaluation of Soil-Climate Criteria of Soil Taxonomy

3.5.1 Evaluation of Current Method of Soil Temperature Prediction

The different models for predicting soil temperature were compared with the objective of selecting the best one, on the basis of criteria such as the coefficient of determination (R^2) and residual mean squares (MSE). The data generated by the selected model and data generated by the current model in use by Soil Taxonomy were compared with the observed temperatures. Conclusions were then drawn from the results obtained and alternatives proposed, when needed.

3.5.2 Evaluation of Soil-Climate Criteria of Soil Taxonomy in Relation to Plant Growth

The criteria used for selecting of the soil temperature model were also used as a basis for selecting the best predictive model for plant growth. Because the methodology used for selecting the variables in each model was based on their relative importance of improving the predictive power of the model, the selected variables were also judged to be the ones that could prove to be best suited for soil classification. The results obtained, in addition to a close examination of the correlation coefficients, were used as an aid in the evaluation process aimed at finding answers to certain questions. These questions were, are soil-climate factors more helpful than atmospheric climate in predicting vegetal production to justify their use in Soil Taxonomy? If so, which soil depth temperature and/or moisture measurements are most appropriate? Do these depths correspond to those currently in use for soil classification?

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Soil Temperature Study

During the period of the study, the mean annual air temperature of the study area varied from 13.37 to 24.03 ^{o}C, while the corresponding soil temperatures varied from 15.86 to 30.03 ^{o}C at 0.1-m depth and from 15.50 to 29.03 ^{o}C at 0.5-m depth (Table 4.1). The total rainfall ranged from 100 to 872 mm. Compared with long-term precipitation records (Table 3.1), the period of the study was drier than the average year. Such a comparison is not possible for either the air or soil temperatures because of the lack of such records.

4.1.1 Variations of Air and Soil Temperature

The air and soil temperatures were lower at the higher altitudes than at the lower altitudes (Fig. 4.1). This was attributed to high rainfall and frequent cloudiness at high altitudes, with the soils receiving much less direct sunlight than at low altitude. Yet a large fraction of that small energy reaching the soil surface is used to evaporate water rather than to heat the moist soils, so that there is less heat flow into the soil. This is in agreement with Jensen (1983) who found that soil temperatures of the intermountain regions of the U. S. decreased by about 4 to 8 ^{o}C for each 1000 m increase in altitude. Embrechts and

Table 4.1. Simple Descriptive Statistics for Some Climatic Factors in the Study Area (Mean Annual).

FACTOR	Mean	Range	Std.Dev.
Air Temperature (°C)	19.71	13.37 - 24.03	3.57
Soil Temperature (°C)			
at 0.1 m depth	22.96	15.86 - 30.03	4.81
at 0.5 m depth	22.20	15.50 - 29.03	4.60
Total Rain (mm)	342	100 - 872	233
Relative Humidity (%)	79.25	72.88 - 85.71	3.32
AMP* (°C)	6.32	4.81 - 7.60	0.85
AMP1* (°C)	4.90	3.77 - 5.96	0.65
DST10** (°C)	3.25	0.72 - 6.00	1.62
DST50** (°C)	2.48	0.30 - 5.03	1.48
Solar Radiation ($Kcal/m^2$)	41.65	34.47 - 47.85	5.01
Altitude (m)	635	36 - 1620	525

* AMP = Max. air temperature - mean air temperature.
AMP1 = Mean air temperature - minimum air temperature.

** DST10 = Soil temperature at 0.1 m depth-air temperature.
DST50 = Soil temperature at 0.5 m depth-air temperature.

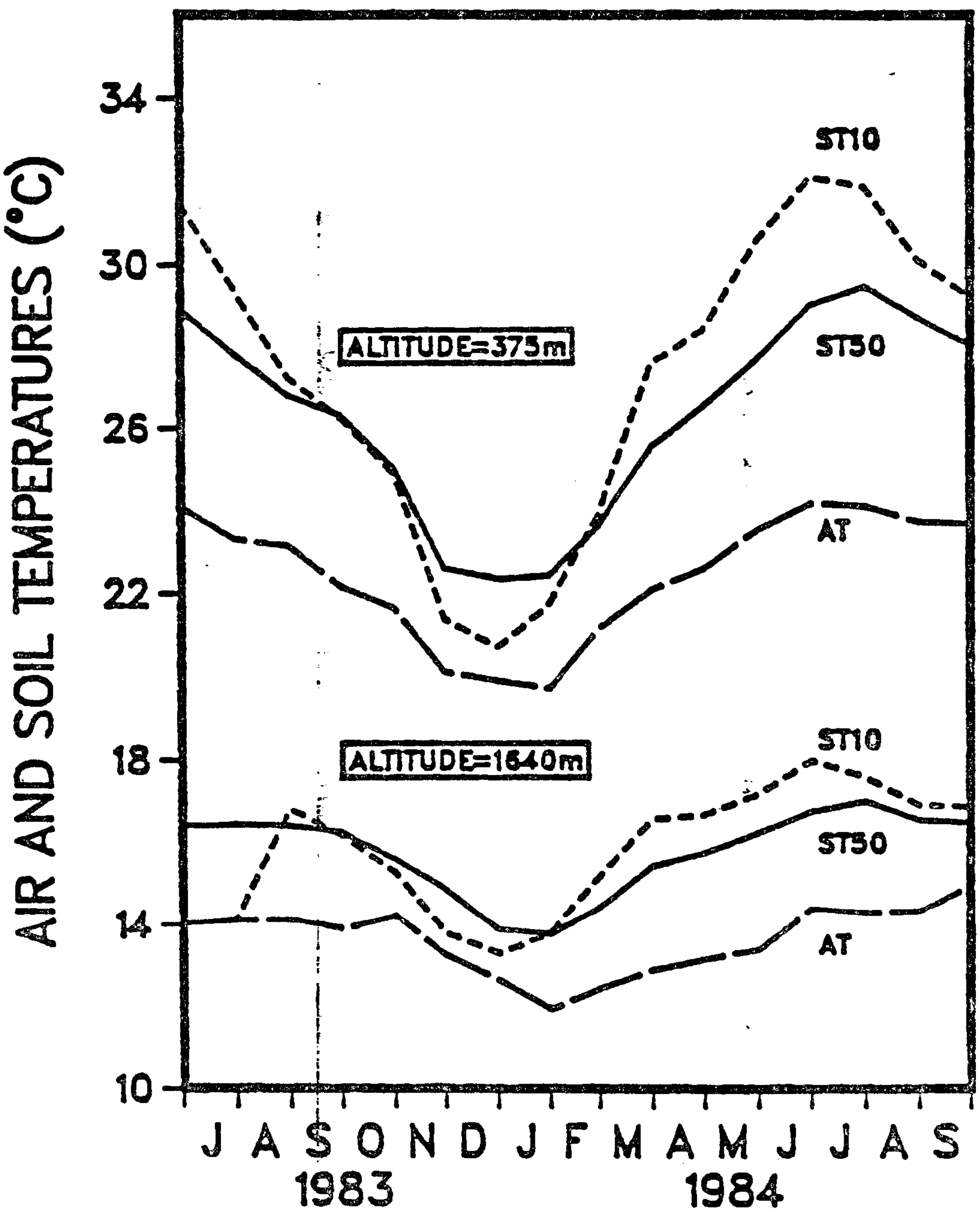


Figure 4.1. Variation of Air and Soil Temperatures with Time.

Tavernier (1985) report a decrease of about 4.5 °C in temperature for each 1000 m in elevation. Britten (1962) also reported similar results for the island of Maui. However, the author added that temperature inversion due to cloud zone may be the source of anomalous situations at places. Such reports, therefore, may raise questions about the validity of using altitude to estimate air or soil temperatures, inasmuch as the temperature inversion zones are not obviously known.

Nevertheless, variations of air and soil temperatures followed similar patterns at all altitudes (Fig. 4.1). Air temperature generally decreased during autumn (September, October, and November) and winter (December, November, and February). So did soil temperatures at 0.1- and 0.5-m depth, suggesting that the heat stored in the soil during the previous summer is being returned to the atmosphere in the fall and winter. Minimum air temperatures were observed in February, whereas minimum soil temperatures at 0.1 and 0.5-m depth were generally observed in December or January, indicating one to two months phase retardation with respect to air temperatures. On the other hand, maximum air temperature and maximum soil temperature at 0.1- and 0.5-m depth were generally observed from July to August. Although variations of air and soil temperature followed similar patterns, soil temperatures either at 0.1- or 0.5-m depth were consistently higher than air temperatures

(Fig. 4.1). Similar results were reported by Britten (1962) who attributed the lower air temperatures to the cooling of the air to a greater extent than that of soil because of faster radiation. Toy et al. (1978), attributed the higher soil temperature to the low specific heat of soil and the reduced air mixing that usually occurred in the air layer adjacent to the soil surface.

In spite of their similar trend of variation, soil temperatures at 0.1-m depth were higher than at 0.5 m during spring and summer (first half-year) but lower during autumn and winter (second half-year), indicating a larger variation of soil temperature at 0.1 m than at 0.5-m depth (Fig. 4.1). The higher temperatures at 0.1-m depth during the first half-year period were ascribed to higher insolation and moisture deficit at that depth during that period, whereas the lower temperatures during the second half-year were attributed to decreasing solar radiation, increasing rainfall, and subsequest high soil moisture content. In the spring and summer, the greater amount of solar energy reaching the soil surface warms the upper layer of the soil to a greater extent than the subsoil. In the autumn and winter, however, the decreasing air temperature and increasing soil water content cause a rather greater cooling of the upper layer than the subsoil. These results are in agreement with Smith (1964) and USDA (1975) who reported that in a given soil, the amplitude of fluctuation was greater at soil surface than in the subsoil, and that the temperature gradient was positive in winter and negative in summer.

4.1.2 Soil Temperature Prediction Models

The weather data from 11-station years were regrouped into three sets of periods, namely monthly, seasonal, and annual. The objective was to develop mathematical models that could be used in providing first approximations of soil temperatures at 0.1- and 0.5-m depth. The Statistical Analysis System (SAS) computer package was used in conjunction with the stepwise regression procedure to fit simple, multiple, and quadratic polynomial functions, as expressed in equations 3.1 through 3.10.

Alternatives Models for Predicting Soil Temperature at 0.1-m Depth--The different models for estimating soil temperature at 0.1-m depth are shown in Table 4.2. These results show that the intercept and the slope were similar for the monthly and seasonal periods when simple linear equations are considered (Equations 4.1 and 4.3). Variation in air temperature accounted for 89 and 90 percent of the variation in monthly and seasonal soil temperature, respectively. The simple linear equation for annual temperature had a higher intercept value (Equation 4.7) when compared with the monthly and seasonal temperature models (Equations 4.1 and 4.3). The simple linear regression models for the three periods show that the coefficient of determination (R^2) increased and the residual mean squares

Table 4.2. Alternative Models for Predicting Soil Temperatures at 0.1-m Depth.

MODEL	R^2	MSe	Equation #
1. Monthly Soil Temperature Prediction Models (n=132).			
Simple linear regression ST10 = - 4.26 + 1.38AT	0.89	3.08	4.1
Quadratic polynomial ST10* = 17.28 - 0.94AT + $0.06AT^2$	0.92	2.42	4.2
2. Seasonal Soil Temperatures Prediction Models (n=44)			
Simple linear regression SST10 = - 4.20 + 1.38MSAT	0.90	2.69	4.3
Multiple regression SST10 = - 2.10 + 1.31MSAT - 0.03MSRN	0.92	2.21	4.4
Quadratic polynomial SST10 = 8.50 + $0.036MSAT^2$	0.92	2.16	4.5
SST10* = 10.76 + $0.034MSAT^2$ -0.073MSRN + $0.0006MSRN^2$	0.94	1.77	4.6
3. Annual Soil Temperature Prediction Models (n=11)			
Simple linear regression MAST10 = -2.79 + 1.31 MAT	0.94	1.60	4.7
Multiple regression MAST10 = -0.77 + 1.26MAT - 0.039 MAR	0.96	1.12	4.8
Quadratic polynomial MAST10 = 9.14 + $0.035MAT^2$	0.95	1.24	4.9
MAST10* = 13.42 + $0.031MAT^2$ -0.178MAR + $0.0018MAR^2$	0.98	0.55	4.10

* The best model for the period considered. The F-test is highly significant (P> 0.01%) for all the models.

(MSe) decreased when the length of the period increased. That is, the predictive power of the models was higher and subject to less experimental error when the observation period was longer. This was attributed to the fact that monthly and seasonal soil temperature fluctuations are affected by several other environmental factors to much more extent than the annual soil temperature (USDA, 1975; Reimer and Shaykewich, 1980) and all these factors were not included in the models. The addition of rainfall at the seasonal and annual levels, however, did not contribute greatly to improvement of the prediction capability of the model when multiple linear regressions were used; for example, Equation 4.4 vs. 4.3 and Equation 4.8 vs. 4.7. These results are in agreement with those reported by Reimer and Shaykewich (1980) who found that inclusion of precipitation and sunshine as variables in multiple regression added very little to the predictive power of the models. This suggests that the relationships between air and soil temperatures may be better expressed in terms of a curvilinear function than in terms of a simple linear model.

Figures 4.2 and 4.4 support the curvilinear relationship between air and soil temperature for the monthly, seasonal, and annual period of time. In these figures, the scattergram represents the observed temperatures, whereas the solid line represents the predicted values calculated from the second degree polynomial. The use of quadratic

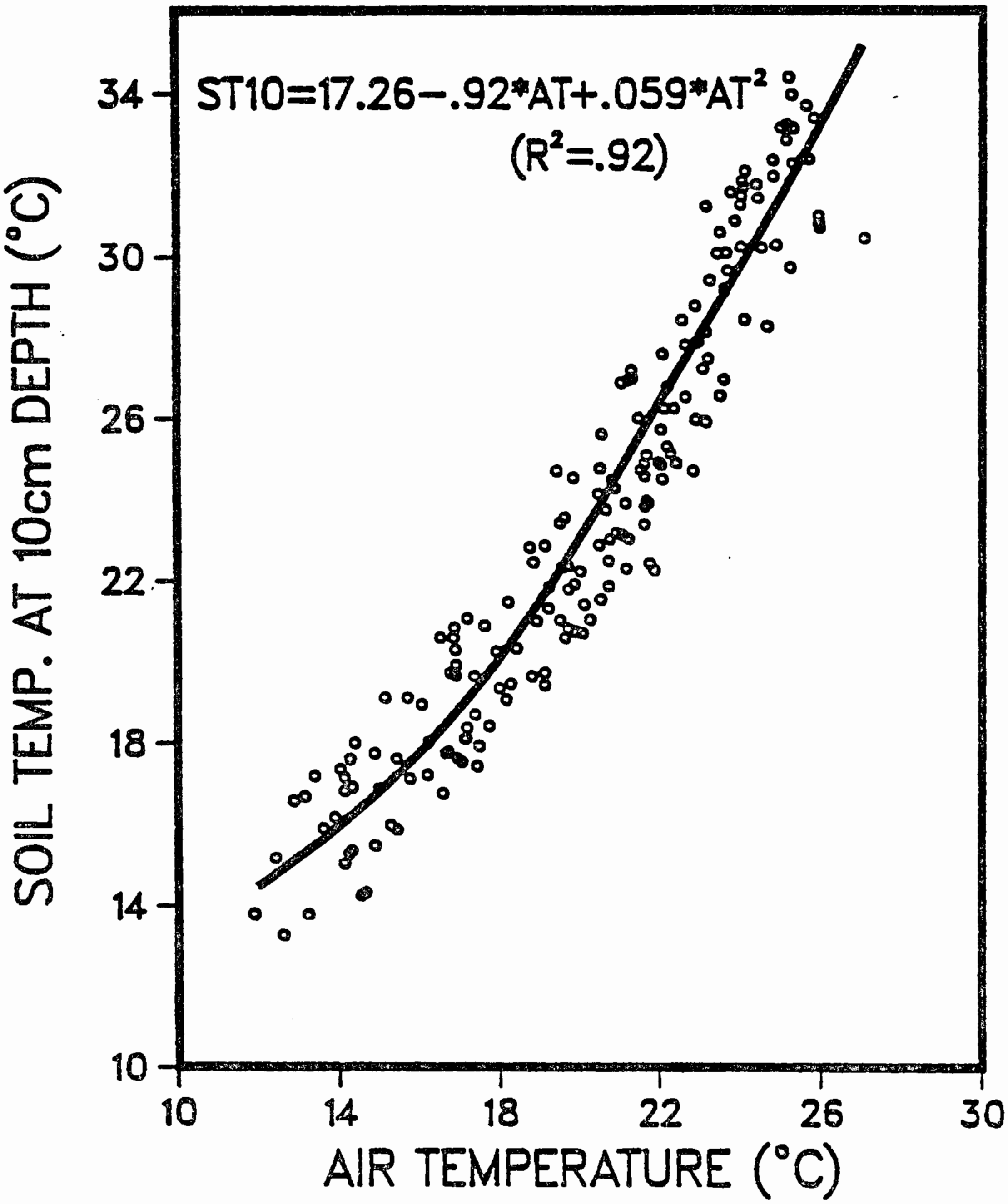


Figure 4.2. Relationship between Monthly Air and Soil Temperatures at 0.1-m Depth (for a 16-month Period).

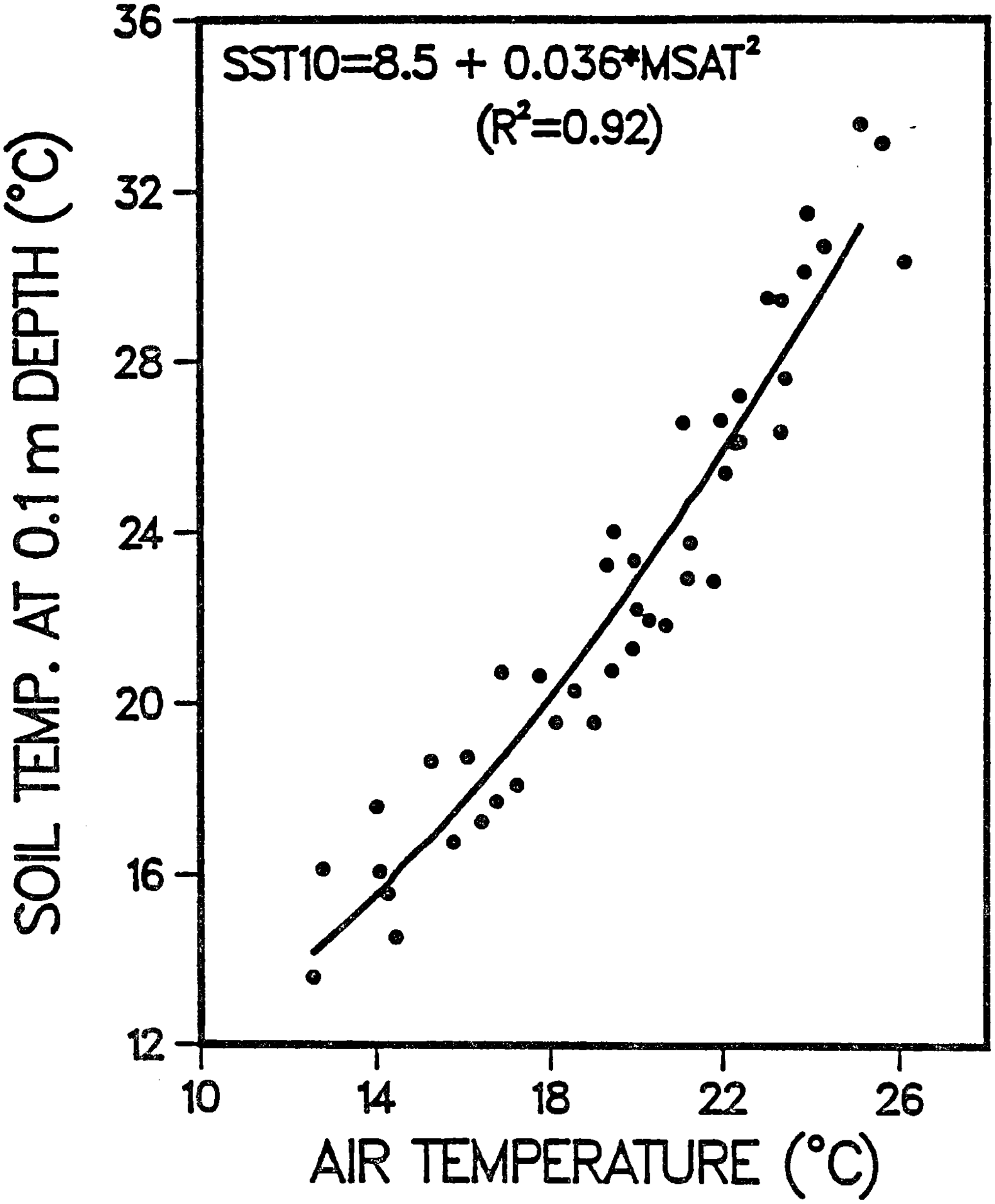


Figure 4.3. Relationship between Seasonal Air and Soil Temperatures at 0.1-m Depth.

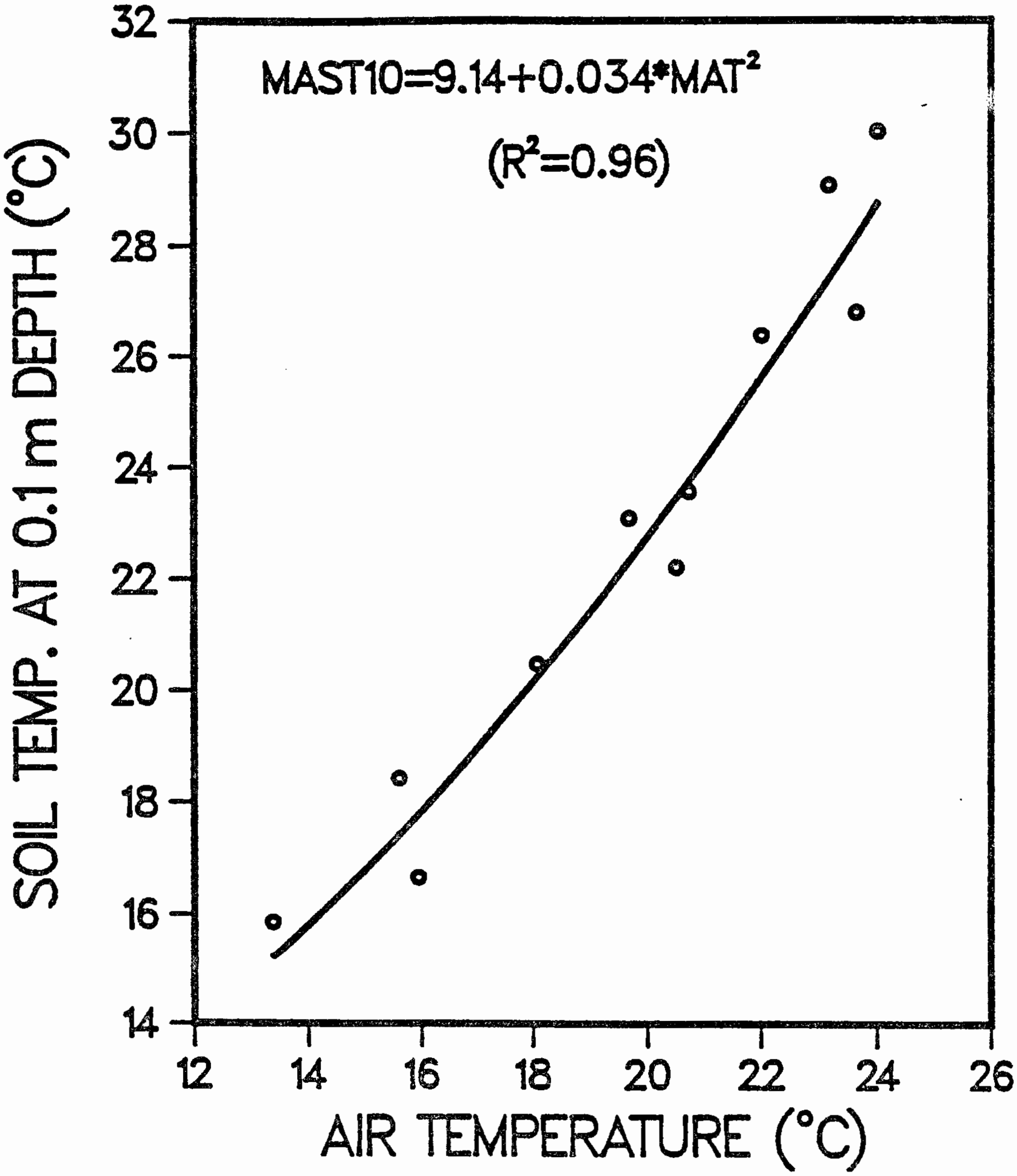


Figure 4.4. Relationship between Annual Air and Soil Temperatures at 0.1-m Depth.

polynomial, using air temperature as the sole driving factor, added little to the predictive power (R^2) of the models (Table 4.2). It contributed, however, to the decrease in the experimental error (MSe), when compared to the simple or multiple linear regression models. The addition of precipitation to the quadratic polynomial, instead, contributed to a greater R^2 improvement and a greater reduction of the error term, as compared to the simple linear regression. Air temperature and rainfall explained 98 percent of the variation in soil temperature (Equation 4.10), 95 percent of which accounted for air temperature alone (Equation 4.9). The addition of rainfall in the quadratic polynomial, nevertheless, reduced the error term by about 56 percent (Equation 4.10 vs. 4.9). The existence of unequal number of variables in these two equations, however, raises the question about the validity of a direct comparison of their R^2 and MSe. These problems are discussed in more detail in Section 4.2.5. The plots of the data using the two equations when compared with the observed values (data not shown) showed that Equation 4.10 was more reliable for prediction purposes than Equation 4.9. Such plots were used as a guide in selecting the best models for the monthly and seasonal periods (See Table 4.2).

Alternative Models for Predicting Soil Temperatures at 0.5-m Depth--The least square method described in the preceding chapter was used to fit the different equations.

The results show that regardless of the length of the period of time considered, the intercept, slope, and coefficient of determination were similar for all of the simple linear regression models (Equations 4.11, 4.13, and 4.16). The intercepts were negative and clustered around 2.3 ^{o}C, whereas the estimated regression coefficients were positive with a value of 1.24. Air temperature for a given period explained about 93 percent of the variation in the corresponding soil temperature at 0.5-m depth. The residual mean squares (MSe), however, tended to decrease when the length of the time period increased. For instance, MSe decreased from 1.77 for the monthly period to 1.57 for the annual period (Equation 4.11 vs. 4.16). Unlike the models for predicting soil temperatures at 0.1-m depth, the nearly invariability of the intercept, slope, and R^2 in the simple regression models relating air and soil temperatures at 0.5 m was ascribed to the greater stability of soil temperature at 0.5 m than at 0.1-m depth. There was also a remarkable similarity between the quadratic polynomial equations for the different periods in relation to the intercept, slope, and coefficient of determination. The intercept was clustered around 9 ^{o}C and the slope around 0.032, whereas the R^2 varied only from 93 to 95 percent for all of the periods considered (Equations 4.12, 4.15, and 4.18). As shown for the simple linear models, the residual mean squares decreased with a longer observation period.

Table 4.3. Alternative Models for Predicting Soil Temperatures at 0.5-m Depth.

MODEL	R^2	MSe	Equation #
1. Monthly Soil Temperature Prediction Models (n=132).			
Simple linear regression			
ST50 = - 2.27 + 1.24AT	0.92	1.77	4.11
Quadratic polynomial			
$ST50^{*} = 9.22 + 0.032AT^2$	0.93	1.47	4.12
2. Seasonal Soil Temperatures Prediction Models (n=44).			
Simple linear regression			
SST50 = - 2.30 + 1.24MSAT	0.93	1.61	4.13
Multiple regression			
SST50 = - 1.19 + 1.21MSAT - 0.016MSRN	0.94	1.49	4.14
Quadratic polynomial			
$SST50^{*} = 9.20 + 0.032MSAT^2$	0.94	1.32	4.15
3. Annual Soil Temperature Prediction Models (n=11.			
Simple linear regression			
MAST50 = -2.34 + 1.24 MAT	0.93	1.57	4.15
Multiple regression			
MAST50 = -0.71 + 1.21MAT - 0.031 MAR	0.95	1.34	4.17
Quadratic polynomial			
$MAST50^{*} = 9.01 + 0.033MAT^2$	0.95	1.21	4.18

* The best model for the period considered. F-test is highly significant (P> 0.01%) for all the models.

In either case, neither the addition of rainfall nor the use of a quadratic model greatly improved the predictive capability of the models.

Unlike the models for predicting soil temperature at 0.1-m depth, the quadratic models for predicting soil temperature at 0.5-m depth showed air temperature to be the only important variable. In addition, the intercept, slope, and R^2 were more constant in the models for soil temperatures at 0.5 m than in the models for soil temperature at 0.1-m depth. This indicates that subsoil temperature is less sensitive to weather variation than soil surface temperature.

Although the quadratic models did not show an appreciable improvement in R^2 when compared with the simple linear equations, the former models were judged to be better predictors than the latter equations. Such a conclusion is based not only on the slightly higher R^2 and reduced error term due to the use of the quadratic polynomial but also on the nature of the relationships between air and soil temperatures at 0.5-m depth. The curvilinear trend of these relationships is illustrated in Figure 4.5 through 4.7. The scattergram of these figures represents the observed values, whereas the solid line is the predicted value calculated from the quadratic equation. The lack of a considerable improvement in the R^2 of the quadratic models over the simple linear regression suggests

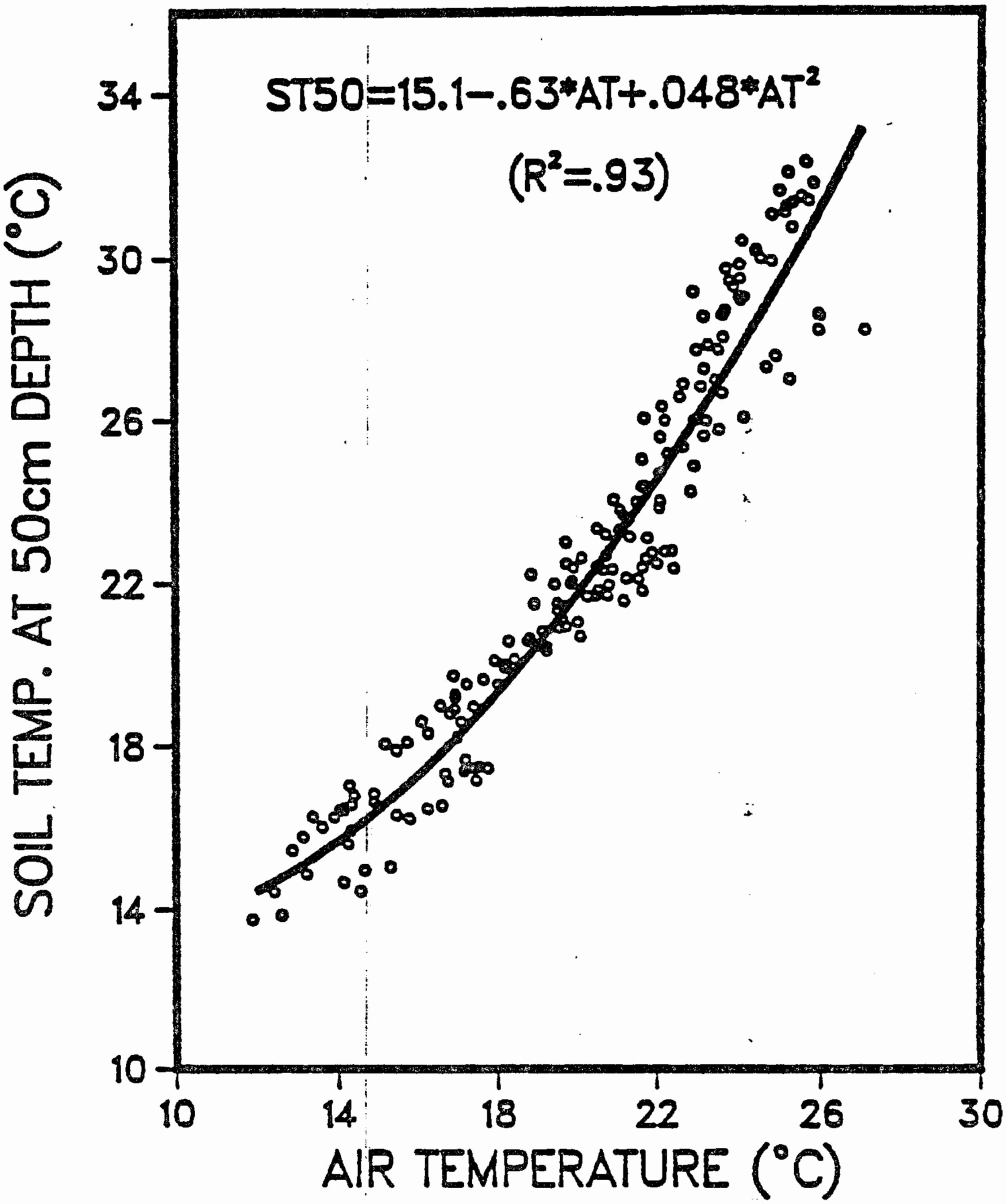


Figure 4.5. Relationship between Monthly Air and Soil Temperatures at 0.5-m Depth (for a 16-month Period).

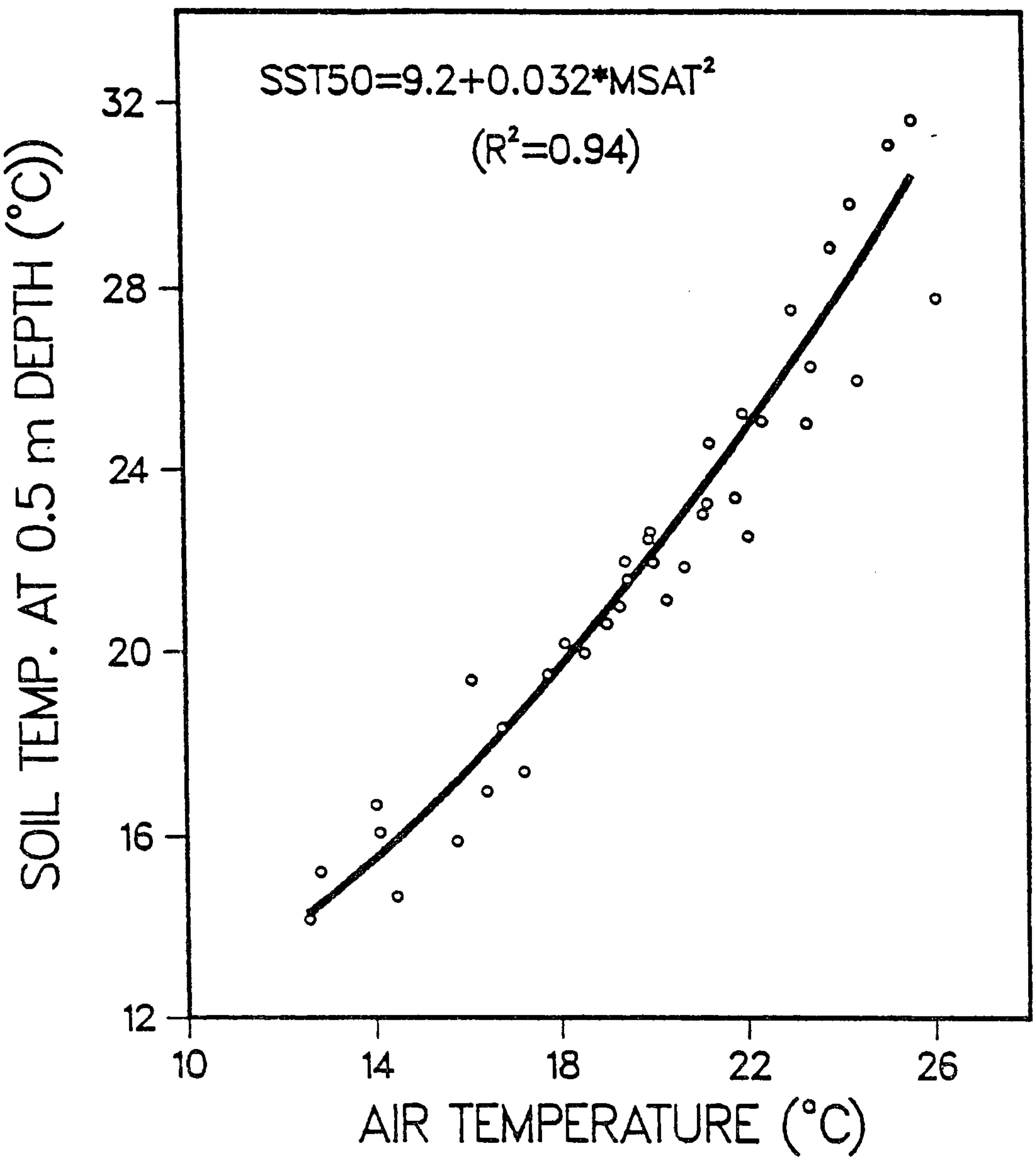


Figure 4.6. Relationship between Seasonal Air and Soil Temperatures at 0.5-m Depth.

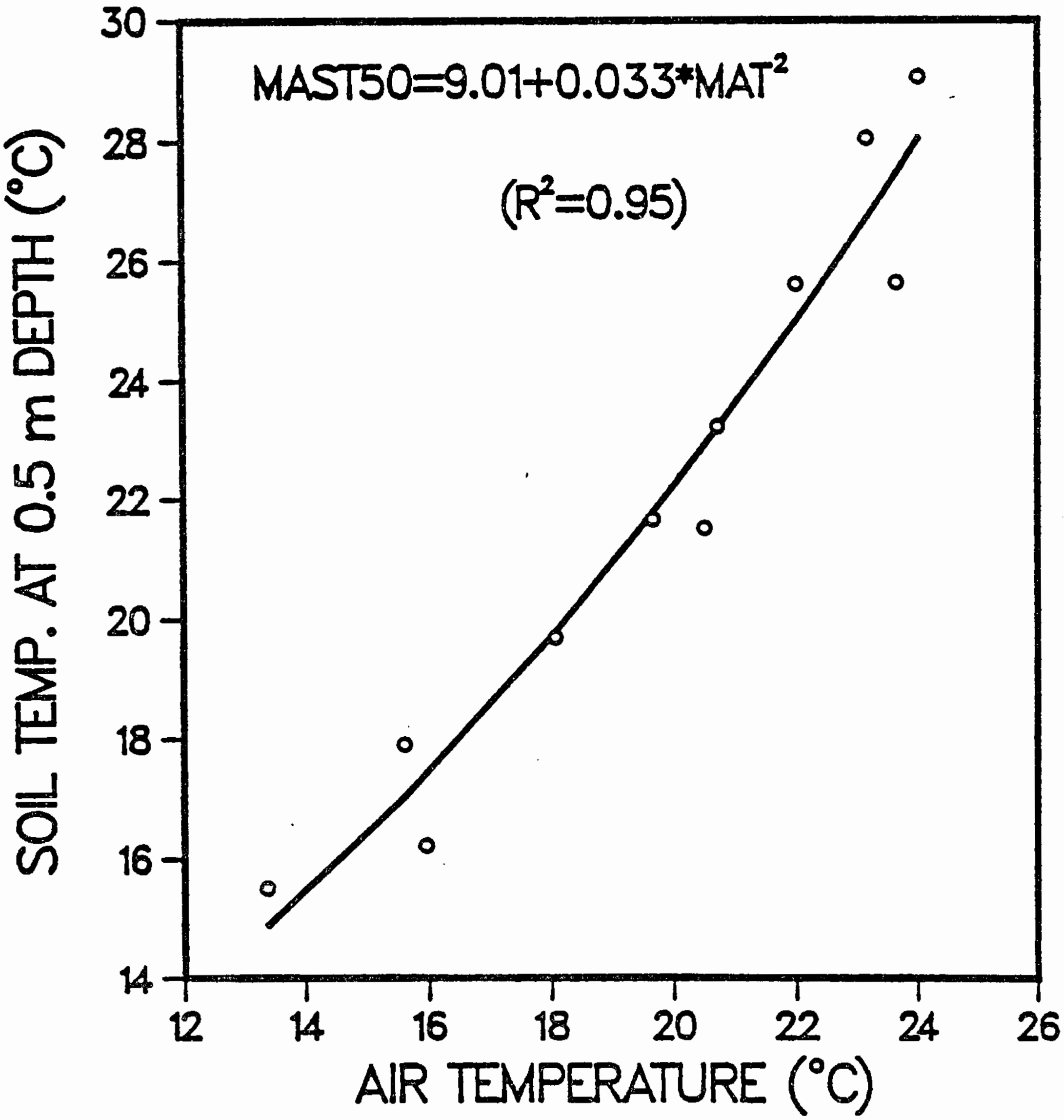


Figure 4.7. Relationship between Annual Air and Soil Temperatures at 0.5-m Depth.

that the nature of the relationship may be better expressed by other curvilinear functions. There is, therefore, a need for further investigation on a most appropriate curvilinear function to relate air and soil temperatures at 0.5-m depth. The point is that the relationship between air and soil temperature is rather curvilinear than linear, although the linear relationship provides an acceptable "goodness to fit" for all of the models.

The curvilinear nature of the relationships between monthly, seasonal or annual air temperature, and the corresponding soil temperatures at 0.1- and 0.5-m depths is also confirmed by curves reported by Gupta et al. (1981) for bare and residue covered soils at different depths. These results differ, however, from findings of Toy et al. (1978) who reported simple linear relationships between mean monthly or mean seasonal air temperatures and the corresponding soil temperatures. Beside the site specificity of the statistical models used in both cases, the difference may be attributed to two reasons. Firstly, Toy et al (1978) studied the relationships between air and soil temperatures at 0.05-m depth, whereas the present study regards these relations for deeper soil temperatures. They claim, however, that the mean annual temperature predicted for the 0.05-m depth would be the same as for the 0.05 to 1.0-m range. Secondly, these workers computed the mean monthly temperatures from single daily readings or from daily maximum and minimum recordings, whereas the mean temperatures used in the present study were based on 15-minute readings. Neither the single daily reading nor the use of maximum and minimum temperature seems to be adequate for soil temperature measurement because considerable uncertainty is introduced (Reimer and Shaykewich, 1980). Computing the mean soil temperatures from the maximum and minimum temperatures has generally been based on the assumption that soil temperatures oscillate as a pure sinusoidal function of time around a mean value. There is evidence that such an assumption is questionable. If the assumption were true, the difference between the maximum temperature and the mean temperature, on one hand, and the difference between the mean temperature and the minimum temperature, on the other, would yield the same value. It turns out that this is not so, as indicated by the relatively large difference between values of AMP and AMP1 (Table 4.1). These deviations from pure harmonic fluctuations are attributable to vagaries of weather such as cloudiness or rain (Hillel, 1980).

The curvilinear relationships between air and soil temperatures reported herein are also in disagreement with Smith (1964) and USDA (1975) who found the relation to be linear. The source of the disagreement lies apparently in the fact that these workers disregarded the upper 5 to 15-cm layer of the soil. A close examination of the graphs presented in these references (USDA, 1975, pp. 60-61) shows that (1) there is a curvilinear trend if the upper soil layer is taken into account, and (2) soil temperature at 0.5-m depth may be assumed as a linear function of soil temperature at 0.1- to 0.15-m depth, but assumption of a simple linear relationship between air and soil temperatures is questionable.

The use of air temperature as the main driving factor regulating variations of soil temperatures is an expediency that may also be questioned. Among other factors, soil temperature is known to be influenced by solar radiation, precipitation, evapotranspiration, soil moisture, and soil color. These influencing factors themselves are, however, influenced in some way by air temperature. Thus, problems of autocorrelations may exist. Such autocorrelations were observed between many variables when correlation matrices were examined. Monthly air temperatures were highly correlated with all other variables. This explains why no multiple regression model was attempted for monthly temperature prediction models. The additional variables included in the other models were not highly correlated. This explains, at least partly, the quasi-inefficiency of these factors in improving the predictive power of the models.

Their inclusion in the proposed model was based on their low linear correlation with air temperature, the major driving factor. Since air temperatures were highly correlated with soil temperatures, factors poorly correlated to air temperatures were also somewhat poorly correlated to soil temperatures. In spite of these poor linear correlations, these factors were included in the proposed models because it was thought that they might have some important curvilinear effects. This proved to be of some relevance particularly in the annual soil temperature prediction model at 0.1-m depth. It should be pointed out, however, that the additional variable (rainfall) in that model was computed as the ratio: total annual rainfall/12.

The use of only one year's weather data at each station in the present study may raise some questions about its representativeness in characterizing the temperature regime of these stations. This, however, should not be a problem because the requirement of long-term weather observation seems to be based on the poor intensity of temperature readings. Most of the soil temperature studies are based on one to two daily readings, so that the uncertainty to obtain an adequate precision is considerable. The precision can be increased with increasing temperature reading intensity (Smith et al., 1964). The mean annual temperature computed from four or more readings at regular intervals of time for any one year provides a very good estimate of the long-term mean annual temperature (USDA, 1975). In virtue of this, the data in the present study characterize well the long-term temperatures although based on 15-minute readings.

The models developed in this paper are based on soil temperature measurements at 0.1- and 0.5-m depths. The results obtained, therefore, are most applicable to these depths within the range of soil (Table 3.1) and climatic conditions (Table 4.1) defined in the present study.

4.1.3 Evaluation of Soil Temperature Models

Difference between Soil and Air Temperatures--To estimate the mean annual soil temperature at 0.5-m depth, Soil Taxonomy uses a procedure that can be mathematically expressed in terms of a model having the following form:

$$MAST50 = 1 + MAT$$

where MAST50 = mean annual soil temperature at 0.5-m depth, MAT = mean annual air temperature in ^oC. Clearly, the equation is of the form of a simple statistical model with the peculiarities that the estimated regression coefficient equals to 1 and the intercept also equals to 1. In other words, according to that model the difference between the mean annual soil temperature at 0.5-m depth and the mean annual air temperature is the unit ^oC. The results of the present study show that the difference is generally greater, ranging from 0.30 to 5.03 ^oC, as shown in Table 4.5. The average difference being nearly 2.5 ^oC. These results are in accordance with those reported by Embrechts and Tavernier (1983) who showed differences of 2.3 to 2.6 ^oC along a climosequence transect in Cameroon. The contradiction between these results and the model in use by Soil

Taxonomy may be related to two reasons. Firstly, the estimate of soil temperature in Soil Taxonomy's model is based on soil temperature measurement at depths that varied widely from site to site, whereas the mean annual air temperatures ranged only from about 8 to 22 ^{o}C, thus excluding most of the temperature regimes of the tropics. Secondly, the model in Soil Taxonomy was conceived for regions where rainfall was adequate in all seasons. One may expect discord for its application, however, under conditions such as those of the present study where soil temperatures were measured at a uniform depth, with the mean annual air temperature ranging from 13 to 24 ^{o}C and the rainfall being scant in some seasons and locations.

Evaluation of the Models--The main purpose of the models in the present study and the model in use by Soil Taxonomy is to predict soil temperature at different depths with the precision that is adequate for soil classification.

The first step of evaluating these models was plotting the output of the quadratic models and the observed temperatures versus air temperatures (Figures 4.2 through 4.7). The results indicated that the quadratic models agreed with the real system better than the simple linear equation.

The second step consisted of the validation of the quadratic models, comparing their output to independent data not included in the model-building process. The validation process was limited to the mean annual temperature because

Soil Taxonomy is primarily concerned with that temperature. The quadratic model for estimating soil temperature at 0.1 m was used to predict soil temperature at Wahiawa (Hawaii) and various other sites reported by Toy et al. (1978) at the depths indicated in Table 4.4. The results indicate that the predicted temperatures are in excellent agreement with the measured temperatures (Figure 4.8). The variance about the 1 to 1 line is small, as indicated by the small residual values (Table 4.4). Except for two sites, the predicted temperatures were within plus or minus 0.7 ^{o}C. This model can, therefore, provide a very good approximation of soil temperature at 0.1-m depth.

The quadratic model predicted well the annual soil temperatures at 0.5 m for most of the sites (Figure 4.9). There was a very good agreement between predicted and observed soil temperatures when air temperatures were between 16 and 22 ^{o}C. Outside of this range, however, there was a tendency for the model to underestimate soil temperatures (Table 4.5). In general, the predictions were within plus or minus 1.8 ^{o}C. The departures from the observed temperatures were higher (1.0 to 1.8 ^{o}C) for the range of air temperature above 22 ^{o}C and lower (0.6 to 0.8 ^{o}C) for air temperatures below 16 ^{o}C. The exception was the sites with annual air temperatures of 23.66 and 15.95 ^{o}C where the model overestimates soil temperatures. This was attributed to the effect of subsoil irrigation or tree-shading.

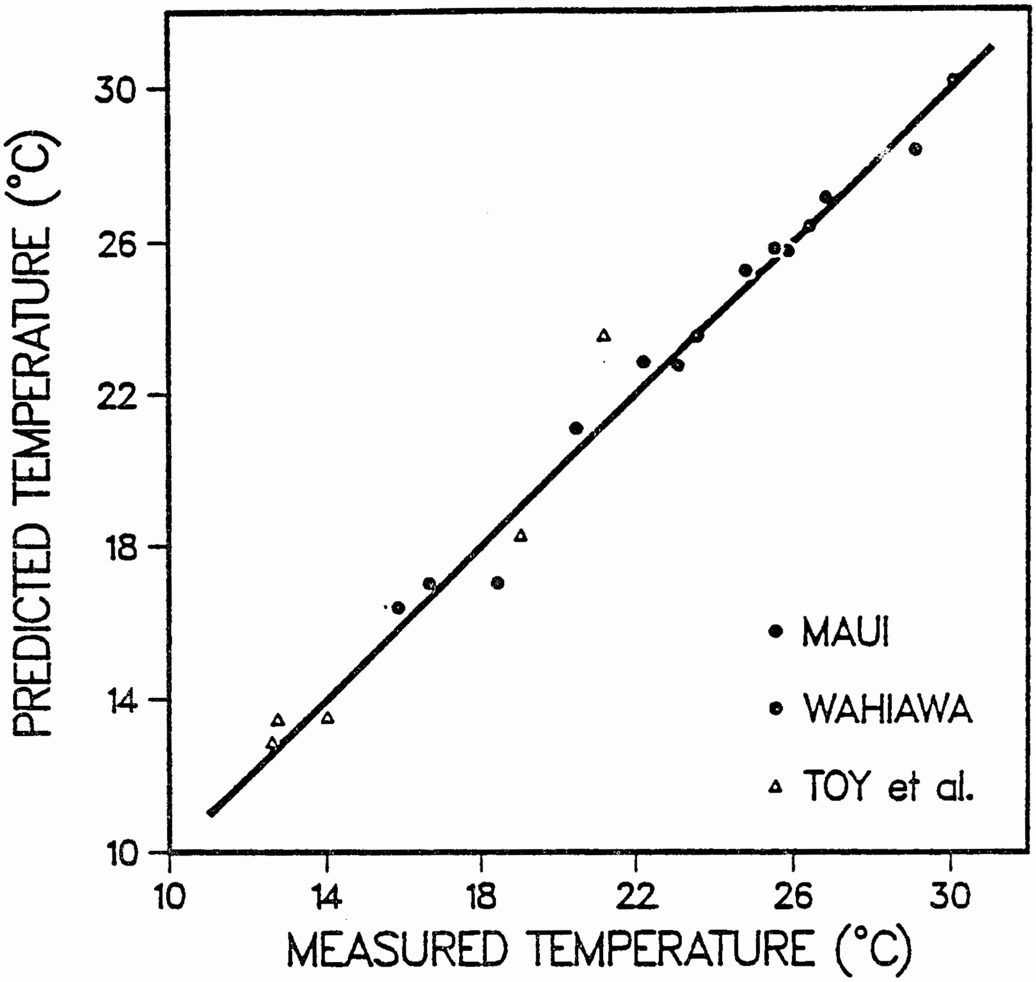


Figure 4.8. Relationship between Measured and Predicted Soil Temperatures within 0.1-m Depth, Using the Quadratic Model.

Table 4.4. Measured and Predicted Annual Soil Temperatures at 0.1-m Depth at Different Sites.

Measured Temperature(°C)			Predicted Soil Temperature(°C)	Residual
Air	Soil	Soil-Air	(oC)	(oC)
Site = Maui (this study)				
24.03	30.03	6.00	30.14	-0.11
23.66	26.80	3.14	27.13	-0.33
23.18	29.07	5.89	28.36	0.71
22.02	26.38	4.36	26.39	-0.01
20.74	23.57	2.83	23.51	-0.06
20.52	22.20	1.68	22.82	-0.62
19.68	23.09	3.41	22.72	0.37
18.08	20.48	2.40	21.08	-0.60
15.95	16.66	0.71	17.02	-0.36
15.61	18.43	2.82	17.03	1.40
13.37	15.86	2.49	16.38	-0.52
Site = Wahiawa *				
22.80	25.85	3.05	25.74	0.11
22.44	24.79	2.35	25.22	-0.43
22.85	25.52	-0.33	25.81	-0.29
Site = U.S. Mainland **				
20.30	21.20	0.90	23.56	-2.36
10.37	12.61	2.24	12.90	-0.29
16.17	19.05	2.88	18.29	0.76
11.16	12.75	1.59	13.50	-0.75
11.23	14.03	2.80	13.55	0.48

* Source: Ekern P.C. (1966b unpublished) soil temperature at 0.07 m depth.

** Source: Toy et al., 1978. Soil temperature at 0.05 m depth.

The quadratic model for estimating the mean annual soil temperature at 0.5-m depth was also used to predict soil temperatures in Peru (Manrique, as cited by Uehara and Gillman, 1981), USSR (Volobuev, 1983), and Venezuela (Comerma and Sanchez, 1983). The results show a good agreement between predicted and measured soil temperatures within the same range of temperatures indicated above for the present study (Figure 4.9). The model tended, however, to overestimate the soil temperature when these temperatures were above 28 ^{o}C, particularly so for Venezuela. This is in agreement with Gupta et al. (1981) who found that the difference between a physically-based model prediction and the measured soil temperature was larger when soil temperatures were greater than 28 ^{o}C.

Predictions from Soil Taxonomy underestimated the measured soil temperatures in general (Figure 4.10) and the differences varied from 0.0 to 4.04 ^{o}C (Table 4.5). The differences, however, ranged from only 0.0 to 1.48 ^{o}C for air temperatures below 22 ^{o}C and from 2.59 to 4.04 ^{o}C for air temperatures above 22 ^{o}C. The real mean difference calculated from air and soil temperature measurements amounted to 3.87 ^{o}C for temperatures higher than 22 ^{o}C and 1.99 ^{o}C for temperatures below 22 ^{o}C. This suggests that a modification of Soil Taxonomy's model whereby a constant is added to air temperature according to a temperature value may provide a better soil temperature prediction. The

Table 4.5. Measured and Predicted Annual Soil Temperatures at 0.5-m Depth.

Measured Temperatures (^{o}C)			Quadratic Model		Soil Taxonomy Model		Modified Soil Taxonomy	
Air	Soil	Soil-Air	Predicted	Residual	Predicted	Residual	Predicted	Residual
24.03	29.07	5.03	28.04	1.02	25.03	4.04	28.03	1.04
23.66	25.64	1.98*	27.45	-1.82*	24.66	0.98*	27.66	-2.02*
23.18	28.06	4.88	26.72	1.34	24.18	3.88	27.18	0.88
22.02	25.61	3.58	24.99	0.62	23.02	2.59	26.02	-0.41
20.74	23.22	2.48	23.22	0.00	21.74	1.48	22.74	0.48
20.52	21.52	1.00	22.88	-1.36	21.52	0.00	22.52	-1.00
19.68	21.67	1.99	21.77	-0.10	20.68	0.98	21.68	-0.01
18.08	19.70	1.62	19.79	-0.09	19.08	0.62	20.08	-0.38
15.95	16.24	0.30*	17.39	-1.15*	16.95	-0.71*	17.95	-1.71*
15.61	17.91	2.30	17.04	0.86	16.61	1.30	17.61	0.30
13.37	15.53	2.16	14.90	0.63	14.37	1.16	15.37	0.16

* Anomalous difference ascribed to infiltration of irrigation water, or shading due to forest.

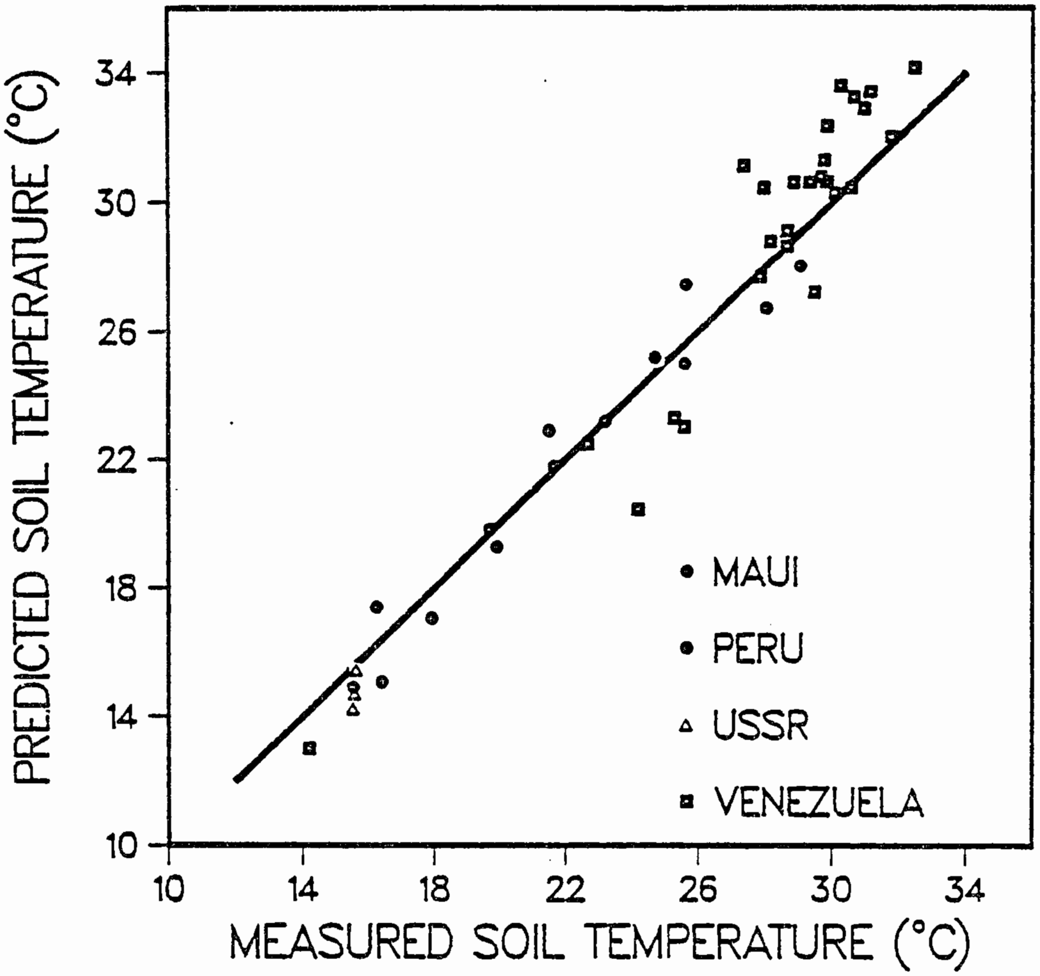


Figure 4.9. Relationship between Measured and Predicted Soil Temperatures from 0.2- to 0.5-m Depths, Using the Quadratic Model.

evidence on hand suggests that the model can be modified as follows:

MAST50 = 2 + MAT, if MAT is less than 22 ^{o}C

MAST50 = 4 + MAT, if MAT is equal to/more than 22^{o}C

where MAST50 = mean annual soil temperature, MAT = mean annual air temperature, and the value of 2 and 4 ^{o}C are approximately the mean differences calculated above.

The predicted soil temperatures computed from Soil Taxonomy's model and from the proposed model are shown in Table 4.5. These results indicate that the modified model predicted soil temperature better than the original model. It seems, however, that addition of 5 ^{o}C may be better for air temperature values that are greater than 24 ^{o}C, but insufficient data preclude such use.

Wilcoxon's two-sample test was used to perform analysis of variance. The nonparametric one-way procedure was used because normality was suspect. The procedure was applied to the output of the quadratic and Soil Taxonomy's models, as compared to the measured soil temperatures. The mean scores were 11.55 for the measured temperatures and 11.45 for the values predicted by the quadratic model (Table 4.6). When the test was performed on the measured temperatures and Soil Taxonomy's model, the mean scores were 12.64 and 10.36, respectively; that is, the predictions from the quadratic model were much closer to the observed temperatures than were those from Soil Taxonomy. In either case, however,

Table 4.6. Nonparametric Analysis of Variance for Testing the Distribution of Measured and Predicted Soil Temperatures at 0.5-m Depth.

MODEL	Level	N	Sum of Scores	Expected Under HO	Std Dev. Under HO	Mean Score	Prob > |Z|
Quadratic	Measured Temp.	11	127	126.5	15.23	11.55	
Model (a)							1.00*
	Predicted	11	126	126.5	15.23	11.45	
Soil	Measured Temp.	11	139	126.5	15.23	12.64	
Taxonomy (b)							0.43*
	Predicted	11	114	126.5	15.23	10.36	

* No evidence of significant difference ($P > 0.05$)

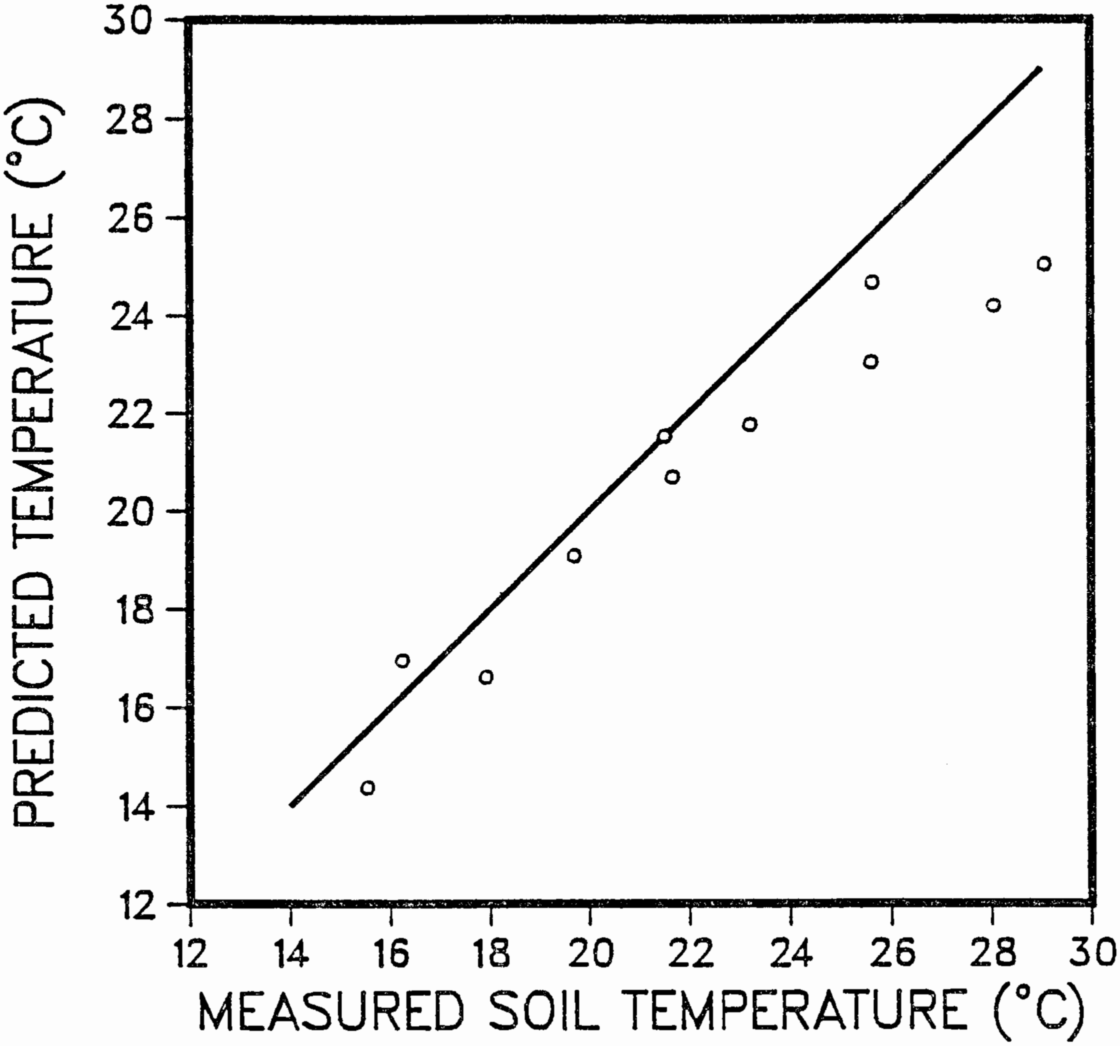


Figure 4.10. Relationship between Measured Soil Temperature and Soil Taxonomy Model.

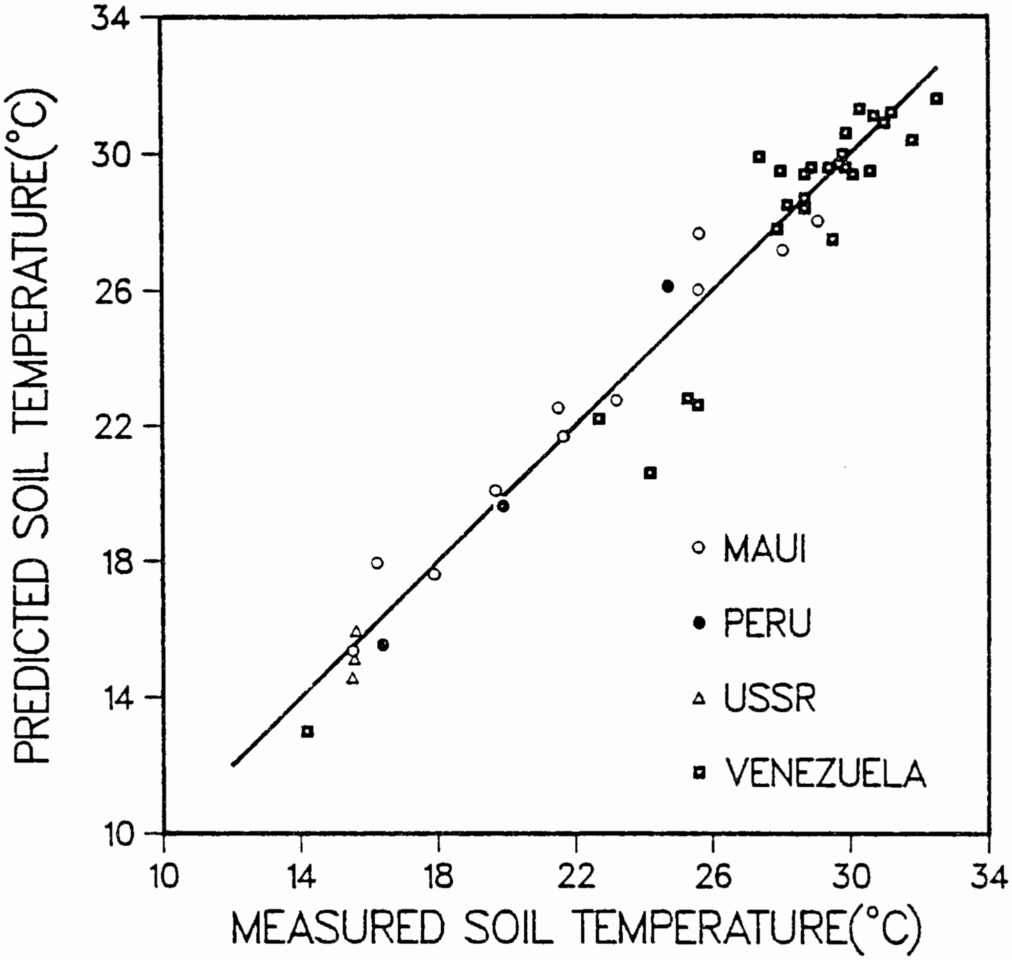


Figure 4.11. Relationship between Measured Soil Temperature and Modified Soil Taxonomy Model.

there was no significant difference (P greater than 0.05) between the observed temperatures and the predicted values (Table 4.6).

The validation of the modified Soil Taxonomy model was carried out using again the data from Peru, USSR, and Venezuela. The results indicated that the model predicted well the soil temperature in all regions, as substantiated by a nearly constant variance about the 1 to 1 line (Figure 4.11). This model is, therefore, preferable to the quadratic model because it is easy to use and it predicts soil temperature adequately over a wide temperature range.

4.2 Relationships between Grass Performance and Environment

Seasonal production of grass fluctuated widely from season to season and from site to site. This depended on the species and a combination of factors such as rainfall and/or soil moisture, temperature, and harvest number (Figures 4.8 through 4.11). In general, growth rate increased from the first to the second or third harvest and then decreased with subsequent harvests (Tables 4.7 through 4.10). The fluctuation of grass performance with season followed a similar pattern at all of the four sites, but the similarity in the trend was most striking at the two sites at lower altitudes (Kihei and Waiakoa) on one hand and at the two sites at the higher altitudes (Kekoa and Puu Pahu) on the other. Consequently, the analysis of fluctuation trends was performed on the basis of altitude.

4.2.1 Seasonal Variation of Herbage Growth at the Low Altitudes

At Waiakoa and Kihei, grass regrew mostly in winter and to a much less extent in spring. There was no regrowth during the other seasons of the years, presumably because of a combination of lack of moisture and too high temperatures. The first effective harvest at these two sites was in the winter of 1984. The mean growth rate at Waiakoa reached a maximum of 87.61 Kg/ha day while that at Kihei was only 15.45 Kg/ha day (Tables 4.7 and 4.8). During the second harvest in the spring of 1984, the growth rate was 22.63 and 13.30 Kg/ha day for Waiakoa and Kihei, respectively. Excluding summer and autumn when there was no regrowth at both sites, the minimum growth rates were obtained during the winter of 1985, 8.04 and 1.42 Kg/ha day for Waiakoa and Kihei, respectively.

The differences in grass performance between winter, 1984 and winter, 1985 at Kihei (15.45 vs. 1.42 Kg/ha day) and at Waiakoa (87.61 vs. 8.04 Kg/ha day) are noteworthy. These differences in production level during the different seasons within a site were attributed not only to the amount of rainfall but also to its distribution and the length of the period of soil moisture availability and the effect of successive defoliations on plant growth. For example, at Kihei, the total seasonal precipitation and temperatures were similar during the winters of 1984 and 1985 (Table

Table 4.7. Seasonal Fluctuation of Herbage Growth Rate and Some Related Environmental Factors at Kihei.

	SEASON					
	Autumn 1983	Winter 1984	Spring 1984	Summer 1984	Autumn 1984	Winter 1985
Growth Rate (Kg/Ha day)	0.00	15.45	13.30	0.00	0.00	1.43
% Max Growth Rate *	0.00	17.63	15.18	0.00	0.00	1.63
ATG**	24.53	22.63	23.31	26.20	24.77	22.16
STG10	31.39	26.59	29.40	34.45	30.66	25.75
STG50	30.24	26.60	28.20	32.50	30.44	26.58
RAD	46.18	34.58	53.06	56.50	38.79	37.40
RNG	14.00	52.00	31.00	0.00	0.00	52.00
ISMG10	1.50	0.96	0.96	1.50	1.50	1.50
SMG10	1.50	1.50	1.18	1.50	1.50	0.56
ISMG50	1.50	0.54	0.09	1.50	1.50	1.50
SMG50	1.50	0.33	0.45	1.50	1.50	1.50
MD10+	0/80	37/90	14/90	0/92	0/92	10/92
MD50+	0/80	44/90	49/90	0/92	0/92	0/92
Rainy days (day)	5	10	6	0	0	8
Harvest #	0	1	2	0	0	3

* % Maximum growth is computed relative to maximum growth at Waiakoa having the same species.

** Variables and measurement units are defined as in the table 3.4.2.

\+ Moist days. The numerator is the number of day when soil moisture tension was < 1.5 MPa and the denominator is the number of day for the growing period.

Table 4.8. Seasonal Fluctuation of Herbage Growth Rate and Some Related Environmental Factors at Waiakoa.

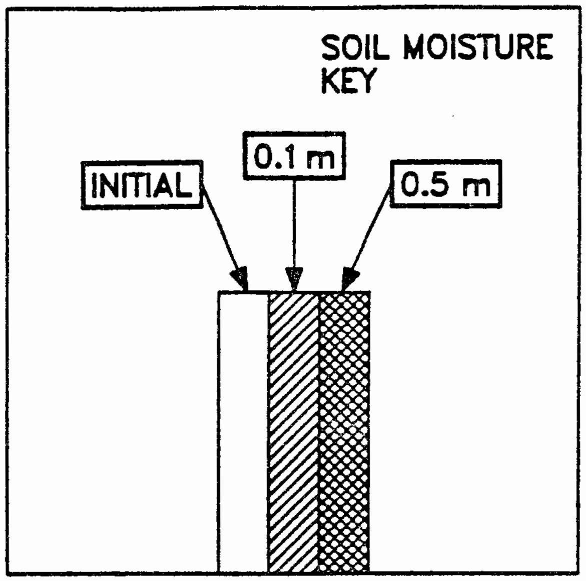
	SEASON					
	Autumn 1983	Winter 1984	Spring 1984	Summer 1984	Autumn 1984	Winter 1985
Growth Rate (Kg/Ha day)	0.00	87.61	22.63	0.00	0.00	8.04
% Max Growth Rate	0.00	100.00	25.84	0.00	0.00	9.18
ATG*	22.63	20.06	21.43	24.12	23.55	19.93
STG10	26.99	21.77	25.48	31.78	29.67	21.90
STG50	26.42	22.98	24.50	28.25	28.33	23.83
RAD	40.73	31.24	45.98	49.67	41.66	31.19
RNG	0.00	70.00	62.00	17.00	3.00	41.00
ISMG50	1.50	1.50	0.16	1.50	1.50	1.50
SMG10	1.50	0.27	0.68	1.50	1.50	0.25
ISMG50	1.50	1.50	0.48	1.50	1.50	1.50
SMG50	1.50	0.43	1.02	1.50	1.50	1.50
MD10+	11/80	57/90	29/90	0/92	0.92	52/92
MD50+	0/80	44/90	18/90	0/92	0/92	0/92
Rainy days (day)	8	14	5	6	3	9
Harvest #	0	1	2	0	0	3

* Variables and measurement units are as defined in the table 3.4.2.

\+ Moist days. The numerator is the number of day when soil moisture tension was <1.5 MPa and the denominator is the number of day for the growing period.

4.7). In spite of this similarity, the growth rate was more than 10 times higher during the winter of 1984 than during the winter of 1985. This was presumably because (1) the rains were earlier and heavy enough during the winter of 1984 to moisten the soil for about 50 percent of the growing period at 0.5-m depth, (2) the amounts and distribution of precipitation during the winter of 1985 were such that the soil was never moistened to the 0.5-m depth, and (3) the effect of successive defoliation on plant growth and the depletion of fertility level due to progressive nutrient removal with successive harvests. This conclusion is in agreement with Harris (1978) who reported that more frequent and more intensive defoliation resulted in reduction of herbage dry matter yield. The author added that this generalization applied to both temperate and tropical pasture species in many environments. Due to the late precipitation during the winter of 1985, it is assumed that the plants had not made use of most of the rainfall received before the preset harvesting time. This, in addition to the nutrient removal due to the previous harvests might also have contributed to the low production during the winter of 1985.

Buffel grass was the dominant species at both Waiakoa and Kihei. Although the soils are classified as Mollisols at both sites, it is deeper at Waiakoa, and the growth rates were much higher at Waiakoa (Table 4.8) than at Kehei (Table 4.7). The differences in the production levels



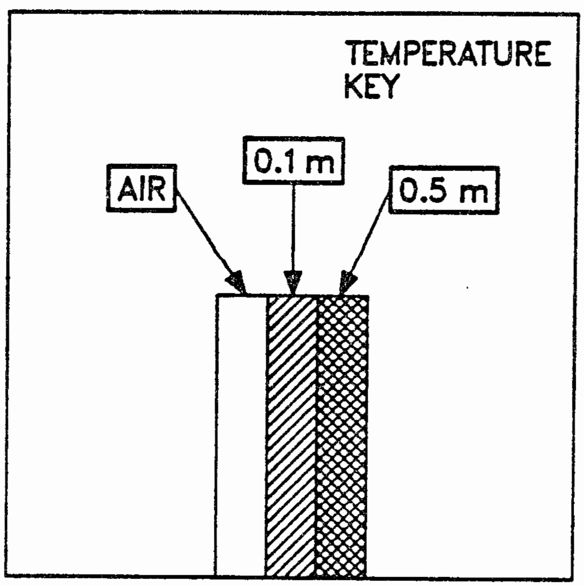


Figure 4.12. Key to Soil Moisture and Soil Temperature Diagrams (Figures 4.13 through 4.16).

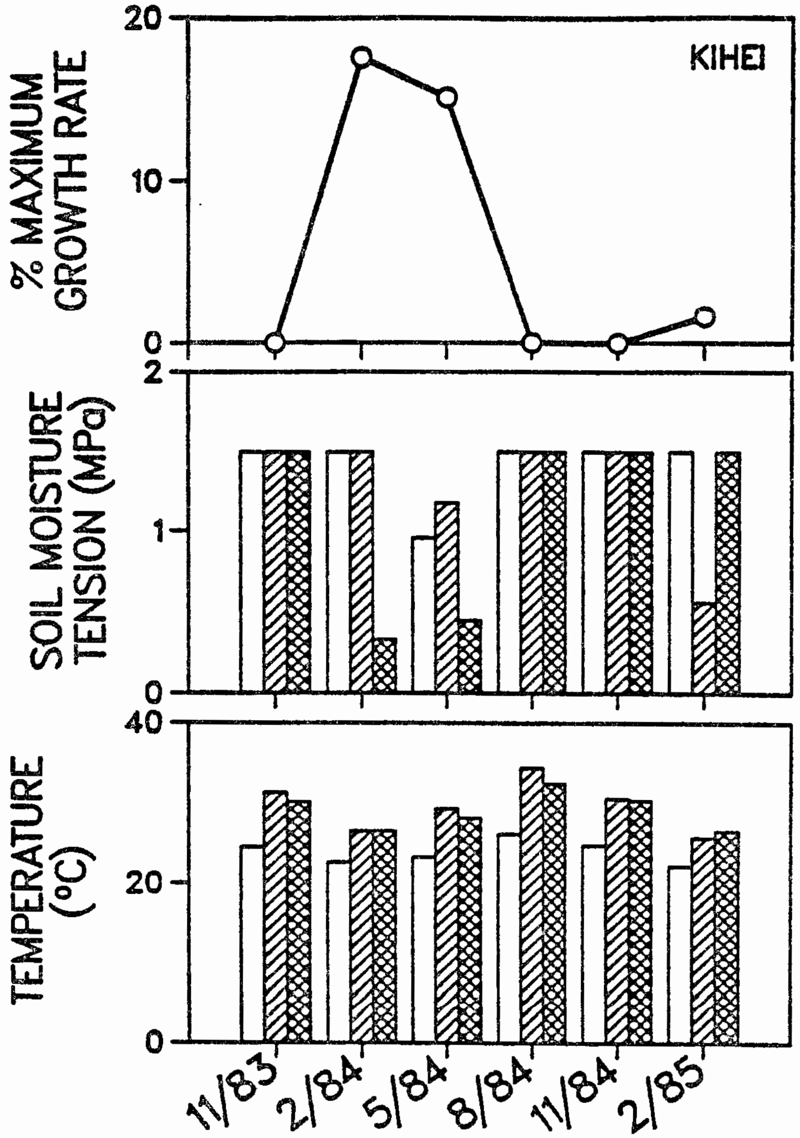


Figure 4.13. Seasonal Fluctuation of Herbage Growth Rate and Some Related Environmental Factors at Kihei Site.

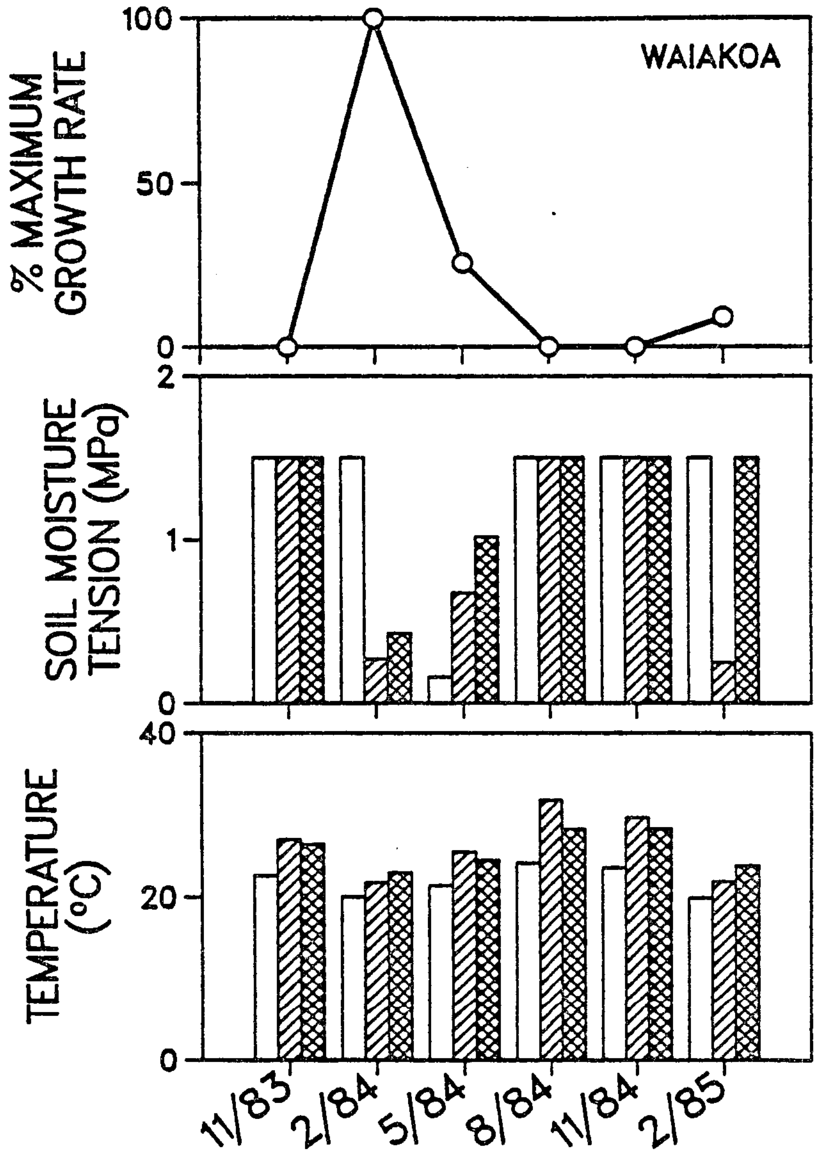


Figure 4.14. Seasonal Fluctuation of Herbage Growth Rate and Some Related Environmental Factors at Waiakoa Site.

between these two sites were attributed not only to differences in the soil phase, but also to differences in climatic conditions. This is in agreement with Thomas et al. (1973) who found that the same plant species growing in different climatic regions responded differently to water stress.

4.2.2 Seasonal Variation of Herbage Growth Rate at the High Altitudes

At the high altitude sites, Kekoa and Puu Pahu, where the rainfall was more regularly distributed over the year, the grass regrew at all seasons. There was, however, deep depressions in growth during some seasons (Tables 4.9 and 4.10). The first harvests at Kekoa and Puu Pahu were in the autumn of 1983, a season earlier than at the lower altitudes. The growth rate at Kekoa increased with successive harvests from the autumn of 1983 to the winter and spring of 1984. The growth then decreased through the summer and autumn of 1984, and finally increased again markedly during the winter of 1985 (Figure 4.15). The seasonal fluctuation of growth at Puu Pahu followed a similar pattern (Figure 4.16). Different grass species or communities are present at these sites. The maximum growth rates at both sites were observed, however, during the spring of 1984 (28.49 and 11.46 Kg/ha day for Kekoa and Puu Pahu, respectively).

Although other factors may have had some effects, these fluctuations were apparently most related to temperatures, amount and distribution of rainfall, and soil moisture over the growing period. Too little or too much soil moisture over the growing season, however, resulted in depression of growth at some site. For example, the growth rate was 3.1 Kg/ha day at Kekoa during the autumn of 1984 when the soil was moistened only to 0.1-m depth for 34 percent of the growing period. The growth rate was 12.64 Kg/ha day (Table 4.9) when the soil was moistened at both 0.1- and 0.5-m depths for 50 and 31 percent of the growing season, respectively, during the autumn of 1983. The lower productivity level during the autumn of 1984 was attributed, to a large extent, to the lower soil moisture. A similar comparison can be shown between the growth during the autumn of 1983 and autumn of 1984 at Puu Pahu (Table 4.10). This table also shows that too long a period of soil wetness depresses growth in some species. For example, the growth rate was only 7.22 Kg/ha day during the autumn of 1983 when the soil was moist 99 percent of the time to the depth of 0.5 m. Despite the lower temperatures during the spring of 1984, the growth rate was, however, 11.46 Kg/ha day when the soil was moist only 80 percent of the time at 0.5-m depth. The lower growth rate during the autumn of 1983 can be attributed to an excess of soil moisture thereby causing a low supply of oxygen to the roots. This conclusion is in agreement with those reported by West and Black (1969) who found that the oxygen flux to the root system of grass swards

Table 4.9. Seasonal Fluctuation of Herbage Growth Rate and Some Related Environmental Factors at Kekoa.

	SEASON					
	Autumn 1983	Winter 1984	Spring 1984	Summer 1984	Autumn 1984	Winter 1985
Growth Rate (Kg/Ha day)	12.64	15.63	28.49	5.78	3.10	13.84
% Max Growth Rate	44.38	55.07	100.00	20.30	10.90	48.59
ATG*	18.73	16.86	17.34	19.13	19.37	16.48
STG10	20.07	17.93	19.92	22.99	22.21	17.95
STG50	20.61	18.60	19.17	20.78	20.92	18.61
RAD	37.52	30.64	43.74	44.26	40.22	30.59
RNG	36.00	68.00	82.00	13.00	24.00	59.00
ISMG10	1.36	0.57	0.08	0.10	1.50	0.08
SMG10	0.26	0.24	0.15	0.76	0.45	0.08
ISMG50	1.50	0.80	0.07	0.28	1.50	1.50
SMG50	0.76	0.28	0.13	0.75	1.50	0.25
MD10+	40/80	58/90	72/90	27/92	31/92	92/92
MD50+	25/80	46.90	90/90	21/92	0/92	68/92
Rainy days (day)	11	15	10	4	6	11
Harvest #	1	2	3	4	5	6

* Variables and measurement units are defined as in the table 3.4.1.

\+ Moist days. The numerator is the number of day when soil moisture was <1.5 MPa and the denominator is the number of day for the growing period.

Table 4.10. Seasonal Fluctuation of Herbage Growth Rate and Some Related Environmental Factors at Puu Pahu.

	SEASON					
	Autumn 1983	Winter 1984	Spring 1984	Summer 1984	Autumn 1984	Winter 1985
Growth Rate (Kg/Ha day)	7.22	9.22	11.46	9.64	3.30	7.79
% Max Growth Rate	63.00	80.50	100.00	84.14	28.84	68.02
ATG*	14.82	12.81	12.40	13.98	14.55	12.84
STG10	16.36	13.70	15.40	17.72	16.84	12.93
STG50	16.20	14.46	14.80	16.52	16.50	14.52
RAD	33.65	29.28	35.73	37.67	32.74	28.99
RNG	61.00	105.00	68.00	51.00	29.00	118.00
ISMG10	0.08	0.78	0.07	0.07	1.50	1.50
SMG10	0.09	0.18	0.13	0.32	0.56	0.29
ISMG50	0.15	0.18	0.08	0.07	0.10	0.57
SMG50	0.15	0.18	0.07	0.08	0.30	0.22
MD10+	79/80	75/90	90/90	92/92	74/92	57/92
MD50+	79/80	86/90	72/90	57/92	39/92	56/92
Rainy days (day)	19	24	9	12	10	18
Harvest #	1	2	3	4	5	6

* Variables and measurement units are defned as in the table 3.4.2.

\+ Moist days. The numerator is the number of day when soil moisture tension was <1.5 MPa and the denominator is the number of day for the growing period.

accounted for differences in dry matter production under wet soil conditions. This seems, however, to be associated with the species. The comparison between growth rate during the autumn of 1983 and spring of 1984 at Kekoa (Table 4.9) shows that the growth rate was twice as much during the spring of 1984 than during the autumn of 1983. The soil at 0.5-m depth was, however, moist 100 percent of the time during the spring. Apparently, these conflicting results are attributable to the species adaptation to soil moisture conditions.

At both sites, Kekoa and Puu Pahu, the growth rate was depressed during the summer and autumn of 1984, as compared to the preceding seasons. This was attributed not only to the high moisture tension during the summer and autumn of 1984 but also the effects of the preceding defoliations and depletion of soil fertility levels. There was, however, a marked increase in growth rate during the winter of 1985, as compared with the preceding season. This was believed to be due to the greater availability of soil water in the winter of 1985. These observations suggest that the adverse effect of successive defoliations and nutrient removal may be alleviated by adequate moisture supply under favorable temperature conditions. This is in agreement with Whitney (1974a) who reported that reduction in grass production due to successive cuttings in irrigated experiment was less than noted in unirrigated pasture grass.

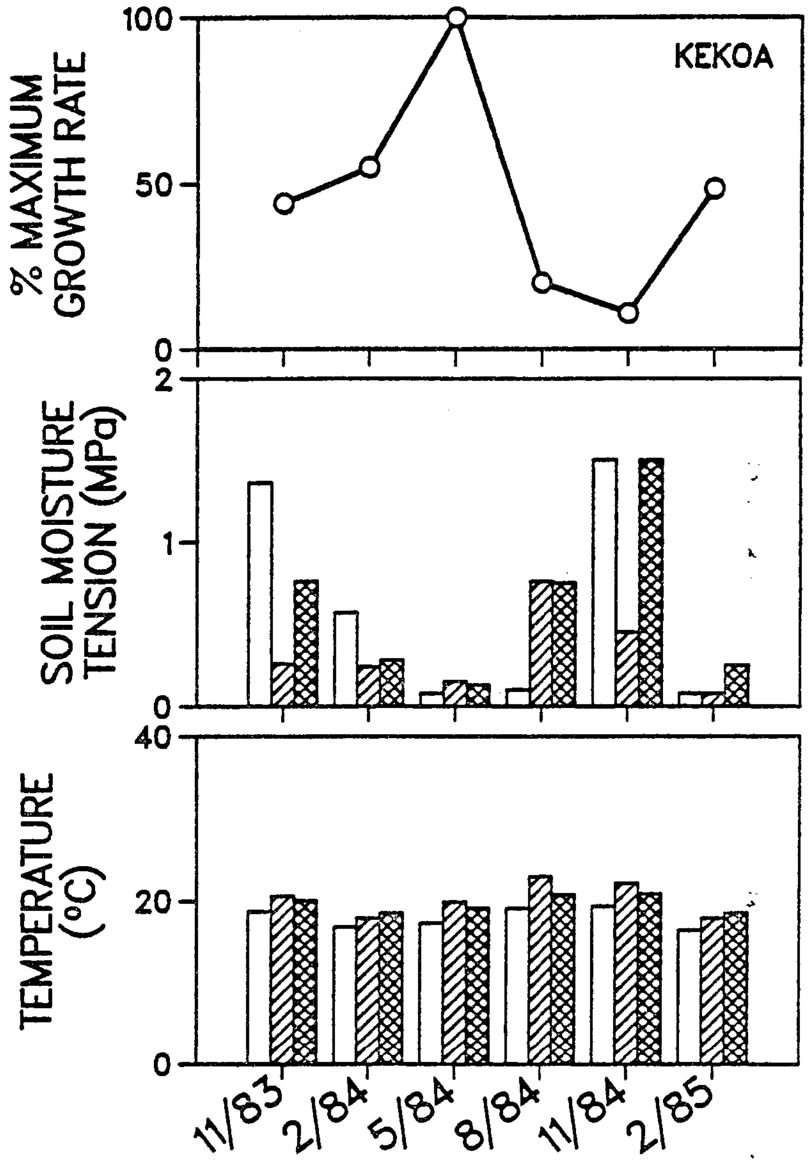


Figure 4.15. Seasonal Fluctuation of Herbage Growth Rate and Some Related Environmental Factors at Kekoa Site.

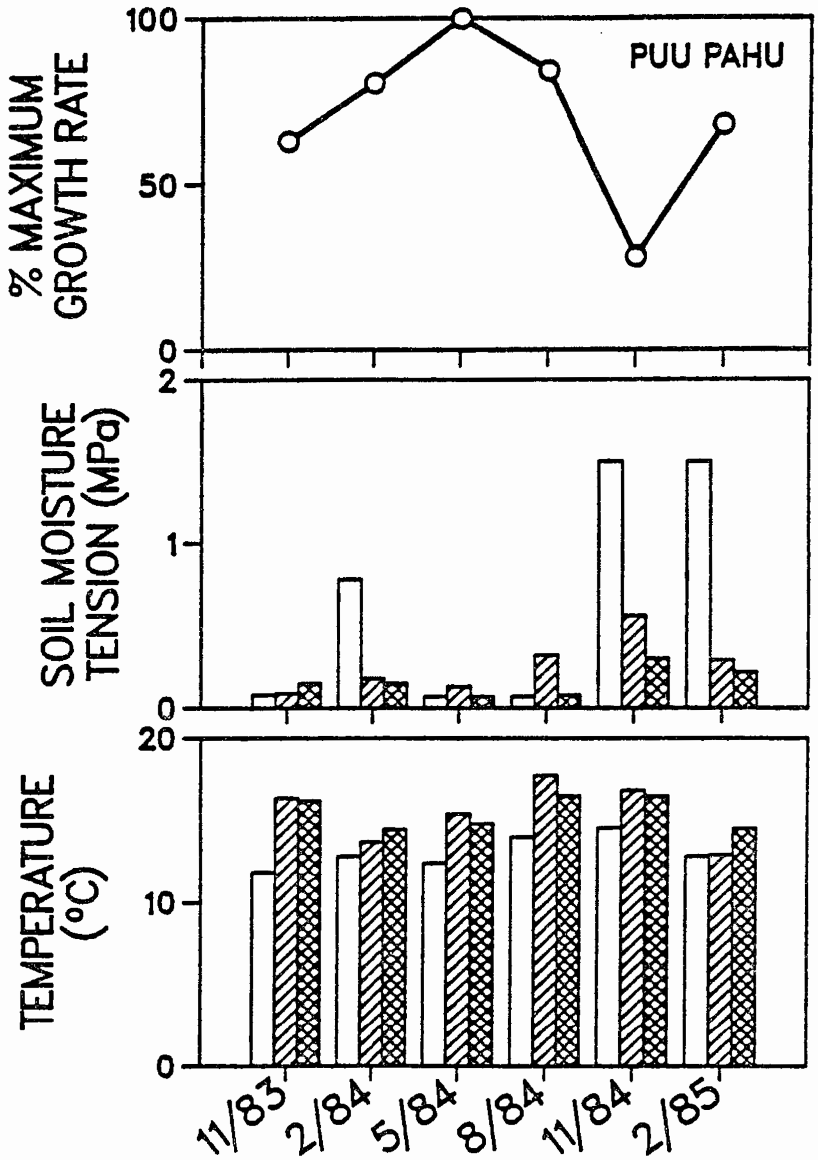


Figure 4.16. Seasonal Fluctuation of Herbage Growth Rate and Some Related Environmental Factors at Puu Pahu Site.

This overview of the data at the low and high altitudes indicates that seasonal variation of grass growth follows fluctuation of seasonal atmospheric weather, soil moisture, and management factors. It does not provide, however, a measure of the closeness of the relation between grass performance and the individual potential causative factors. This approach was carried one step further in an attempt to relate the percent maximum growth rate to individual environmental factors by means of linear correlation analysis. Because the present research deals mainly with the relationship between growth and soil-climate, the simple linear correlation analysis is, however, limited to correlation between herbage productivity and temperature, rainfall, and soil moisture.

4.2.3 Linear Correlation between Grass Performance and Some Environmental Factors

When simple linear correlation coefficients were computed between seasonal mean growth rate of the sites and the environmental factors, the relation was significant (P less than 0.05) only between the mean growth rate and rainfall (r = -0.41). The correlation, however, became significant with most of the factors when percent maximum growth rate was used instead. Consequently, the percent maximum growth rate was further used as an expression of the relative growth in the analysis of relationships between pasture grass performance and the environmental factors.

The percent maximum growth rate or relative performance of pasture grass was directly correlated to seasonal precipitation but inversely correlated to temperature, solar radiation and soil moisture tension (Table 4.11). Growth correlations involving rainfall or soil moisture tension at 0.1-m depth were slightly weaker than those between growth and mean temperatures. A reverse situation was observed at 0.5-m depth. The coefficient of correlation between growth and mean moisture tension at 0.5-m depth was higher than between growth and any other single factor considered in the present study (r = -0.84**). Although low or high simple linear correlation between two variables is not always proof of lack or existence of a cause and effect relationship, it does suggest that causality may be involved. This is made even more plausible in the present study inasmuch as the nature of the relationships expressed by the nature of the correlation coefficients was that observed under the conditions of this experiment. Furthermore, in this study, close correlation between relative pasture grass performance and climatic factors are mostly interpreted as a cause and effect relationship.

The positive correlation between growth and precipitation indicates that high grass productivity attained at a particular season tends to be generally associated with high seasonal precipitation. This result is in agreement with Pengra (1946) who reported significant positive correlation

Table 4.11. Coefficient of Correlations between Grass Performance and Some Environmental Factors (%).

	%M.GRATE	ATG	STG10	STG50	RNG	SMG10	SMG50	RAD	OCA
ATG	-79*								
STG10	-77	98							
STG50	-78	99	98						
RNG	78	-73	-78	-72					
SMG10	-76	83	88	86	-74				
SMG50	-84	79	76	78	-72	86			
RAD	-48	67	77	67	-61	64	41		
OCA	67	-92	-88	-94	53	-74	-71	-49	
pHA	61	84	81	87	-48	72	68	43	-97
HARV	32								

* significance level at 5% probability = 40.4

significance level at 1% probability = 51.5

between crop yield and precipitation. However, correlation coefficients for preseasonal precipitation and yields were larger than the corresponding coefficients for yields and seasonal precipitation for small grains. A reverse situation was noted for corn. Similar results were reported by Rogler and Haas (1947) and Blaisdell (1958) who found highly significant correlations between yield and precipitation within selected periods of years. Instead, Passey et al. (1982) found significant correlations between annual production and precipitation but on only four of 117 soils studied. Among other factors, this inconsistency was attributed to error in adjustment of data to the study locations and few periodic measurements that did not reveal the influence of precipitation during short but critical times.

On the other hand, the growth was inversely correlated with soil moisture tension (Figure 4.17) and temperatures (Figures 4.18 and 4.19). That is, low soil moisture tension and low temperatures were associated with high growth achieved in a particular season. Soil moisture tension is best interpreted as an expression of soil moisture deficit corresponding to high productivity. The depression of grass growth with soil moisture stress has been reported by many workers. Henderson and Robinson (1982), for example, found that imposed moisture stress sharply reduced dry matter production of dallis grass. Wilson (1983), on the other hand, reported that water stress slowed stem development in others.

Despite the negative significant correlations between temperatures and grass growth, it is believed that the range of the temperature in this study did not have a deleterious effect on most of the grass species subjected to these temperatures. The apparent effect of high temperature in this study was then ascribed to the lack of rainfall and the high temperatures, the latter being associated with high water stress. Actually, the soil moisture deficit and temperature are positively correlated (Table 4.9). The apparent detrimental effect of temperature, therefore, is associated with the deleterious effect of water stress rather than the temperature per se. These results are in agreement with those reported by Herbel and Sosebee (1969) who found that low temperature regime was more favorable for plant growth than high temperature regime and by Varde (1984) who reported negative correlation between temperatures and production of various irrigated crops where negative correlations were also observed between precipitation and yields of these crops.

Simple linear correlation analysis reveals the degree of association between growth and a given factor and the direction of change among these variables. It does not, however, show the quantitative measure of change in one variable associated with a unit change in the other variable. Moreover, such analysis refers to a simple linear relationship between only two variables and fails to describe

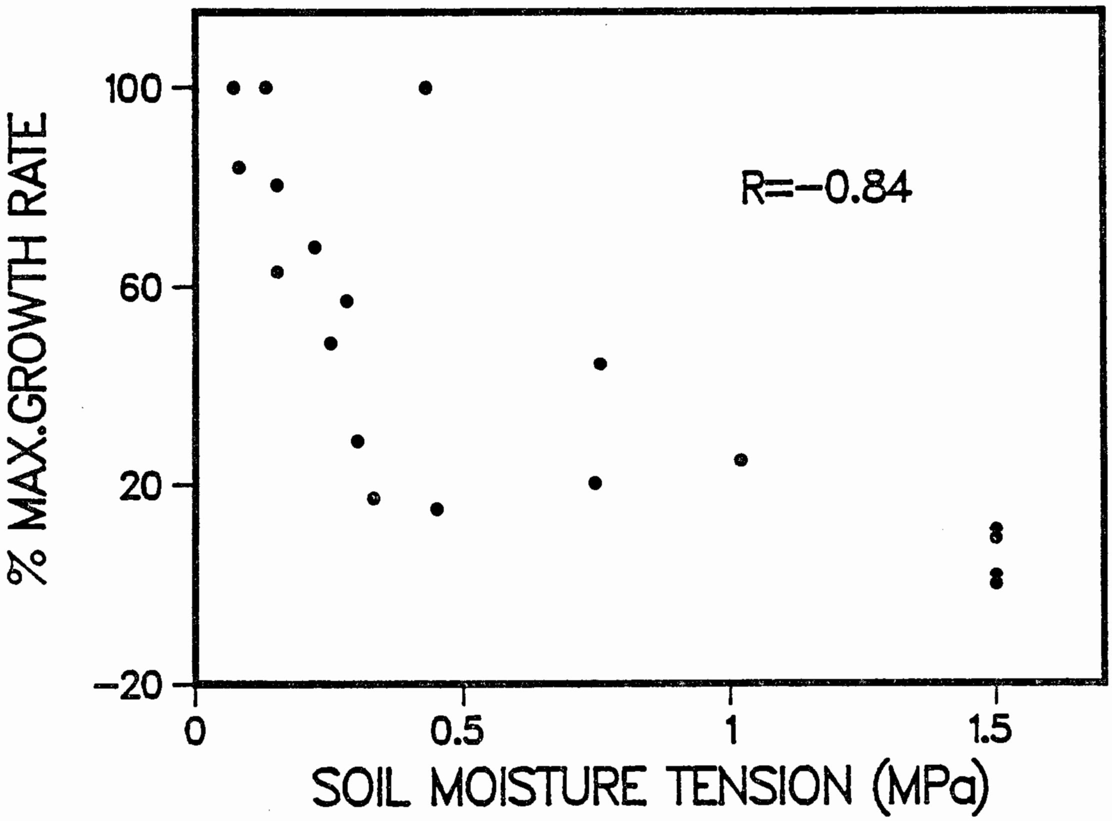


Figure 4.17. Relationship between Grass Performance and Mean Soil Moisture Tension at 0.5-m Depth.

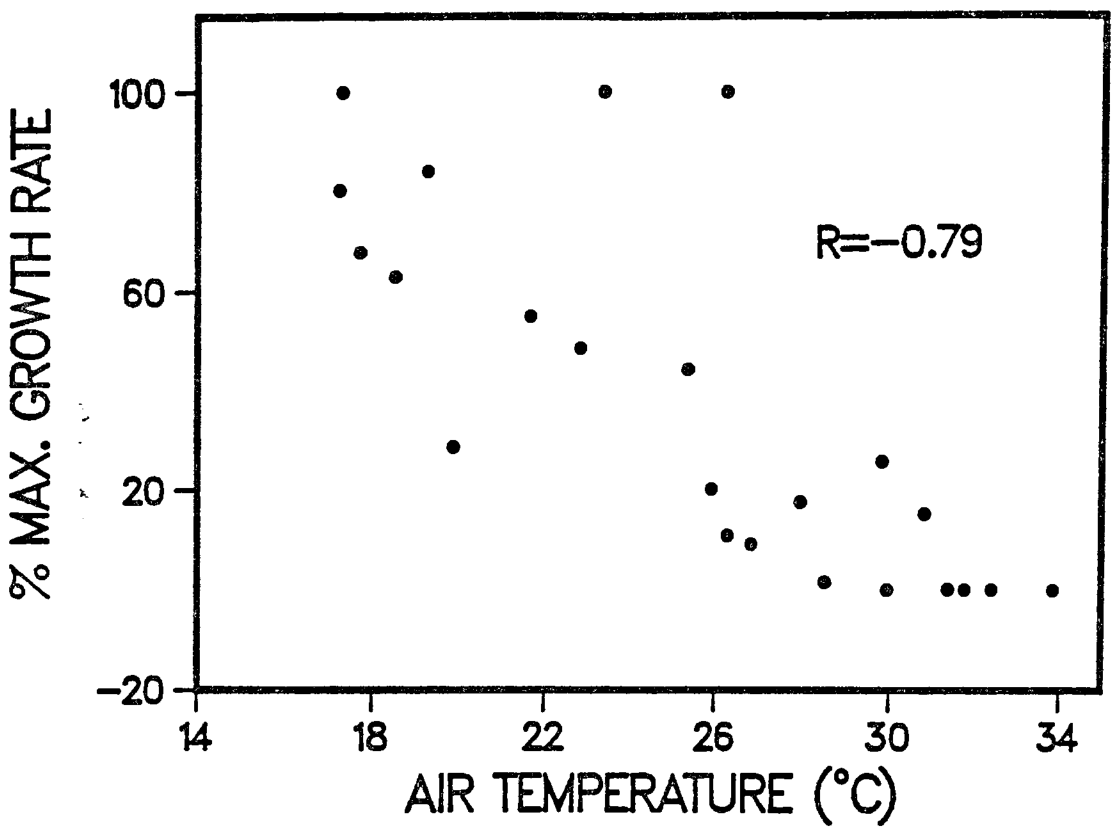


Figure 4.18. Relationship between Grass Performance and Mean Air Temperature.

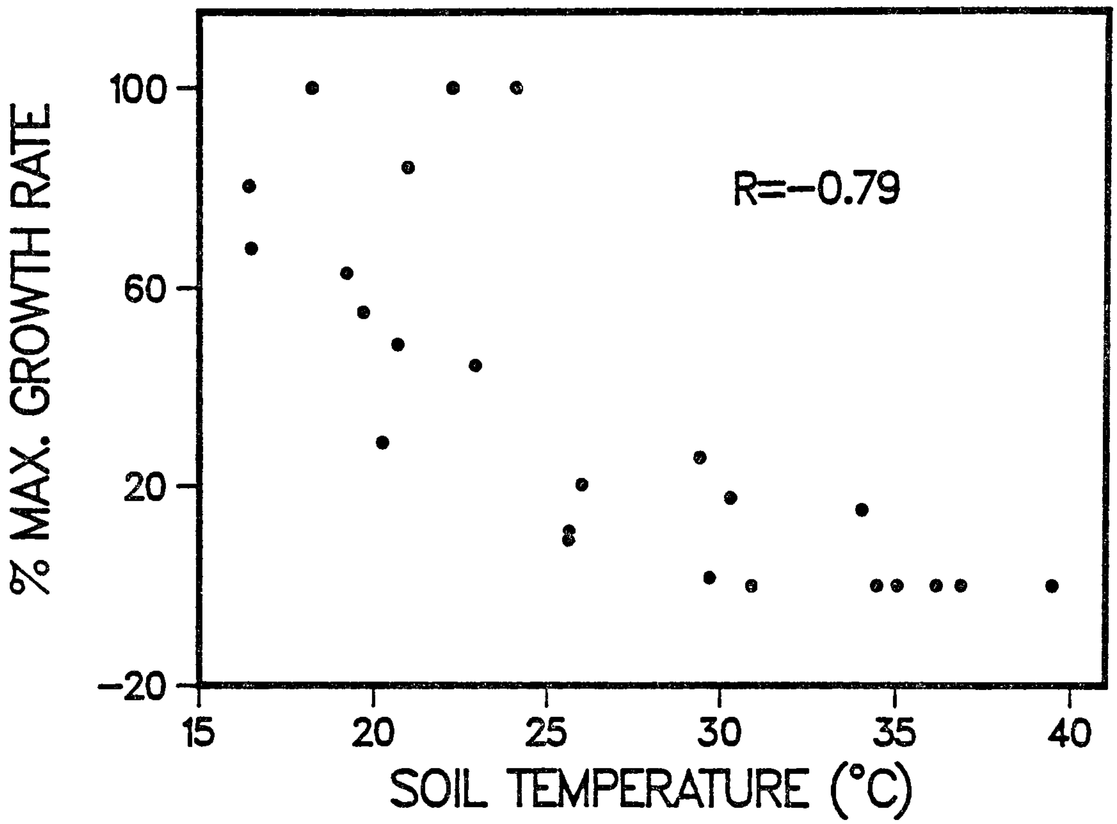


Figure 4.19. Relationship between Grass Performance and Soil Temperature at 0.1-m Depth.

adequately situations in which growth reaches a maximum and then decreases. Yet, more than one variable are involved in the plant growth. Consequently, the development of polynomial quadratic models was undertaken to seek for multiple correlation between relative pasture grass performance and a combination of the influential factors.

4.2.4 The Models and Their Interpretation

A total of 190 variables were defined, including measurement variables, transformed data, and interactions. The goal was, however, to build models containing only the most significant factors that go together to determine herbage production. Sensitivity analysis was, therefore, performed on different groups of factors through several preliminary studies in order to assess the relative importance of their effect.

Many variables were found to be nonsignificant because their presence did not improve the predictive capability of the models, based on the R^2 and residual mean squares criteria. These variables were therefore ignored. This process allowed practically the elimination of all of the soil properties except the rooting depth. The remaining variables were used to fit the polynomial quadratic functions by the least square method, using stepwise regression procedure and the SAS computer package.

Model I: Relation between Growth, Soil, and Atmospheric Weather--The least square method was used to fit the following second degree polynomial equation:

$$\% \text{ Max. Growth Rate} = b_o + b_1ATG + b_2ATG^2 + b_3RNG + b_4RNG^2 + b_5RAD + b_6RAD^2 + b_7HARV + b_8HARV^2 + b_9DEPTH + b_{10}DEPTH^2 + c_1(ATG \times RNG) + c_2(ATG^2 \times RNG) + c_3(ATG \times RNG^2) + c_4(RAD \times RNG) + c_5(RAD^2 \times RNG) + c_6(RAD \times RNG^2) + c_7(HARV \times RNG) + c_8(HARV^2 \times RNG) + c_9(HARV \times RNG^2) \quad (I)$$

where b_o = expected growth when all input data are zero, b_i and c_i are partial estimated regression coefficients and the other symbols are defined in Table 3.3.

Table 4.12 indicates that the most influential factors determining productivity at the atmosphere level are air temperature, harvest number, and the interaction between solar radiation and rain. Together, these factors explain 79 percent of the variation in the percent maximum growth, as indicated by the coefficient of determination (R^2 = 0.79).

According to the linear correlation analysis, air temperature is inversely related to growth. The importance of temperatures on plant growth lies primarily on its effect on photosynthesis, but this effect depends upon the species and the environmental conditions (Salisbury and Ross, 1978). For most tropical and subtropical grass species, the minimum temperature of regrowth following defoliation is below 15 ^oC and the optimum temperature is between 25 and 30 ^oC (Whitney

1974a; McWilliam, 1978). The mean seasonal air temperature at the three of the four sites varied from 16 to 26 ^{o}C. The apparent decrease in growth with increase in temperature was, therefore, attributed to increasing water deficits associated with the period of high temperatures. The cardinal temperatures generally shown in literature refer mostly to conditions when the effects of other environmental stress have been eliminated. The present study suggests that in the presence of other environmental stress such as water and/or nutrient deficiency, the cardinal temperatures may significantly differ from those reported above. This is in agreement with Blaisdell (1958) who found negative correlations between herbage production and temperatures in experimental conditions comparable to those of this study. The author added that the inverse relation existed irrespective of rainfall. The correlation, however, became positive when the effect of soil moisture was removed. Blaisdell also cited Hooker's work where the temperature was negatively correlated with grain and hay yield, even after elimination of the effect of precipitation.

The grass performance, on the other hand, was positively associated with the interaction between solar radiation and rainfall. This was due to the beneficial effect of both irradiance and rainfall on plant growth. These results are in agreement with those of Monteith (as cited by Baver et al., 1972) who outlined the importance of solar radiation

Table 4.12. Independent Variables in the Regression Models Relating Relative Growth of Pasture Grass to Soil, Atmosphere and Soil-climate.

Independent Variables	Estimated coefficients	F
a) Model I, Using Soil and Atmospheric Factors (R^2=0.79)		
Intercept, bo	142.15	
Mean Air Temperature	-5.99	19.37***
Solar Rad. x Rain	1.54×10^{-2}	11.21**
Harvest Number	-6.92	6.02*
b) Model II, Using Soil, Atmosphere and Soil-climate at 0.1 m depth (R^2=0.83)		
Intercept, bo	246.65	
Soil Max. Temp.	-13.544	6.42*
Moist. tension x $(\text{Harvest number})^2$	-0.214	2.93^+
Rainfall x $(\text{Solar, Rad.})^2$	3.15×10^{-5}	3.27***
$(\text{Mean Soil Temperature})^2$	0.24	3.39^+
c) Model III, Using Soil, Atmosphere and Soil-climate at 0.5 m depth (R^2=0.90)		
Intercept, bo	48.49	
Moisture Tension	-4.83	33.34***
Solar Rad. x $(\text{Rain})^2$	1.51×10^{-5}	19.21***
$(\text{Initial Moist. Tension})^2$	0.624	12.42**
Initial Moist. Tension	-9.07	9.23**
Rooting Depth	23.96	5.53*
$(\text{Harvest Number})^2$	-0.655	3.81^+

***, **, *, + significant at the 0.1, 1, 5, and 10% probability levels, respectively. To indicate also their relative importance, the variables are listed according to their order of entry in the model.

and rainfall to plant growth in defining agriculture as an exploitation of solar energy in presence of adequate supply of water and nutrients.

Model I also indicates that grass performance was depressed as the harvest number increased. Because the plots were not fertilized, the yield depression is presumed to be due to the combined effect of severe defoliation and the progressive depletion of nutrient level with successive harvests. Harvesting operation by defoliation is a disturbance, one of the major determinants of pasture grass growth (Harris, 1978). The relationship between herbage production and harvest number expressed in Model I is consistent with the findings of other workers such as Hubbard and Harper (1949) who found that successive severe clippings reduced tiller number and green forage yields. They also relate to the work of Oldeman (1971) and Kourouma (1979) who reported that the ratoon crop produced less than the plant crop of sugarcane. Curl and Davidson (1983) also reported the lowest net herbage production during weekly cuttings in a series of defoliation treatments. Hunt and Brougham (1967) assigned these effects to an interplay of factors such as differences in light, moisture and nutrient utilization as well as the intensity of defoliation in relation to root survival and energy storage. The most adverse effects occurred under the most intensive and severely defoliated systems of pasture management.

Model I, therefore, rationally explains 79 percent of the variation in grass response to the environment. The model fails, however, to express the quadratic effect of temperature and the direct effect of rainfall on herbage production.

Model II: Relation between Growth, Soil, and Soil-Climate at 0.1-m Depth--The same methodology of data reduction described in the previous sections was also used to fit a polynomial quadratic equation having the following general form:

$$\begin{aligned}\text{\% Max. Growth Rate} = {} & b_o + b_1\text{STG10} + b_2\text{STG10}^2 + \\ & b_3\text{SMG10} + b_4\text{SMG10}^2 + b_5\text{ISMG10} + b_6\text{ISMG10}^2 + \\ & b_7\text{RAD} + b_8\text{RAD}^2 + b_9\text{HARV} + b_{10}\text{HARV}^2 + b_{11}\text{DEPTH} + \\ & b_{12}\text{DEPTH}^2 + c_1(\text{STG10 x SMG10}) + c_2(\text{STG10}^2\text{ x SMG10}) + \\ & c_3(\text{STG10 x SMG10}^2) + c_4(\text{RAD x RNG}) + c_5(\text{RAD}^2\text{ x RNG}) + \\ & c_6((\text{RAD x RNG}^2) + c_7(\text{HARV x SMG10}) + \\ & c_8(\text{HARV}^2\text{ x SMG10}) + c_9(\text{HARV x SMG10}^2) \qquad \text{(II)}\end{aligned}$$

where b_o = expected grass response when all input values are zero, b_i and c_i are estimated partial regression coefficient, and the meaning of the other symbols is given in Table 3.3).

The variable selected were the maximum soil temperature interaction between harvest number and soil moisture tension, interaction between rain and solar radiation, and the quadratic effect of mean soil temperature (Table 4.12).

Model II indicates that the percent maximum growth rate decreased when maximum soil temperature increased and also decreased when the product of soil moisture tension x quadratic term of harvest number increased. The grass performance, however, increased with the interaction of rainfall x quadratic term of solar radiation. It also increased with the quadratic term of mean soil temperature. The rational behind the contribution of each of the variables in Model II has been discussed earlier. In particular, the inverse relation between herbage productivity and temperature was attributed to a concomitant soil water stress. Stomatal closure has often been associated with large soil water deficit; that is, when water is limiting, the stomata close, the CO_2 exchange and photosynthesis are reduced, and cellular expansion is retarded (Salisbury and Ross, 1978; Turner and Begg, 1978). These factors all contribute to depressed growth.

There is, therefore, a good logic in the relationships between plant growth and the selected variables, as expressed in Model II. The combined effect of these variables explained 83 percent of the variation in maximum growth rate. In contrast to Model I, Model II has a curvilinear relationship between grass growth and temperature. This is in agreement with Wijk et al. (1959), Burrow (1963), and Willis et al. (1969), who found that corn growth increased with temperature up to an optimum and then decreased with further increase in temperature. The coefficient of determination (R^2) is also higher for Model II with soil temperature than for Model I with air temperature. Soil temperature rather than air temperature is, therefore, the main determinant of grass growth. These findings are in agreement with Whitney (1974b), who reported that soil temperature at 0.05-m depth rather than air temperature as being the second major factor after nitrogen in predictive value.

A noticeable feature in Model II is the dominance of soil temperature terms and a relative small importance of soil moisture at 0.1-m depth. This suggests that soil temperature at 0.1-m depth may be a more significant indicator of failure or success of herbage production than soil moisture at that depth.

Model III: Relation between Growth, Soil, and Soil-Climate at 0.5-m Depth--The least square method was also used to fit a polynomial quadratic regression equation with the following general form:

$$\begin{aligned}\%\ \text{Max. Growth Rate} = {} & b_o + b_1\text{STG50} + b_2\text{STG50}^2 + \\ & b_3\text{SMG50} + b_4\text{SMG50}^2 + b_5\text{ISMG50} + b_6\text{ISMG50}^2 + \\ & b_7\text{RAD} + b_8\text{RAD}^2 + b_9\text{HARV} + b_{10}\text{HARV}^2 + b_{11}\text{DEPTH} + \\ & b_{12}\text{DEPTH}^2 + c_1(\text{STG50} \times \text{SMG50}) + c_2(\text{STG50}^2 \times \text{SMG50}) + \\ & c_3(\text{STG50} \times \text{SMG50}^2) + c_4(\text{RAD} \times \text{RNG}) + c_5(\text{RAD}^2 \times \text{RNG}) + \\ & c_6(\text{RAD} \times \text{RNG}^2) + c_7(\text{HARV} \times \text{SMG50}) + \\ & c_8(\text{HARV}^2 \times \text{SMG50}) + c_9(\text{HARV} \times \text{SMG50}^2) \qquad \text{(III)}\end{aligned}$$

where b_o is the expected percent maximum growth rate when all input values are zero, b_i and c_i are estimated partial regression coefficients, and the other variables are as in Table 3.3.

The resulting model indicates that the most limiting factors of pasture grass growth were soil moisture tension at 0.5 m, the interaction between solar radiation and the quadratic term of rainfall, the quadratic and linear terms of soil initial moisture tension, rooting depth, and the quadratic term of harvest number (Table 4.12).

Herbage production increased with increasing rooting depth, the quadratic term of the initial soil moisture tension, and the interaction irradiance x quadratic term of rain. On the other hand, grass performance decreased linearly when the mean soil moisture tension and the initial soil moisture tension increased. The performance also decreased with the quadratic term of harvest number. The logic behind the individual and interaction effect of these factors has been discussed earlier. Of the three models developed for the different level of stratification, Model III best conforms to the seasonal variation of grass production.

Unlike Model II, Model III is characterized by the absence of soil temperature terms and the presence of soil moisture terms at 0.5-m depth. The absence of soil temperature at 0.5-m depth in the model may be associated with the confounding effect of solar radiation. The importance of soil moisture at 0.5-m depth, instead, was attributed to a better conservation of water from evapotranspiration than at the 0.1-m depth. The high coefficient of determination in Model III (R^2 = 0.90) suggests that, in contrast to Model II, soil moisture at 0.5-m depth may be a better predictor of plant growth than soil temperature at that depth.

Many soil factors, such as soil organic matter, base saturation, cation exchange capacity, soil acidity, bulk density, and available water capacity, did not consistently appear in any of the models in the sensitivity analysis. This may be due partly to their strong correlation with the climatic factors in the models, particularly accentuated by the peculiar distribution pattern of the soils along the climosequence of the experiment. The overshadowing of the soil properties by climatic factors, however, seems to be more universal than specific to the conditions of the present study. In a study of relationships between soil, vegetation, and climate on rangeland, Passey et al. (1982) also reported that variations in weather conditions modified or masked the effects of specific soil properties on plant growth and distribution.

4.2.5 Analysis of Variance for Regression: Model Selection

The analysis of variance of the three regression models is shown in Table 4.13. The criteria for judging the worth of a prediction equation have generally been based on the coefficient of determination (R^2) and the residual mean of squares when the F-test of the models are significant at a certain level of probability chosen by the investigator. The higher the coefficient of determination and/or the smaller the residual mean of squares, the greater the predictive capability of the model.

The F-test was highly significant for all of the models (P less than 0.0001) and the R^2 values were 0.79, 0.83, and 0.90 for Models I, II, and III, respectively. In addition, the residual means of squares were 335.01, 276.31, and 172.88 for the three models, respectively. The F-test performed on these variances was not significant. Model III with the highest R^2 value and the smallest residual mean of squares, however, appears to be more reliable in predicting grass performance than either Models I or II, with II being better than I. The difference between the predictive capacity of Models I and II does not seem large enough to justify the additional cost for obtaining soil-climate data at 0.1 m.

The use of R^2 and residual mean squares as model selection criteria, however, presents two major disadvantages.

Table 4.13. ANOVA for Regression Models Relating Relative Growth Rate of Pasture Grass to Soil, Atmosphere and Soil-climate.

Source	dF	SS	MSe	F	R^2
a) Model I, Using Soil and Atmospheric Factors Only.					
Regression	3	23,705.82	7901.94		
Error	20	6,700.20	335.01		
Total	23	30,406.02		23.59***	0.79
b) Model II, Using Soil, Atmosphere and Soil-climate factors at 0.1 m depth.					
Regression	4	25,156.10	6289.02		
Error	19	5,249.92	276.31		
Total	23	30,406.02		22.76***	0.83
c) Model III, Using Soil, Atmosphere and Soil-climate factors at 0.5 m depth.					
Regression	6	27,467.05	4577.84		
Error	17	2,938.97	172.88		
Total	23	30,406.02		26.48***	0.90

*** Significant at the 0.01 probability level.

Firstly, if R^2 values indicate a relative "goodness to fit" of the model (Laird and Cady, 1969), in some instances, these values can be misleading because the prediction equation may not fit the data (Voss et al., 1970). Secondly, the multiple coefficient of determination (R^2) generally increases and the residual mean squares decrease as more variables are added to the model.

The first disadvantage relates to the validity of the model. An indication of the usefulness of a prediction model can be adequately assessed by plotting the model output versus the observed values. Such a validity test was made for Models I, II, and III. The plot for Model I showed that the observed productions were not predicted well, being too high in the low yield regions and too low in the high yield regions. This is indicated by the large deviation from the regression line at the two extremes of the production range (Figure 4.20). Model II predicted well most of the observed values but the high yields, say above 80 percent maximum growth rate (Figure 4.21). Model III predicted well the observed yields at all values because the variance about the regression line is small and nearly constant (Figure 4.22). Again, Model III proved to be a better predictor than Model II, which in turn proved to be better than Model I.

The variation of R^2 and residual mean squares with the number of variables in the model may raise some questions about the validity of their use as a selection criterion when the models to be compared contain unequal number of variables. In addition, the absence of a direct effect of rainfall or soil temperature at 0.5-m depth introduces more uncertainty in the comparison. This might have been caused by the effect of rain or temperature being confounded with the interaction of solar radiation x rain. It was, therefore, desirable to remove these effects by including only factors pertaining to the same stratum in the respective model and excluding the interaction of solar radiation x rain. The variables selected by the stepwise procedure are shown in Table 4.14. To indicate their relative importance, the variables selected are listed in their order of entry in the model. The R^2 and MSe are given for each step so that comparison can be made for any even number of variables in the different models.

Model Ia indicates that the most influential factors at the atmospheric level are maximum air temperature, rainfall, and the quadratic term of harvest number (Table 4.14). The maximum air temperature and harvest number were negatively associated with grass performance, whereas rainfall was positively related. The combined effect of these variables explained 75 percent of the variation in herbage productivity, 4 percent less than in Model I (Table 4.13). Rainfall was second after air temperature with a relative contribution of 7 percent increase in the R^2 (Table 4.14).

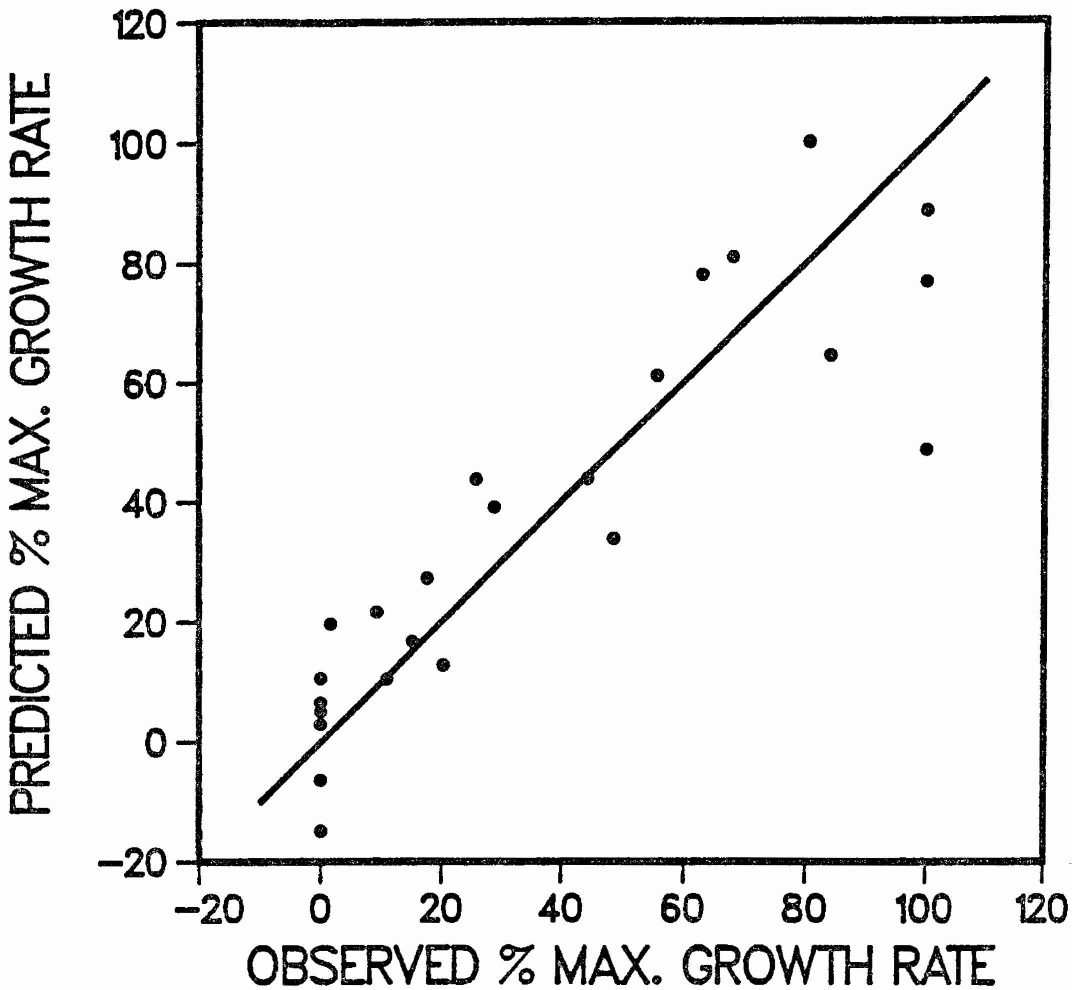


Figure 4.20. Relationship between Observed Growth and the Output of the Model Based on Atmospheric Factors.

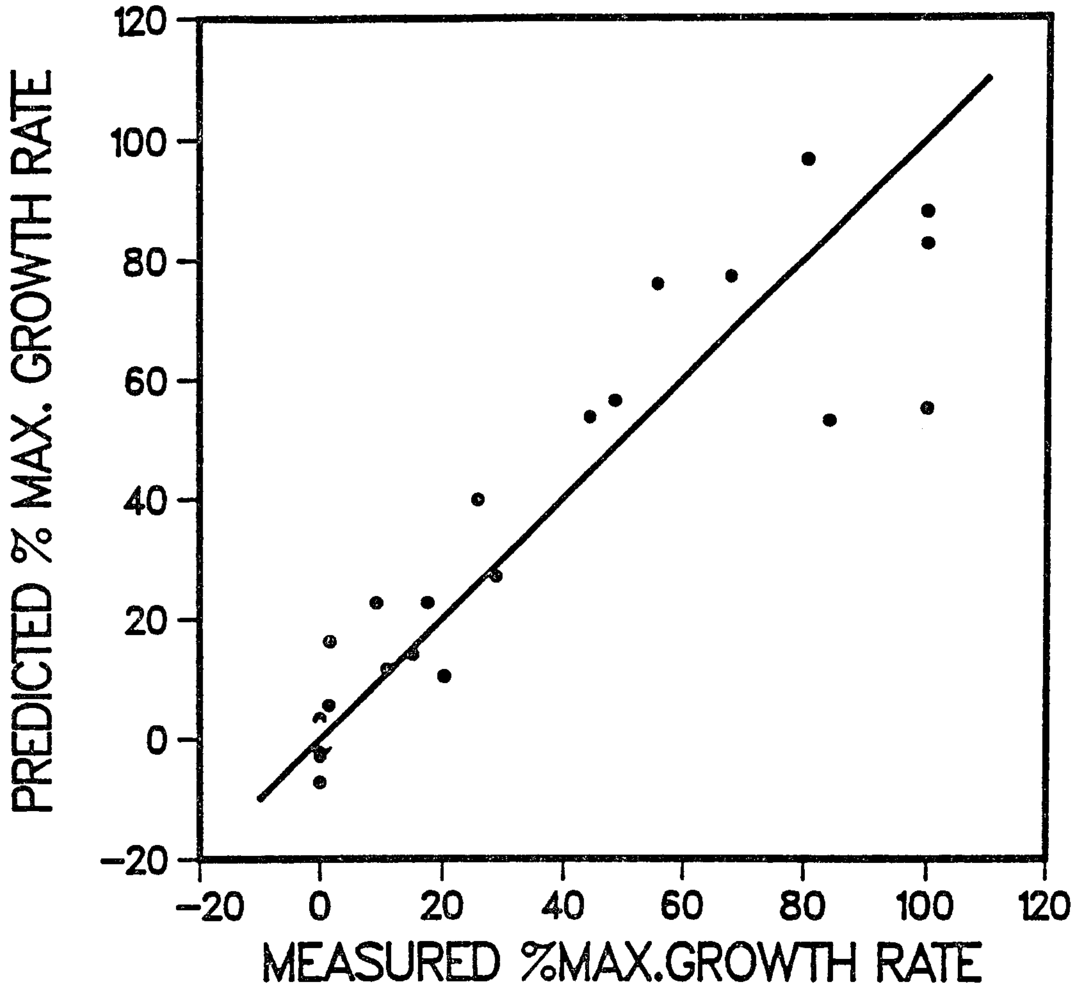


Figure 4.21. Relationship between Observed Growth and the Output of the Model Based on Soil-Climate at 0.1-m Depth.

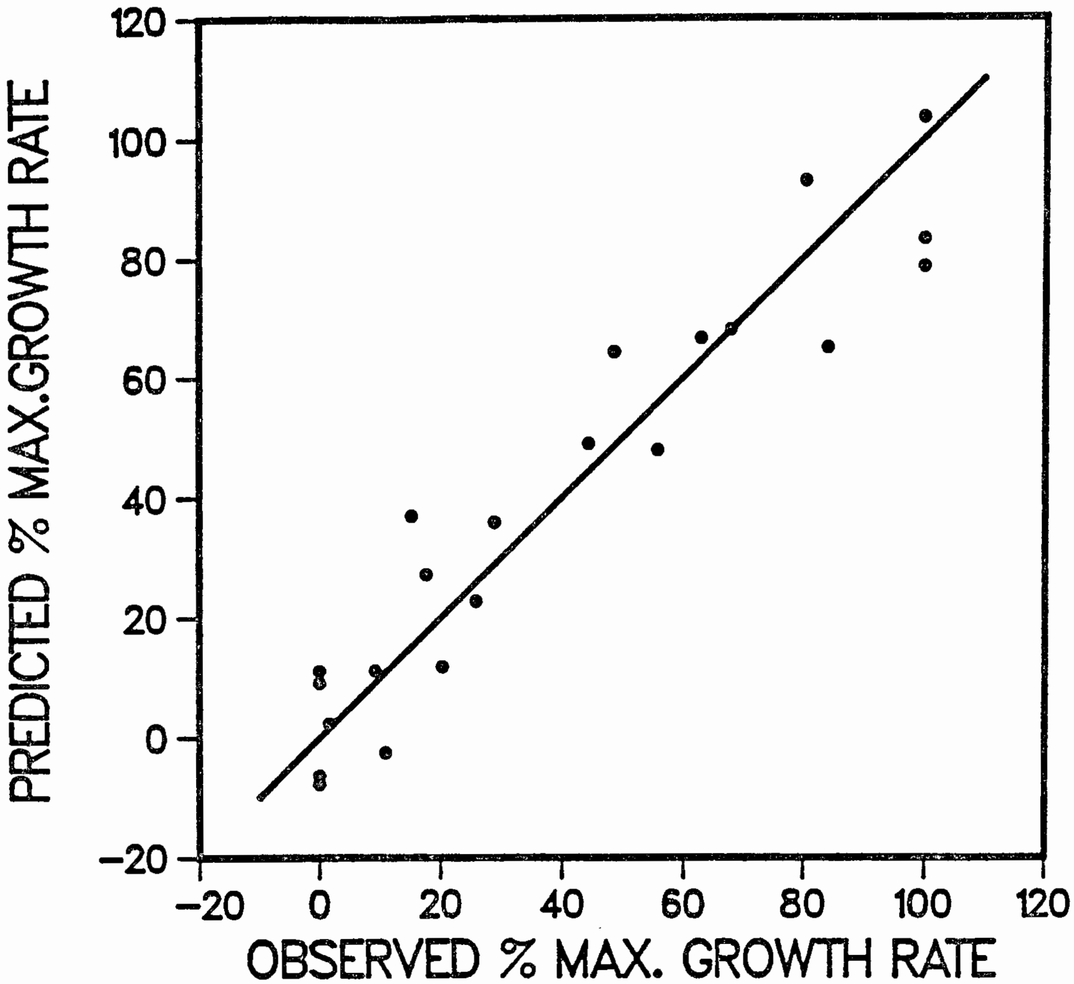


Figure 4.22. Relationship between Observed Growth and the Output of the Model Based on Soil-Climate at 0.5-m Depth.

Table 4.14. Independent Variables in the Reduced Models Relating Relative Growth of Pasture Grass to Soil, Atmosphere and Soil-Climate.

Independent Variables	Estimated coefficients	F
a) Model Ia, relating grass performance to atmospheric factors (R^2=0.79)		
Intercept	142.15	
Mean Air Temperature	-5.99	19.37***
Solar Rad. x Rain	1.54×10^{-2}	11.21**
Harvest Number	-6.92	6.02*
b) Model IIa, relating grass performance to soil-climate at 10cm depth (R^2=0.75)		
Intercept	171.29	
Max. Soil Temperature	-4.25	33.17***
$(\text{Harvest Number})^2$ x Soil Temp.	-7.41×10^{-2}	6.11*
Initial Soil Moisture Tension	-13.17	3.22^{+}
c) Model IIIa, relating grass performance to soil-climate at 50cm depth (R^2+0.80)		
Intercept	59.89	
Moisture Tension	-10.28	22.00***
Moisture Tension x Initial Moisture Tension	0.32	6.12*
Rooting Depth	12.97	4.81*

***, **, *, + significant at 0.1, 1, 5, and 10% probability level, respectively.

Model IIa shows that the limiting factors at 0.1-m depth are the maximum soil temperature, the quadratic terms of harvest njmber and mean soil temperature, and the initial soil moisture tension. Again, the maximum soil temperature, harvest number, and soil moisture tension were inversely associated to herbage production. The growth expression was, however, directly related to the quadratic term of mean soil temperature at 0.1-m depth. Together, these variables accounted for 76 percent of the variation in the grass performance, 7 percent less than in Model II (Table 4.13). The relative effect of the soil moisture expression at 0.1-m depth accounted only for 3 percent of the variation. The initial soil moisture at 0.1 m was the only moisture expression in the model. The moisture carryover from the preceding season is, therefore, the most important moisture factor for plant growth, as far as the 0.1-m depth stratum is concerned.

Model IIIa indicates that the most limiting factors at 0.5-m depth were the soil moisture tension, temperature, harvest number, and the quadratic term of the initial soil moisture tension (Table 4.14). The combined effect of these factors explained 82 percent of the variation in grass performance, 8 percent less than in Model III (Table 4.13). The soil temperature at 0.5-m depth was the second most influential factor after the soil moisture tension and it accounted for a 4 percent increase in the R^2.

The F-test of the variance (MSe) of the three regression models was not significant (P greater than 0.05). The comparison between the R^2 values for Model Ia and IIa indicates that the model based on atmospheric factors has a greater predictive ability than the model based on soil-climate at 0.1-m depth, when both models include the three variables. At this step, Model Ia has a higher R^2 and the smaller residual mean squares. In addition, the model that is based on the atmospheric weather is preferable to that based on soil-climate at 0.1-m depth, because the data associated with the atmospheric weather are most readily available.

In contrast, the model that is based on soil-climate at 0.5-m depth shows a higher R^2 and a smaller MSe than the model that is based on the atmospheric weather, even though both models have the same number of variables. Although the F-test is not significant, there is a relative difference in the variance at the third step of the procedure (342.22 vs. 380.17). The model based on soil-climate at 0.5-m depth is, therefore, preferable to those based either on the atmospheric weather or on soil-climate at 0.1-m depth.

The models that are considered so far are based on variables pertaining to one stratum only. The selection of the most influential factors among the variables from the three strata should ultimately confirm their predictive importance. A final analysis was, therefore, carried out by performing stepwise regression, using all of the variables of the three strata together. The resulting Model IV explained 92 percent of the variation in the relative performance of the grass, as indicated by the R^2 value of 0.92. The residual mean squares (MSe) was 138.47 (Table 4.15). These statistics are very close to those in Model III which is essentially based on soil-climate at 0.5 m. Moreover, three of the five variables in Model IV relate to soil-climate at 0.5 m. These variables are shown in their order of entry. Only one variable represents the soil-climate at 0.1 m in the model, the interaction between the initial and mean moisture tension. This comes second after soil moisture tension at 0.5-m depth position and contributes to only 5 percent increase in the predictive capability of the model (Table 4.15).

Compared to Model III (Table 4.12), Model IV has only a slight advantage in respect to R^2 (0.92 vs. 0.90) and variance (138.47 vs. 172.88). The small advantage of Model IV is, however, too little to justify the additional cost in time and money needed to obtain an additional variable, the soil moisture tension at 0.1-m depth. Model III contains a larger number of variables than Model IV. Two of them, however, are just different forms of the same variable, the initial soil moisture tension. The rooting depth is a variable that any investigator will presumably measure at

Table 4.15. Relative Effect of Weather, Soil, Soil-Climate, and Management on Pasture Grass Performance.

Step	Independent Variables+	Final Model Coefficients	Final Model F	Step by Step R^2	Step by Step MSe
	bo	81.83			
1	SMG50	-68.98	27.68***	0.70	417.02
2	SMG10 X ISMG10	-20.23	19.57***	0.75	358.66
3	HARV X $STG50^2$	- 0.02	13.17***	0.84	244.76
4	ISMG50 X $SMG50^2$	18.79	13.96***	0.88	184.51
5	RNG X RAD^2	2.4×10^{-4}	7.32*	0.92	138.42

+ SMG10 and SMG50 are soil moisture tension at 0.1 and 0.5 m depth, respectively.

ISMG10 and ISMG50 are initial soil moisture tension at 0.1 and 0.5 m depth, respectively.

HARV = harvest number; RNG = rainfall; and RAD = solar radiation.

the end of his experiment and, therefore, practically adds no additional cost to the routine work. Under these conditions, Model III that is based on soil-climate at 0.5-m depth is preferable.

The lack of the temperature term in Model III (Table 4.12) was not associated with the lack of importance of this variable for plant growth, but to the fact that its effect was presumably confounded with that of solar radiation. In the absence of solar radiation, soil temperature at 0.5 m becomes the second major determinant of pasture grass growth after soil moisture (Table 4.14). In all of the models constructed by the different strategies, the models based on soil-climate at 0.5-m depth had consistently a higher predictive capability than the others. In contrast, there was little difference between the predictive capability of the models based on atmospheric variables and those using soil-climate at 0.1-m depth. The diagnostic criteria for soil classification should, therefore, be based on soil-climate at 0.5-m depth to ensure a better prediction and interpretation of soil, climate, and vegetation relationships.

Models Ia, IIa, IIIa, and IV were intended only to search the consistent evidence supporting the selection of the stratum that would be most appropriate for prediction purposes. The number of candidate variables was reduced upon the exclusion of some of the factors that were known to affect grass production, except for Model IV. Failure to consider influential variables may, however, result in biased predicted value (Cady and Allen, 1972). Further discussion will, therefore, be based on the most complete Model I, II, and III (Tables 4.12 and 4.13) unless otherwise indicated.

4.2.6 Evaluation of Soil Moisture Control Section Criteria

The noticeable differences between the models based on the three different strata of plant environment are the absence of a marked direct effect of rainfall or the soil moisture terms in Model I or II, and an affluence of soil moisture expressions in Model III.

The absence of a main effect of rainfall in Model I might partly be due to the use of the total seasonal rain instead of the preseasonal precipitation or the effective rainfall. In fact, there is a general consensus about the importance of rainfall on plant growth. The specific period during which precipitation is most effective remains, however, a subject of much controversy. In a study of relationships between native plants and some climatic factors, Blaisdell (1958) reported a positive correlation between annual herbage weight and precipitation of the nine-month period immediately preceding the growing season, but the correlation was negative with the April-June precipitation. Colville et al. (1962) reported that even with the addition of 40 pounds of nitrogen fertilizer, bromegrass failed to exhibit a significant response to rainfall. Others (Nielsen, 1934; Cole, 1938; and Craddock and Forsling, 1938) agree with Blaisdell (1958) in concluding that precipitation before the growing period influences herbage production more than precipitation during the growing period. Considering the initial soil moisture tension as an expression of preseasonal precipitation, the present study indicates that precipitation before and during the growing period are the two most important important factors. Preseasonal precipitation gains much importance only when the amount and distribution of precipitation during the current growing period are such as to uphold the soil moisture at adequate level for plant growth. An example of this is the comparison between the winter and spring productions in 1984 at Waiakoa (Table 4.8). Despite lower temperature, solar radiation, and initial moisture in the winter than spring of 1984, the winter production was nearly four times higher than in spring of 1984, presumably because of higher and better distribution of rainfall in winter than in spring. However, neither initial moisture term at 0.1-m depth nor the direct main effect of seasonal mean moisture tension at that level entered Model I. Soil moisture tension showed a slight contribution only in terms of a secondary effect by its interaction with harvest number. This quasi-nonexistent importance of soil moisture expression at 0.1-m depth was ascribed not only to the irregularity and lack of rainfall to provide an adequate moisture at that level but also to a rapid depletion of soil moisture from this upper root zone due to evapotranspiration and downward flow of soil water. Conversely, the initial and mean seasonal soil moisture terms of the 0.5-m stratum were omni-present in Model III which proved to be a more reliable predictor of herbage production than Model I or II in which rainfall or soil moisture expressions had only a secondary effect. To further clarify the rainfall, soil moisture, and production relationships, the initial soil moisture at 0.5-m depth was included as a variable in the proposed model at each stratum level. But the variable did not enter any other model other than Model III where current seasonal soil moisture at 0.5-m depth was the first variable to be selected. The current soil moisture tension is itself, however, a resultant of precipitation prior and during the growing period.

These results indicate that if rainfall is the main source of water supply in rainfed agriculture, precipitation would do plants little good were it not for the capacity of the soil to store water for plant use between successive rains. The influence of preseasonal rainfall on grass growth is not obviously due to its immediate influence on vegetation but merely assurance of soil moisture for the next growing season (Blaisdell, 1958). The use of soil moisture rather than atmospheric rain is, therefore, justified in Soil Taxonomy.

Because the soil moisture tension at 0.1 m shows but little importance for predicting plant growth under limited water supply, there raises the question as to which depth soil moisture should be considered as a differentiating criterion. The evidence on hand in this study suggests that the upper limit of soil moisture control section be located at 0.5-m depth, regardless of soil texture. An additional portion of 0.1 m below that depth may be allowed for sampling area so that the soil moisture control section for any soil lies between 0.5 to 0.6 m. In shallower soils, the lithic or paralithic contact may then serve as lower limit of the soil moisture control section.

The proposal to locate soil moisture control section between 0.5 and 0.6 m, regardless of the particle size classes, is suggested not only because of the statistical models developed in this study but also because of experimental results reported in literature. Cole and Mathews (1939) examined the effect of precipitation on subsoil moisture under semiarid conditions and soils with texture varying from sandy to clayey soils. Their results indicate that the depth to which water penetrates depends not only on the quantity and type of precipitation but also on soil character and cropping system. However, the annual cycle of charge and discharge was generally confined to the first two feet of soil in a continuously cropped wheat plot. The wetting front was deeper for the soil in fallow. In another experiment, Cole and Mathews (1940) studied the relationship between wheat production and the depth to which the soil was wet in the Great Plains. They concluded that under limited precipitation, soils that were wet to a depth of two feet were associated with the highest yield. The lowest yield was associated with soils that were wet to a depth of one foot or less, with the highest assurance of good yield being related with soils that were wet to a depth of three feet or more. The latter condition, however, was not frequent in a continuous cropping system. Blaisdell (1958) found significant correlation coefficients between herbage production and the average soil moisture of the surface 46 cm of soils. The author reported that these coefficients were similar to those between yield and the nine-month preseasonal precipitation.

Although continuous data records were limited to only 0.5-m depth in the present study, periodic measurements of soil moisture were made by Legowo (1985) to a depth of 1.5 m, using a neutron probe at three of the pasture sites. Soil moisture profiles obtained from his study showed large differences between the upper and lower field limits in the upper 0.4 m of the surface soil. Although they were both Dystrandepts, the soils at Kekoa and Puu Pahu sites showed marked differences in the moisture changes in the various sections. This may be due not only to the frequent occurrence of fog and the variation in the soil profile at Puu

Pahu but also to the presence of gravels and stones in the soil profile at Kekoa. The large differences observed in the upper 0.4 m, nevertheless, were considerably less at about 0.5-m depth. A similar trend was observed at Waiakoa where the soil is classified as an Haplustoll. The reduction in soil moisture losses at 0.5-m depth and below in the different soils and under different soil cover and management practices are also reported by Long and French (1967), Cohen and Strickling (1968), and Harlan and Franzmeier (1974). The use of soil moisture at these depths of course depended on the plant species, soil texture, and management. Van Riper (1964) reported that alfalfa and alfalfa-grass mixtures used more moisture below the two-foot depth than any other grass species or association and they produced more forage in a silty clay loam soil. Cohen and Strickling (1968) found that moisture removal was most intensive from the upper 0.24 m and moderate below 0.6-m depth in a sandy clay loam soil under different grass species and nitrogen treatment. They concluded, however, that the advantages ascribed to deep-rooted crops with regard to moisture use were not apparent in their study. Long and French (1967) found that timothy grass rooted less deeply than fescue. Timothy took more water from the top 0.4 m of the profile, whereas fescue took more from the lower depths of the clay soil. As a result, fescue produced twice as much dry matter than timothy. Similar results were reported by Chinene (1983) who found that regardless of the fertilizer treatments, corn extracted about the same amount of water from the upper 0.4 m of a clayey Oxisol. The difference between treatments became evident only with the variation of the amount of extractable water below 0.4-m depth. There was less than one chance in six of producing a good crop when the depth of the wet soil did not exceed one foot. Two feet of wet soil gave a fairly adequate condition even though it did not provide a sufficient margin of high production level (Cole and Mathews, 1940).

Although some of these conclusions are apparently conflicting in some aspects, they all agree in a general way, that is, regardless of the particle-size class, soil moisture in the upper 0.4 m is not well suited for production prognosis under limited rainfall condition.

The location of the soil moisture control section below 0.5 m for all soils, therefore, regardless of their texture, may be more indicative than the current method used in Soil Taxonomy. This method will not only regard the moisture control of some soils to be less than 0.5-m depth but also leave out soils with cracking clay and/or amorphous material. The method will furthermore require different handling of soils that receive water runoff from a higher landscape.

If the moisture control section of the soils in this study were determined by the general guide as recommended by

Soil Taxonomy, the section would be between 0.1 and 0.3 m for the Kihei and Waiakoa sites. Such a section, however, cannot be determined for the Andepts at the Kekoa and Puu Pahu sites. Since the water content at 0.1 m does not discriminate well between productions and since the soil at Waiakoa is much deeper than at Kihei, a prediction based on soil moisture to the given depth can be misleading. The soil moisture control section at the Kekoa and Puu Pahu sites, therefore, would have to be located by the experimental method outlined in Soil Taxonomy (USDA, 1975). However, beside the practical difficulties pointed out earlier in using such a method, it may not apply well to the Andepts. Some of these soils not only dry irreversibly but also exhibit a field moisture of several hundred percent even under well-drained conditions (Uehara and Gillman, 1980).

In addition, the ranges of the soil moisture control section of Soil Taxonomy overlap so widely that it does not practically allow much discrimination between the interpretive importance of water in the upper soil layer and that of the subsoil. For example, two soils with coarse-loamy particle size class can be considered. If one of the soils is moist in some or all parts to only 0.25-m depth and the other is moist in some or all parts to 0.55-m depth for a period of time, they are both classified with the same moisture regime. That is, the interpretation for the soil moisture to 0.25-m depth will be the same as that for the soil moisture to 0.55-m depth, and this would be misleading. The presence of moisture at 0.55 m means that the amount and distribution of rainfall are such that the water can flow to that depth. The plants, therefore, can exploit soil water within that depth for some time. In contrast, the plant can use soil water to only 0.25-m depth if the soil moisture is limited to that depth. Needless to say, that much soil water is lost from this upper soil layer owing to evaporation. Many examples of this type can be found, even between soils with different particle size classes.

It seems, therefore, opportune to give the same chance to the presence of water at a given depth, regardless of the texture. The evidence on hand suggests that the soil moisture to 0.5-m depth is most indicative of this role. Soil moisture phases may then be envisaged for soil that are moist to a depth less than 0.5 m and those that are moist to more than 0.5 m.

4.3 Influence of Environment on Forage Mineral Concentrations and Quality

4.3.1 Forage Mineral Concentrations

According to Whittington and Ward (1984), the concentration of P, K, Ca, Mg, Mn, and Fe in this study can be interpreted as being generally adequate for above critical requirement levels for cattle and sheep. By contrast, the concentration of Cu was generally below the critical level after the first harvest. On the other hand, the Zn level was deficient in all seasons, while N concentration was above the critical level only at the last harvest (Tables 4.16 through 4.18).

The concentrations of N, Ca, Mg, Si, Al, Mn, Fe, and Zn were negatively but significantly associated with air and soil temperatures, soil moisture tension, and solar radiation (P less than 0.05). They were, however, positively and significantly correlated with rainfall and harvest number (Table 4.19). The correlation between P, K, or Cu and air or soil temperature was not significant. The nature of all of the negative linear correlations is not well understood but seems to be associated with the soil moisture deficit. In fact, nutrient concentration decreased while soil moisture tension increased and the periods of high temperatures and high solar radiation corresponded to period of high moisture deficit. Moreover, the non-significant linear correlation between certain elements and

Table 4.16. Seasonal Variation of Forage Mineral Composition at Kihei and Waiakoa.

Element	SEASON: Winter 1984	Spring 1984	Winter 1985	Winter 1984	Spring 1984	Winter 1985	Critical Level (Whittngton and Ward, 1984): Cattle	Sheep
	Site = Kihei			Site = Waiakoa				
N (%)	0.95	0.45	2.97	1.02	0.52	2.64		
CP (%)	5.92	2.79	18.56	6.40	3.27	16.50	< 7*	
P (%)	0.35	0.21	0.37	0.27	0.26	0.42	0.18	0.16
K (%)	1.93	1.00	4.15	2.15	1.24	3.96	0.60	0.50
Ca (%)	0.32	0.35	0.39	0.24	0.26	0.37	0.18	0.21
Mg (%)	0.23	0.21	0.32	0.23	0.18	0.42	0.18	0.06
Si (%)	1.80	1.95	1.03	2.29	2.45	1.80	---	---
Al (ppm)	346	1026	924	89	343	267	---	---
Mn (ppm)	118	82	140	58	52	98	20	20
Fe (ppm)	291	432	450	96	204	148	30	30
Cu (ppm)	6	0	0	6	0	0	4	5
Zn (ppm)	28	17	38	23	18	37	30	35

* According to Peducassé et al., 1983

Table 4.17. Seasonal Variation of Forage Mineral Composition at Kekoa.

Element	SEASON						Critical Level reported by (Whittngton and Ward, 1984) For	
	Autumn 1983	Winter 1984	Spring 1984	Summer 1984	Autumn 1984	Winter 1985	Cattle	Sheep
% Max. Growth	44.38	55.07	100.00	20.30	10.90	48.59		
N (%)	0.94	1.13	0.75	0.75	1.34	1.77		
CP (%)	5.85	7.08	4.69	4.69	8.38	11.06	< 7*	
P (%)	0.22	0.27	0.19	0.17	0.23	0.24	0.18	0.16
K (%)	1.53	1.62	0.91	0.71	1.33	1.99	0.60	0.50
Ca (%)	0.37	0.31	0.32	0.37	0.41	0.38	0.18	0.21
Mg (%)	0.38	0.35	0.32	0.34	0.23	0.42	0.18	0.06
Si (%)	1.15	1.38	1.28	1.21	1.02	1.16	---	---
Al(ppm)	869	409	709	1304	870	394	---	---
Mn(ppm)	96	61	59	78	68	78	20	20
Fe(ppm)	377	273	449	657	652	296	30	30
Cu(ppm)	12	5	2	8	0	0	4	5
Zn(ppm)	28	27	22	21	23	28	30	35

* According to Peducassé et al., 1983

Table 4.18. Seasonal Variation of Forage Mineral Composition at Puu Pahu.

Element	S E A S O N						Critical Level reported by (Whittngton and Ward, 1984) For	
	Autumn 1983	Winter 1984	Spring 1984	Summer 1984	Autumn 1984	Winter 1985	Cattle	Sheep
% Max. Growth	63.00	80.50	100.00	84.14	28.84	68.02		
N (%)								
CP (%)	7.38	8.83	7.42	5.63	7.04	8.65	< 7*	
P (%)	0.14	0.13	0.13	0.13	0.11	0.21	0.18	0.16
K (%)	0.85	0.59	0.71	0.53	0.75	0.69	0.60	0.50
Ca (%)	0.43	0.42	0.44	0.45	0.49	0.49	0.18	0.21
Mg (%)	0.18	0.15	0.15	0.31	0.05	0.26	0.18	0.06
Si (%)	2.07	2.86	2.41	2.33	2.17	2.68	---	---
Al(ppm)	541	1546	660	1770	2075	2998	---	---
Mn(ppm)	124	132	106	168	116	217	20	20
Fe(ppm)	307	962	414	930	1377	1824	30	30
Cu(ppm)	2	0	0	4	0	0	4	5
Zn(ppm)	27	15	18	17	19	26	30	35

* According to Peducassé et al., 1983

temperatures suggests that these relations might be of a more complex nature than a simple linear relation. It further suggests that factors other than climate may be involved. This is in agreement with Nielsen et al. (1961), who found but only few consistent trends between the nutrient composition of crops in relation to soil temperature, and Gomide et al. (1969), who found significant interactions between mineral composition and year, age, and species. Noteworthy is the fact that all of the element concentrations, except for Cu, were positively and significantly correlated with the harvest number (P greater than 0.05), indicating that there was a trend for forage mineral concentration to increase when yield decreased inasmuch as increasing the harvest number tended to depress growth.

The patterns of seasonal variation of the forage mineral composition were similar at Kihei and Waiakoa (Table 4.16) but to a lesser extent at Kekoa and Puu Pahu (Tables 4.17 and 4.18. In general, there was a trend for the grass grown in winter and spring to have a higher mineral content than those grown in the other seasons, but the concentraions during the second year were also higher than those during the first year. This can be related not only to a greater water availability in winter and spring but also to the positive correlation between mineral concentrations and number.

4.3.2 Forage Quality

Crude protein content was used as a measure of forage quality. Except for the last harvest, the crude protein contents of grass were below the critical level during all seasons at all sites (Tables 4.16 through 4.18). This suggests a need for nitrogen fertilization not only to increase herbage production but also to improve forage quality.

Crude protein content was negatively but significantly correlated (P less than 0.05) with air and soil temperatures, solar radiation, and soil moisture tension at 0.1-m depth. The correlation with the moisture tension at 0.5-m depth, however, was not significant. In contrast, the correlation coefficient for the moisture tension at 0.1-m depth was the strongest, compared to any other factor (Table 4.19) and highly significant (P less than 0.01). The negative association of crude protein content with soil moisture tension indicated that the high crude protein content attained in a particular season tended to be associated with high soil moisture content, or high rainfall, as substantiated by the positive and significant correlation between crude protein content and rainfall (P less than 0.05). Thus, this explains the higher crude protein content obtained during the winter than during the other seasons at all locations. While the crude protein content was below the critical level during the first winter, it was above that

Table 4.19. Correlation between Forage Mineral Composition and Some Environmental Factors (%).

	N (CP)	P	K	Ca	Mg	Si	Al	Mn	Fe	Cu	Zn
ATG	-45*	-25	- 7	-81	-44	-76	-69	-75	-71	-10	-49
STG10	-55**	-38	-21	-83	-54	-77	-66	-76	-69	-16	-60
STG50	-45	-29	- 9	-82	-49	-74	-67	-73	-70	-18	-53
RAD	-64	-47	-45	-56	-45	-53	-36	-60	-42	-16	-60
RNG	-50	-51	-30	-67	-50	-80	-53	-72	-55	- 5	-58
SMG10	-68	-55	-45	-81	-72	-70	-46	-65	-47	-20	-74
SMG50	-21	-27	-	-70	-43	-76	-53	-64	-54	-29	-44
OCA	28	6	12	72	37	55	68	61	70	18	35
CECA	27	12	- 6	67	48	44	56	48	58	28	39
BSA	-26	1	17	-71	-22	-62	-73	-68	-75	- 5	-28
PHA	-28	-10	8	-71	-45	-45	-63	-56	-64	-26	-39
BD	-28	- 5	13	-73	-36	-55	-69	-63	-71	-17	-35
HARV	62	49	35	78	61	53	70	67	74	- 8	61
GROW	22	3	56	41	69	38	51	39	25	36	

* Significant level at 5% = 40.4
** Significant level at 1% = 51.5

level during the second winter. This increase was due not to an external source of nitrogen fertilizer but presumably to reduction in yield during the second winter. These results are similar to those of Mislevy and Everret (1981) who found that forage crude protein content during the winter was higher than those during the summer. Griffin and Watson (1982) also found that crude protein content was higher during the first year. They, furthermore, associated these trends to the non-dilution of available nitrogen which are related to the lower yield of the second year.

The crude protein content was also negatively but significantly correlated with the soil temperature at 0.1-m depth and solar radiation (P less than 0.01) and with air and soil temperatures at 0.5-m depth (P less than 0.05). That is, the low protein content was associated with the high temperature. This is in agreement with Whitney (1974a) who found that crude protein content of kikuyu grass decreased by 1.3 to 1.7 units for each unit increase in average minimum temperature.

Because no factor was controlled during this study, the polynomial quadratic models were constructed at the level of the three strata previously defined to detect the environmental factors that most influenced the forage crude protein content. The stepwise procedure was used to select the five variables that were significant at the 15 percent probability in each stratum. Although the decision to stop the process after five steps was arbitrary, it was based on the maximum number of variables that entered the model at the atmosphere level when no limitation was imposed on the number of variables. In addition, this facilitates the comparison of models having the same number of variables.

At the atmospheric level, Model Ib indicated that the factors that most limited forage crude protein content were solar radiation, the interaction harvest number x air temperature, the quadratic term of harvest number, the interaction between air temperature and the quadratic term of solar radiation, and the quadratic term of available water capacity of the A horizon (Table 4.20). Model IIb based on the soil-climate at 0.1-m depth indicated that the limiting factors at that level were the percent maximum growth, rooting depth, soil reaction, the interaction of soil temperature x moisture tension, and the interaction between soil moisture tension and the quadratic term of the initial soil moisture tension (Table 4.20). At the level of soil-climate at 0.5 m, the factors limiting the forage crude protein content were the interaction harvest number x temperature, solar radiation, harvest number, the quadratic term of available water capacity in A horizon, and the initial soil moisture tension (Table 4.20).

Model Ib explained 83 percent of the variation in the forage crude protein, whereas Models IIb and IIIb explained 87 percent and 86 percent of the variation, respectively.

Table 4.20. Independent Variables in the Regression Models Relating Forage Crude Protein Content to Soil, Atmosphere and Soil-Climate.

Independent Variables	Estimated	F	MSe (df=18)
a) <u>Model Ib, Soil and atmospheric factors</u>			5.34
(R^2=0.83) 5.34			
Intercept	29.34		
Solar Radiation	-0.10	15.16*	
Harvest number x Air temp.	0.25	34.36**	
$(Harvest)^2$	-0.53	16.02**	
Air Temp. x $(Solar Rad.)^2$	$3.28x10^{-6}$	7.42*	
$(Avail. Water Capacity)^2$, A horizon	$7.47x10^{-4}$	2.49+	
b) <u>Model IIb, soil and soil-climate at 0.1m depth</u>			4.00
(R^2=0.87) 4.00			
Intercept, bo	-13.83		
% Max. Growth	- 0.08	22.90***	
Rooting Depth	- 5.98	13.69***	
pH, A horizon	5.41	14.15***	
Temp. x Moist. tension	- 0.54	61.60***	
Moist.Tension x $(Initial moist. tension)^2$	1.56	3.91*	
c) <u>Model IIIb, soil and soil-climate at 0.5m depth</u>			4.36
(R^2=0.86) 4.36			
Intercept, bo	10.91		
Harvest number x temp.	0.41	33.95***	
Solar Radiation	-0.03	17.36***	
$(Avail.water capacity)^2$, A horizon	$1.82x10^{-3}$	8.69***	
Initial moist. tension	2.01	4.10*	

+,*,**,*** significant at 15, 10, 5, and 1% probability level, respectively.

The residual mean squares were 5.34, 4.00, and 4.36, respectively, for these models. Model IIb, using soil-climate at 0.1-m depth, has, therefore, the highest R^2 and the smallest residual mean square and is judged to be a better predictor of forage crude protein concentration than Model Ib or Model IIIb. The differences in R^2 values and residual mean squares between Models IIb and IIIb, however, are very small. Because Model IIb contains the percent maximum growth as a variable, a factor that is not always known, Model IIIb is considered to be most practical for prediction purposes and the prediction of herbage production based on the soil-climate at the 0.5-m depth is more reliable than one based at the 0.1-m depth.

Noteworthy is the similarity between the variables in the Models Ib and IIIb. The only difference is the substitution of the initial soil moisture tension in Model IIIb for the interacting of air temperature x (solar radiation)^2 in Model Ib. Model IIIb, with a higher R^2 and a smaller residual mean squares, however, is preferable. This, again, indicates that the use of soil-climate in Soil Taxonomy is justified. And, as far as the pasture grass growth is concerned, the soil-climate at 0.5 m is the most efficient predictor of herbage production and forage quality.

As its subtitle indicates, Soil Taxonomy was developed to serve as a basic system of soil classification for making and interpreting soil surveys. In turn, the fundamental purpose of soil survey is to make predictions, for example, about crop response to soils as well as about soil response to management. Soil Taxonomy is a natural system of classification, as opposed to a technical classification for specific uses. Soil survey results have been applied to engineering problems, but most of the applications are in the field of agriculture, including forestry and grazing (USDA, 1951). Dudal (1979) added that because the major applications of Soil Taxonomy and soil survey are to supply basic information for making optimum use of available land resources, the diagnostic criteria used in Soil Taxonomy must be investigated in terms of their significance for plant growth. In this connection, the present study shows that models based on soil-climate at 0.5-m depth in conjunction with other agroenvironmental factors were more adequate in predicting herbage production and forage quality than models using atmospheric factors or soil-climate at 0.1-m depth. If Soil Taxonomy is to be the basis for predicting plant response to soil, soil-climate, and other crop production parameters, the diagnostic criteria of soil-climate at 0.5-m depth best serve the purpose.

CHAPTER V

SUMMARY AND CONCLUSIONS

The term soil-climate is used in this study to refer to soil temperature and soil moisture regimes. Because Soil Taxonomy includes soil-climate in taxonomic names, the system can be used not only for making and interpreting soil survey but also for relating plant growth to agroenvironment. The soil temperature currently used in Soil Taxonomy is that measured at 0.5-m depth. Soil temperature measurements at that depth, however, are both time-consuming and costly, so that soil temperature data on which to base the classification are most often unavailable. Moreover, the soil moisture regime is defined in terms of ground-water level and in terms of the presence or absence of water held at a tension of 1.5 MPa in the soil moisture control section (SMCS) for a period of time. The SMCS is defined as the depth to which a dry soil will be moistened by 2.5 cm of water within 24 hours, with the lower boundary being the depth to which 7.5 cm of water will wet a dry soil within 48 hours.

The depths so defined for the determination of soil-climate have been given, however, without presenting any evidence of any particular effect of soil-climate at these depths on soil genesis or plant growth. Apparently, these depths have been selected arbitrarily. There is a need, therefore, not only to estimate the soil temperature from other environmental factors but also to evaluate the depths at which soil temperature and/or soil moisture most influence plant growth. Such knowledge, furthermore, could serve as a criterion for the location of soil temperature and/or soil moisture control section. The objectives of this study were (1) to develop empirical models for predicting soil temperatures at 0.1 and 0.5-m depths, using minimal set of environmental factors, (2) to develop functional mathematical models that correlate pasture grass growth to the soil-climate environment as well as to atmospheric weather, and (3) to evaluate the present soil-climate criteria of Soil Taxonomy and to propose alternative, where needed, for a better identification and interpretation of soil-climate in relation to plant growth.

Field experiments on soil-climate study were conducted from July 1983 to February 1985 along a climosequence extending from low altitude (36 m) to high altitude (1620 m) on the island of Maui, Hawaii. Temperatures are high and rainfall scant at low altitudes, whereas a reverse situation exists at high altitudes. Eleven stations were selected along the climosequence so that a wide range of ecological zones could be included. Automatic weather stations were installed at each site to monitor atmospheric and soil-climate environment factors at 15-minute intervals. The measurements included air temperature at 2-m height, soil temperatures at 0.1 and 0.5-m depths, soil moisture at 0.1 and 0.5-m depths, rainfall, relative humidity, and solar radiation. The soils varied from relatively young Inceptisols (Andepts) at the higher altitudes to Mollisols and Oxisols at the middle and lower altitudes. The environment was stratified at three levels, namely atmospheric level, soil-climate at 0.1-m depth, and soil-climate at 0.5-m depth.

In the soil temperature study, the 15-minute readings for climatic data were used to compute monthly, seasonal, and annual means. These means were in turn used to develop simple, multiple, and second degree polynomial equations that could be used to provide first approximations of soil temperatures for the corresponding periods. Although factors such as rainfall and soil properties were included as potential factors influencing soil temperature, air temperature was assumed to be the major driving force. The statistics and output of the different equations obtained were then compared to select the most satisfactory model. Finally, the data generated by the selected model for the mean annual soil temperature prediction and the data generated by the current model in use by Soil Taxonomy were compared with the observed temperatures.

All of the models exhibited a satisfactory coefficient of determination (R^2). Variation in air temperature accounted for 89 to 94 percent of the variation in soil temperature for the simple linear models. The addition of rainfall increased the R^2 to 92 to 96 percent for the mean seasonal and mean annual temperatures, respectively. The use of quadratic polynomials yielded R^2 values of 94 and 98 percent for the mean seasonal and mean annual temperatures, respectively. In many cases, neither the addition of rainfall nor the use of quadratic polynomials contributed greatly to improve the predictive capability of the models (for a given period). The variance (MSe) for the quadratic models was smaller than that of the other models, however, In addition, the plot of air temperature against soil temperature revealed a rather curvilinear trend. The quadratic models were, therefore, judged to have a greater predictive ability than the others. Future investigations on a most appropriate curvilinear function to relate air to soil temperature is suggested.

The addition of rainfall did not always contribute to a large improvement in the R^2, particularly at the 0.5-m depth. Its presence in the quadratic model for prediction of mean annual soil temperature at 0.1-m depth had, however, a great impact on the coefficient of determination. This suggested that rainfall influences the temperature of the upper soil layer to a much larger extent than the subsoil temperature.

Comparison between the quadratic model output and the observed temperatures showed a good agreement between predicted and measured values, particularly for the mean soil temperature at 0.1-m depth. The predicted temperatures were within ± 0.7 °C and ± 1.8 °C for soil temperatures at 0.1- and 0.5-m depths, respectively. The comparison between the output of the model in use by Soil Taxonomy and the measured temperatures showed that the model generally underestimated the soil temperatures, particularly so when the air temperatures were 22 °C or above. This suggested that Soil Taxonomy's model could be modified as follows:

MAST50 = 2 + MAT if MAT is less than 22 °C

MAST50 = 4 + MAT if MAT is greater than or equals 22 °C

where MAST50 = mean annual soil temperature at 0.5-m depth, MAT = mean annual air temerature. The constants of 2 and 4 are the means calculated from the real differences observed when the air temperatures were less than 22 °C or greater than or equal to 22 °C, respectively. Such an adjustment allowed the prediction to be within ± 1 °C when anomalous situations such irrigation-effect or shading were disregarded. In the same situations, the values predicted by the modified Soil Taxonomy model were very close to those predicted by the quadratic model. When the two models were used in predicting soil temperatures in areas other than the present study, however, the modified Soil Taxonomy model appeared to be most recommendable. On the other hand, an analysis of variance based on Wilcoxon's two sample test did not show any significant difference between the measured temperatures and the output of the models.

Application of Soil Taxonomy and soil survey is primarily in the field of agriculture. The soil-climate criteria of Soil Taxonomy should, therefore, be investigated in terms of their significance to plant growth. A study of relationships between pasture grass growth and soil-climate, thus, was undertaken for such a purpose.

Four of the 11 sites in the soil-climate study were selected to examine pasture grass response to soil, atmospheric weather, and soil-climate at different soil depths. Each of the experimental sites, measuring 15 x 15 m, was protected from animal entrance with a barbed wire enclosure. Nine to 15 plots were then randomly distributed throughout the area by throwing a metal quadrat of a size that was 0.5 x 0.5 m. The growing seasons were adjusted to about 13-week periods so that they corresponded, as closely as possible, to the duration and variation of natural seasons. The major grass species were kikuyu grass, buffel grass, and an admixture of sweet vernal, rattail, Yorkshire fog, and white clover. The agro-environment was subdivided into three different strata, namely atmosphere, soil-climate at 0.1-m depth, and soil-climate at 0.5-m depth. All of the three levels of stratification had a common denominator, soil properties and harvest number. Given its well known influence on plant growth, solar radiation and its interaction with atmospheric factors were also included in each stratum. Alternatives for adding or removing other variables were further explored to check for consistency in the validity of each model. The data from each stratum so defined were used separately to fit the second degree polynomial equations by the least squared method. This was so designed to allow the evaluation of the stratum that would influence pasture grass growth the most. The results were used as a guide in reccommending the location of the soil temperature and moisture control sections and for a better identification and interpretation of soil-climate in relation to plant growth.

The results indicated that seasonal fluctuations in herbage production depended primarily on the fluctuation of climate and management as well as plant characteristics. In particular, grass performance was positively correlated to rainfall and rooting depth but inversely associated with soil moisture tension, soil temperatures, and harvest number.

The model for the atmospheric level showed that the most limiting factors of pasture grass growth are mean air temperature, the interaction of solar radiation and rain, and harvest number. Together, these factors explained 79 percent of the variation of the grass performance. When the effect of the interaction term was removed, in an attempt to discern the main effect of precipitation and solar radiation, rainfall came second after air temperature, followed by harvest number. The coefficient of determination, however, decreased by 4 percent.

The predictive model of soil-climate at 0.1-m depth indicated that the most influential variables are maximum soil temperature, the interaction of moisture tension x harvest number squared, the interaction of rain x solar radiation squared, and the quadratic term of mean soil temperature. These factors accounted for 83 percent of the variation in the pasture grass growth. When the effect of the interaction of rain x solar radiation was disregarded, the variables in the model were maximum soil temperature, the quadratic term of harvest number and mean soil temperature, and initial soil moisture. These factors explained 76 percent of the variation in the herbage production, of which 66 percent accounted for the soil temperature, 7 percent for the harvest number, and only 3 percent for the initial soil moisture. This indicates that the temperature at 0.1-m depth is much more predictive than soil moisture at that depth. The quasi-nonexistence of the soil moisture at 0.1-m depth was ascribed to (1) the irregularity and insufficiency of rainfall to ensure continuous supply of moisture at that level and (2) a rapid depletion of moisture from the upper root zone, owing to evapotranspiration and downward flow of soil water.

The model of soil-climate at 0.5-m depth included the soil moisture tension, the interaction of solar radiation x rainfall squared, the quadratic and linear terms of soil initial moisture tension, rooting depth, and the quadratic term of harvest number. This model explained 90 percent of the variation in herbage production. When the interaction between solar radiation and rainfall was removed from the model, the new set of limiting factors were soil moisture tension, soil temperature, and the quadratic term of harvest number and initial soil moisture tension. This model explained 82 percent of the variation in herbage production, of which 75 percent accounted for soil moisture, 4 percent for soil temperature, and 3 percent for harvest number. The soil temperature at 0.5-m depth was second after soil moisture. This means that the absence of soil temperature expression in the previous models was not due to a lack of a real effect but due to the effect of either solar radiation or rooting depth. Unlike the model on soil-climate at 0.1-m depth, the soil moisture at 0.5-m depth is of much more relevance in predicting grass growth than soil temperature at that depth. The affluence of soil moisture at the 0.5-m depth was attributed to the accumulation of rain water and to less evaporation of water at that depth.

The above showed that the models based on soil-climate at 0.1-m depth did not always have a greater predictive ability than the models based on atmospheric factors, as indicated by the R^2 values and the residual mean squares. The models based on soil-climate at 0.5-m depth, on the other hand, consistently exhibited a higher R^2 and a smaller variance than the other two models. This led to the conclusion that the model based on soil-climate at 0.5-m depth with the higher R^2 was the best model for predicting herbage production. The factor that most contributed to the predictive power of this model was soil moisture. This was proven so even when all of the factors from the three strata were subjected to the selection procedure. It is, therefore, recommended that the soil-climate criteria of Soil Taxonomy be based on measurements or estimates at 0.5-m depth, irrespective of soil texture.

The soil temperature in Soil Taxonomy is measured at 0.5-m depth because of much variation in the upper soil layer. The same reason must lead to the consideration of the soil moisture at that depth, as suggested by this study and many examples cited in the literature.

As its subtitle indicates, Soil Taxonomy was developed to serve as a basic system of soil classification for making and interpreting soil surveys. In turn, the fundamental purpose of soil survey is to make predictions about crop response to soil and other agro-environmental factors. Although Soil Taxonomy is a natural system of classification, as opposed to a technical classification for specific purpose, applications of soil surveys are mainly in the field of agriculture. The diagnostic criteria used in Soil Taxonomy should, therefore, be investigated in terms of their significance to plant growth. The evidence on hand suggests that models based on soil-climate at 0.5-m depth, in conjunction with other crop parameters, have a greater predictive ability than those based on atmospheric weather or soil-climate at 0.1-m depth. The major implication of this study is, therefore, that if Soil Taxonomy is to serve as a basis of stratifying agro-environments for predicting yield potentials, the diagnostic criteria based on soil-climate at 0.5-m depth would best accomplish the mission.

In conclusion,

(1) Air temperature alone or in conjunction with other environmental factors can be used to provide good approximations of soil temperature for a given period, using statistical models.

(2) In many instances, the addition of other environmental factors to air temperature or the use of quadratic model for predicting soil temperature did not appreciably improve the coefficient of determination of the models. The quadratic models were, however, found to be of better predictive tool than the others because they conformed better to the curvilinear nature of the relationship between air and soil temperatures.

(3) More often than not, the model currently used by Soil Taxonomy fails to provide good estimates of soil temperature, particularly for zones where the mean annual air temperature is 22 ^{o}C or above. This model can be modified to allow a greater precision in predicting soil temperatures at the 0.5-m depth.

The modification is that MAST50 = 2 + MAT, if MAT is less than 22 ^{o}C, and MAST50 = 4 + MAT, if MAT is greater or equal to 22 ^{o}C, where MAST50 and MAT are the mean annual soil and air temperatures, respectively.

(4) Seasonal fluctuation in herbage production was greatly influenced by (a) climatic factors such as air and soil temperatures, solar radiation, rainfall, and soil moisture, (b) management factors such as harvest number, and (c) soil and plant factors such as rooting depth.

(5) Current season rainfall influenced pasture grass growth less than soil moisture. Although rainfall is the main source of water supply in rainfed agriculture, precipitation contributes little to plant growth if the soils do not have the water storage capacity for plant use between successive rains.

(6) Soil temperature at the 0.1-m depth had a greater impact on herbage production than the soil moisture at that depth. By contrast, soil moisture at 0.5-m depth was a greater determinant of grass growth than soil temperature at that depth.

(7) When atmospheric weather, soil-climate at 0.1-m depth, and soil-climate at 0.5-m depth are considered, soil mois- at 0.5-m depth influenced the relative performance of grass more than any other single factor.

(8) Because of large variation due to evapotranspiration and downward flow of water, the moisture content in the

upper 0.5 m of the soil does not seem to be appropriate for production prognosis, regardless of the soil texture. The location of the soil moisture control section at 0.5-m depth is, therefore, recommended to allow a better identification and interpretation of soil-climate and plant relationships.

(9) The models based on soil-climate at 0.5-m depth had a greater predictive ability than the models based on either atmospheric weather or soil-climate at 0.1-m depth, as substantiated by higher R^2 and smaller residual mean squares.

(10) Finally, if Soil Taxonomy is to be the basis for predicting plant response to soil, soil-climate, and other crop production parameters, the diagnostic criteria of soil-climate at 0.5-m depth best serve the purpose.

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