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The use of chemicals such as the triazines (especially atrazine) and mixtures of the triazines and 2,4-D or 2,4,5-T has become almost standard practice in some parts of the world for selectively controlling grasses and other herbaceous weeds to conserve moisture for and/or prevent the smothering of newly-planted conifers. In the Pacific Northwest, where application is mainly to control grasses in forest and Christmas tree plantations of Douglas-fir [Pseudotsuga menziesii (Mirb.) Franco.], a single such treatment dramatically increases first year survival and growth of the trees mainly because of increased moisture availability. However, this predisposes the site for heavy infestations of forbs and forbs plus annual grasses in the second and subsequent several years. 'To what extent can these be justifiably ignored?', is a question which this dissertation attempts to answer in terms of the effects of vegetation manipulation on soil moisture.

Data for this study came from observations and experimentation mainly during the summer of 1970 in a series of already existing herbicide trial plots located in a grassy meadow in the Oregon Coast Range

about 18 miles west of Corvallis. The vegetative covers of the plots reflected histories of zero to three years herbicide treatment and could be classified into: (1) non- or lightly vegetated with forbs, (2) moderate to dense pure forbs, (3) dense forbs plus annual grasses, (4) heavy bent grass (*Agrostis tenuis* Sibth.).

An attempt was made to develop regression models to describe soil moisture use as a function of cumulative open-pan evaporation, soil depth, standing biomass of herbaceous vegetation, fresh weight of trees, root distribution of the herbaceous vegetation, and vegetation type. This was only partially successful. The models described the dynamic characteristics and interrelations of the soil moisture profiles under the four vegetation types in a general way only, and they lacked sufficient predictive accuracy to make them of practical use in their present form.

Response surfaces were developed from the data which portrayed the changes in specific soil moisture content, specific soil moisture used, specific available soil moisture content, and cumulative available soil moisture content with changes in depth, cumulative open-pan evaporation, and vegetation type. They demonstrated that bent grass made heavy demands on the soil moisture in the upper profile early in the season but only moderate demands on the lower profile, a pattern consistent with its aestivating and rooting characteristics. Moderate to dense pure forbs made relatively light early season demands on the upper profile, but came on strongly later in the season with heavy moisture use at all levels in the profile. The forb/annual grass mixture was the most demanding of all. It caused heavy, early season, upper profile moisture withdrawal coupled with sustained lower profile moisture depletion. Again, this was a pattern consistent with the phenological and rooting habits of the vegetation.

There was evidence that a substantial amount of water, which because of weed control was not transpired, was eventually lost, probably through increased surface evaporation and unsaturated flow. Nevertheless, although the overall effect of weed control may have been to make available to the trees only a small amount of the moisture saved from transpirational loss, this component is of major importance in the relief of tree moisture stress.

Using the conventional 15 bar estimate of permanent wilting point it was shown that the average rate of descent of the permanent wilting point front was about 0.17 in and 0.14 in per day for the bent grass and mixed forb/annual grass types, respectively. The late season rate of descent under pure forbs was even faster. These are rates which the root growth of new transplants or natural seedlings cannot match under field conditions so that their roots are sooner or later deprived of access to available soil moisture.

It is apparent that bent grass, forbs, and forb/annual grass mixtures represent hostile ecosystems for the establishment of Douglas-fir in areas characterised by Mediterranean type summers. Pure forbs and forb/annual grass mixtures additionally make heavy demands on the lower profile, presumably causing elevated moisture stresses, and reduced photosynthesis and growth even in well-established trees. It would therefore seem desirable (and perhaps economically justifiable) to prolong the period of complete or semi-complete herbaceous weed control in young conifer plantations being established under these conditions.

Summer Soil Moisture Dynamics in a Young Douglas-fir Plantation as Influenced by Three Herbaceous Weed Communities

by

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SUMMER SOIL MOISTURE DYNAMICS IN A YOUNG DOUGLAS-FIR PLANTATION AS INFLUENCED BY THREE HERBACEOUS WEED COMMUNITIES

INTRODUCTION

The advent of modern chemical herbicides has given man the capacity to manipulate vegetation easily and economically. Both quantity of vegetation and species composition are manageable to a degree only previously attainable at great cost. Nowhere is this more true than in the establishment phase of forestry, where chemicals are enabling man to favor crop species by eliminating or reducing the ability of weeds to usurp planting site resources.

In particular, herbicides such as atrazine, 2,4-D and 2,4,5-T have been gaining acceptance for the selective control of grass and herbaceous broadleaf weeds (forbs) in young plantations of conifers. Often the immediate objective of such treatments is to prevent the physical smothering of small planting stock by rank vegetation. It is recognised, however, that even where the trees are in no danger of smothering, weed control results in higher survivals, faster growth, and healthier coloration. Thus factors additional to competition for light must be involved. It is conjectured that this improvement may be some function of:

(i) increased availability of moisture,

(ii) reduced competition for nutrients,

(iii) release of nutrients from the decaying vegetation,

(iv) elimination of inhibitors normally produced by the weeds,

(v) a stimulating effect directly attributable to the herbicide itself.

Other factors, such as: altered soil temperature; the mulching effect of dead vegetation; the effect of decayed grass roots on soil moisture movement and aeration; and changes in the composition and/or activity of soil microorganisms, possibly have some minor effects.

Of all these it seems probable that reduced competition for moisture and nutrients are the major significant factors. In fact, in moderately fertile soils having low summer rainfalls, nutrient uptake will be positively correlated with soil moisture uptake. Improved soil moisture availability is therefore undoubtedly the most important fundamental beneficial effect of weed control.

The range of herbicide mixtures available for selective weed control in coniferous regeneration provides considerable flexibility in the manipulation of weed communities. By a suitable choice of herbicides, and rates and timing of application, or sequence of applications, almost any desired plant cover can be induced, or total weed eradication accomplished. It has been found relatively easy, for instance, to replace a bent grass (_Agrostis tenuis_ Sibth.) dominated pasture cover with a pure stand of false dandelion (_Hypochaeris radicata_ L.). Foresters and Christmas tree growers are frequently satisfied when this has been accomplished without really knowing if the overall habitat for tree growth has been improved. Does, in fact, a vigorous stand of false dandelion persisting throughout most of the summer represent a greater or lesser demand on the available soil water than a stand of bent grass, which matures and aestivates early in the season? To what extent is total weed eradication beneficial or desirable relative to the water requirements of the crop? The study reported here is part of a project designed to answer some of these questions. In particular this report describes an attempt to investigate the relationship between residual soil moisture and some factors related to vegetation, climate, and soil.

One of the primary objectives was to provide a predictive model for the particular site studied for subsequent use in a study on tree growth response in relation to soil moisture. No attempt was made to verify or generalise the model beyond the area studied.

BACKGROUND AND REVIEW

General Comments on Soil Moisture

The movement and storage of soil water and its availability to higher plants has been reviewed by Baver (1956), and Buckman and Brady (1967), and more particularly with reference to forest soils by Lutz and Chandler (1946). Of particular importance are pore size distribution and the affinity of the soil particles for moisture. These in turn are determined by soil texture, structure, chemical composition, and organic matter content. The conventional view is that the soil pore space may be occupied by water or air, and that the amount of water held in a particular soil at any time is determined by a dynamic equilibrium between forces of retention and of extraction. The former are related to the physico-chemical properties of the soil which determine the energy associated with the various air-water interfaces. The latter is determined by gravity and certain atmospheric, solar, and biological energy inputs.

A number of somewhat arbitrary but useful definitions of different soil water retention levels are recognised, including saturation point (SP), field capacity (FC), permanent wilting point or coefficient (PWP), and hygroscopic coefficient (HC). These, and certain other terms are described in a glossary in Appendix 1, and in the standard texts referred to above.

It is generally accepted that during dry weather the bulk of a plant's water supply is provided by capillary conductivity from that held in the soil between FC and PWP. Below PWP, capillary conductivity is virtually zero, moisture movement to the roots takes place in the vapor phase and is very slow. The average value of the soil water potential at the PWP has been arbitrarily standardized at 15 bars, but in view of the high water stresses sustained by some species (Cleary, 1968; Pharis, 1966) it is obvious that it can be considerably in excess of 15 bars in regions of the soil in immediate contact with the roots. This indicates that some plants at least can continue to draw down the soil moisture content (SMC) to levels below the PWP.

Below the PWP further moisture loss occurs through direct evaporative drying and, to a diminishing extent, by transpiration until the plants die.

Soil Moisture in Relation to Vegetation

The influence of vegetation on soil moisture has been conceived of as acting in four ways:

(i) by increasing precipitation,

(ii) by intercepting precipitation,

(iii) by influencing runoff and infiltration,

(iv) by modifying soil moisture losses.

The importance, or even existence, of the first is questionable and is generally discounted (Holtzman, 1937; Kittredge, 1948; Penman, 1963). The effects of the second and third are generally acknowledged to be real enough (Horton, 1919; Kittredge, 1948; Leonard, 1967; Zinke, 1967) but are not of concern in this study. It is with the effect of vegetation in modifying soil moisture losses that our interest lies.

Vegetation generally has a long term beneficial effect on soil. Increasing levels of organic matter result in increased moisture absorbing and holding capacity, while at the same time improved structure enhances drainage (Newnham, 1949). To the extent that vegetation and its litter insulate the soil from the sun's heat, reduce air movement, and increase the depth and humidity of the boundary layer, it will reduce evaporative drying of the surface soil layers. Vegetation can thus be important in maintaining the surface soil layers in a moist condition for a limited period. Its most profound and far-reaching short-term effect however is depletive through transpiration.

Earlier investigators of water use by plants tended to regard consumption as a function of growth or dry matter production. The concept of 'transpiration ratio' (i.e. water used/unit dry matter produced) was used as a descriptive measure of a plant's efficiency of water use. Water use was regarded largely as a biological phenomenon, a 'life-function' (e.g. Warrington, 1900); and growth has even been used as an index of water use (Horton, 1923; Leather, 1910).

While water uptake is essential to plant growth and survival, and evaporation from the leaves is an important factor in regulating plant temperature, it has become clear that none of these requirements of the plant is in any sense a cause of transpiration. Instead, the transpiration process can conveniently be regarded as a semi-mechanical system:

(i) driven primarily by energy sources such as radiant, conductive and convective heat, air movement, the diffusion pressure deficit of the surrounding atmosphere;

(ii) constrained by the availability and viscosity of soil water, and certain inherent and induced characteristics of the plant itself (structure, form, size, etc.);

(iii) under limited feedback control through stomatal movement and incipient drying (Slatyer, 1966).

Plants thus effectively expose the soil in or near their rooting zones to the drying effects of sun and air.

Soil Moisture in Relation to Climate

Climate has two basic impacts on soil moisture working in opposition: Replenishment through precipitation, and depletion in response to solar radiation, low relative humidity, and air movement. Temperature increases resulting from solar radiation increase the water vapor pressure in the soil and plants, and raise the moisture holding capacity of the surrounding air. Air movement or wind serves to remove water vapor from evaporative surfaces (boundary layer reduction) and thus helps maintain the saturation deficit of the atmosphere in the vicinity of the evaporating surface.

Some Models for Evapotranspiration

If E is the energy equivalent of total evapotranspiration (i.e. soil surface evaporation plus transpiration) and H[1] is the net radiation received over the same period and expressed in the same units, it is found that

$$E = H$$

is a good first approximation when water is non-limiting (Penman, 1967).

A somewhat closer approximation is given by

$$E = H + Q$$

where E and H are as already defined, and Q is the sensible heat transfer between plant and air, expressed in the same units. Q is positive if the net transfer is from air to plant. These relationships imply that when water is non-limiting, evapotranspiration as a whole is essentially a thermodynamic phenomenon.

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[1]H is comprised of:

(i) a net solar radiation term, $R_i(1.0-r)-R_b$ where R_i and R_b are the incoming and back radiation respectively, and r is the reflectivity of the vegetation: $r \simeq 0.25$ for agricultural crops (Monteith, 1959), and is uncertain for forest crops, but is probably in the range 0.15 to 0.25. [Gay (1972) gives an albedo of 0.09 for a young, closed-canopy Douglas-fir forest, indicating Penman's figures may be somewhat high.];

(ii) a kinetic energy term associated with air movement;

(iii) a potential energy term relating to the diffusion pressure difference between the evaporating surfaces of the leaves and the external atmosphere.

Various other more complex expressions have been formulated to take into account atmospheric mixing processes or air turbulence, aerodynamic transport of the water vapor, and roughness of the vegetation (Penmann, 1967), but these are not of concern here.

Frequently actual evapotranspiration is less than potential evapotranspiration because the water supply is limiting. Evapotranspiration is then no longer solely a function of the drying power of the air and the net energy input to the system; it is also related to the capacity of the specific vegetation to extract moisture from the soil. Complex, semi-empirical expressions to describe evapotranspiration under these conditions have been developed for some agricultural crops. Turc (1955), for instance, designed the following formula to describe short term evapotranspiration from cropped areas:

$$E = \frac{P + a + V}{[1.0 + \{(P+a)/L + V/2L\}^2]^{\frac{1}{2}}}$$

E = evapotranspiration in a ten day period (mm);

p = precipitation in a ten day period (mm);

a = estimated evaporation in a ten day period from bare soil assuming no precipitation, and is not greater than 10 mm;

V = crop factor = 25 M.C/Z, where 1000M is the final yield of dry matter (Kg/ha), 10Z is the length of the growing season in days, and C is a crop constant (e.g. 0.67 for maize and beet to 1.33 for lucerne, meadow grass and mustard);

L = evaporation capacity of the air = $(i^{\frac{1}{2}}/16)(T+2)$, where T is the mean air temperature over the ten day period in °C, and i is the incoming radiant energy in cal cm^{-2} day^{-1}.

While such expressions may not have much utility in describing the progressive depletion of soil moisture throughout a long, hot, dry summer, they at least indicate one type of quantitative approach and the nature of the factors which might be considered. In this regard Newton (1965) found that under prolonged, warm, dry summer conditions the number of days required for exhaustion of available soil moisture within the rooting zone of herbaceous vegetation growing in a young conifer plantation could be predicted approximately by the equation:

$$D = \frac{780\ (M+R)}{0.30(\text{Cos } A)(\text{RAD})(\%\ \text{cover})} \times 100$$

where:

D = days of available moisture after last effective rainfall (<u>i.e.</u> since last spring fall of half an inch or more);

M = inches of available moisture in the soil profile within reach of weed roots;

A = slope difference between plantation and 28° south slope along north-south line (This apparently assumes east and west aspects are self compensating.);

RAD = average daily incoming solar energy expected during the drying period in langleys;

% cover= percent point frame hits in herbaceous vegetation;

R = inches of rainfall in spring showers after soil profile begins to dry.

Newton (1964) also developed regression models which described available soil moisture and soil moisture loss per day as functions of date, open-pan evaporation, site drainage class, soil depth, vegetation quantity, and a vegetation composition factor (percent annuals), but these did not specifically identify vegetation type effects.

Once water becomes limiting, the specific water harvesting and conserving abilities of the plant species present become important. It seems probable that these are related to the root distribution profile, foliage structure and form, and cuticular and stomatal characteristics, factors which could also be considered in expressions for comparative evapotranspiration. In this connection, differences in the transpirational loss of major cover types have been interpreted at a coarser resolution level in terms of their differing energy balances (Baumgartner, 1967). Forests, especially coniferous forests, with their high absorption of shortwave (and also their roughness, large evaporative surface area, and deep rooting habit), show the most intensive water use; cultivated and grassland areas are intermediate; and bare soils, with their high reflectivity, have the lowest loss rates. Presumably then there must be some interconnection between the morphological and anatomical characteristics of the vegetation, the energy budget and soil moisture use.

Soil Water Availability to Plants

Following soaking rains or irrigation of free draining soils, excess water drains away within a few days to leave the upper soil horizons at field capacity. Thereafter, soil moisture is largely depleted by surface evaporation, and, if plants are present, by transpiration; the latter becoming the overwhelmingly significant route as time passes. As already indicated, an approximate lower limit of water availability to plants is represented by the soil moisture content within the rooting zone at which permanent wilting occurs. This limit is relatively constant for many plants (Veihmeyer and Hendrickson, 1928).

Whether the soil moisture between field capacity and wilting point is equally available to plants, or becomes increasingly more difficult to extract, is unresolved. On the one side, the equal availability school as represented by Veihmeyer and Hendrickson (1950, 1955), maintains that transpirational water loss is largely independent of soil moisture content down to near wilting point (Penman, 1963). Veihmeyer and Hendrickson argue that even near wilting point the energy required to extract 1 gm of water from the soil is insignificant ($.16 \times 10^8$ erg gm^{-1}) compared with that required to evaporate the same quantity from the leaves at 40% RH.(9.4×10^8 erg gm^{-1}). If the latter energy requirement can be met there should be little difficulty in meeting the former. Thornthwaite and Mather (1954, 1955) on the other hand present evidence which to them demonstrates the non-equal availability of water, and that after a certain point the rate of removal is proportional to the ratio of unused available water to that present at field capacity.

Penman (1963) considers the preponderance of evidence in favor of the equal availability doctrine. The situation however is complicated by at least four factors:

(i) the 'foraging' ability of the roots is unknown;

(ii) soil in immediate contact with the roots may be at the wilting point moisture content long before soil a short distance away which is still supplying the roots with water;

(iii) the stomata of some plants are relatively insensitive to plant moisture stress and remain open right up to wilting point, so that high transpiration rates are maintained, whereas the stomata of other species are more responsive to moisture stress and tend to close so that the transpiration rate falls off as the wilting point is approached;

(iv) in the field, deep-rooted plants often have roots which are in soil horizons which vary all the way from well below wilting point in the vicinity of the soil surface to near field capacity at considerable depth.

The differences in opinion between the two schools can probably be explained on the basis of their failure or inability to take into account one or more of these complicating factors.

Vegetation Manipulation and Soil Moisture

Irrespective of the kinetics of soil moisture withdrawal, the amount of soil water available to plants is mainly limited to that held between field capacity and wilting point within, or relatively close to, the rooting zone. The reserve of moisture actually available at any one place and time is a function of the inherent properties of the soil, including texture, structure, and colloid composition, together with the summation of the various moisture inputs and outputs which have occurred since the last saturating rain. Because the potential for transpiration during a Mediterranean type summer is well in excess of the water storage capacity of the soil, plants will compete for this reserve. The extent to which an individual is successful will largely determine its ability to survive and grow. Vegetation manipulation can be used to reduce, or even eliminate, the competitive ability of undesirable species, making more of the site resources available to the desirable species.

Setting aside the important influence that vegetation manipulation can have on interception, infiltration and run-off, it will have basically two effects on soil moisture:

(i) it will influence water yield as measured in terms of stream flow, which is important to the hydrologist;

(ii) it will alter the amount of water available to individual plants on the site, which is important to the agriculturalist and the tree grower.

Reduction of transpiration surface and alteration of species composition can both be used to influence water yield and available soil moisture.

Reduction of Transpirational Surface

This is accomplished in crop management by crop thinning, weed control, or total vegetation control, the emphasis being on the partial or complete removal of the weed transpiration surface so as to minimize transpirational losses. This is the rationale for most weed control in summer crops, dry fallow systems of agriculture, control of grass and forbs in young forest plantations, crop thinning, and orchard cultivation practices. The accounts of substantial increases in water yield and available moisture for crops or other preferred plants are legion. Hibbert (1967), Rothacher (1970), and Johnson (1970) may be cited as recent examples with respect to manipulation of forest cover.

Hibbert tabulated the results of thirty-nine studies of the effects on water yield. Taken collectively, they showed that forest reduction increases water yield, and that reafforestation decreases water yield. A practical upper limit of yield increase appeared to be about 4.5 mm per year for each percent reduction in forest cover. Most treatments, however, produced less than half this increase. The rate of decline of the enhanced yield following clear-cutting appears to be related to the rate of forest recovery.

The importance of herbaceous vegetation in depleting the upper soil horizons of moisture, and the value of herbaceous weed control in minimizing soil drought in forest re-establishment have been demonstrated by Newton (1964). He showed that grassy vegetation could account for 92% or more of the total moisture depletion during the period of most rapid soil drying; and that chemical vegetation control resulted in the conservation of 84% of the moisture present in the top 36 inches of soil at the end of the spring rains until the onset of the fall rains. This resulted in a dramatic improvement in survival and vigor of newly-planted Douglas-fir seedlings. The mathematical models developed indicated that drought amelioration was approximately linearly related to the reduction in vegetation density. At higher vegetation densities where competion for soil moisture becomes important one would expect significant nonlinearity to set in.

Manipulation of Species Composition

Here the objective is to maintain a more or less continuous vegetation cover but to alter the depth from which soil moisture is withdrawn. For instance, if deep-rooted forest or range brush is replaced by grass, water yield during prolonged dry weather is enhanced because the grass exhausts the available moisture within its shallow root zone and then aestivates; but the deeper-rooted trees and brush survive throughout the dry period and go on transpiring water absorbed at greater depths.

There are numerous reports of differences in water yield and use consequent upon the manipulation of vegetation composition. For example, some earlier work in California dating back to 1940 on relative water use by brush, grass and forbs is described by Veihmeyer (1953). Rowe and Reiman (1961) showed that conversion from dense, scrub-oak brush to grass resulted in a significant increase in soil moisture, but that the amount of increase was dependent on the depth and storage capacity of the soil, the amount and distribution of annual rainfall, and the kinds of vegetation occupying the site before and after conversion. Increases of 2 to 6 inches in water yield have been reported after converting oak woodland to annual grassland in Placer County (20 to 28 inches rainfall), California by Lewis (1968); and Hibbert (1971) found increases of 2 to 12 inches in yield following conversion of chaparrel to grassland in Central Arizona. In both cases the magnitude of the yield increase was positively correlated with annual precipitation.

EXPERIMENTAL PROCEDURES

Experimental Approach

The experimental approach to this investigation was one of field experimentation and observation in already existing herbicide plots whose vegetative covers reflected histories of zero to three years chemical weed control. Data collection included: measures of the transpirational surface of the weeds and trees; characterization of the different weed-type root profiles; the determination of soil moisture profiles through soil sampling and gravimetric determination of SMC; the determination of wilting coefficients using a pressure plate apparatus; and the measurement of soil bulk densities. Meteorological data was used to provide an index of the ongoing climatic factors affecting the system.

Location, Plot Selection and Description

The trial plots were located in a grassy meadow owned by Starker Forests Ltd., bordering Highway 20, approximately 2.4 miles west of Blodgett in the Oregon Coast Range (see locality map, Fig. 1a).

The soils appeared to be intermediate between the Knappa and Chitwood series which are typical of the stream terraces of the small tributary valleys within the Coast Range (Simonson and Norgren, 1969). They are deep, moderately well-drained, acid soils having 12-18 inches of dark brown, friable, silty loam grading into a yellowish brown, silty clay loam subsoil which tended to be mottled at depths in excess of 30 inches. Climatically, the area is characterised by warm dry summers with a well defined drought of 3-5 months, cool, wet winters, and an annual precipitation of approximately 70 inches.

The 0.01 ac (16 ft x 27 ft) observation plots were selected from among 66 plots (Fig. 1b) laid down in the spring of 1968 by staff of the Oregon State University Forest Research Laboratory in cooperation with Starker Forests Ltd., to study herbicide effects and interactions

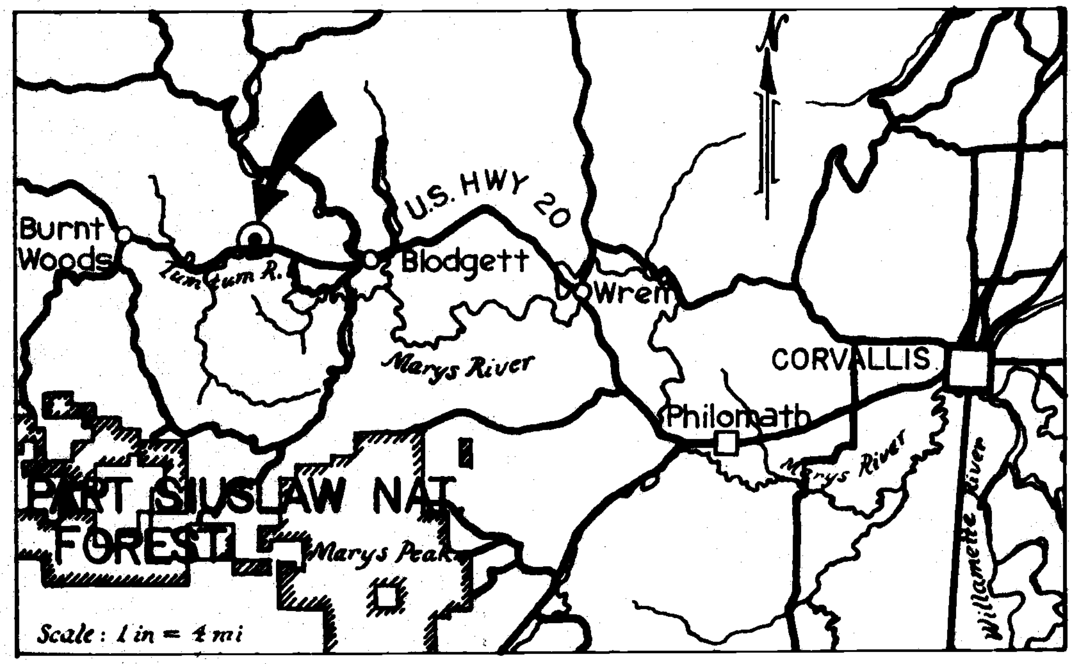

Fig. 1a. - Map showing location of experimental area.

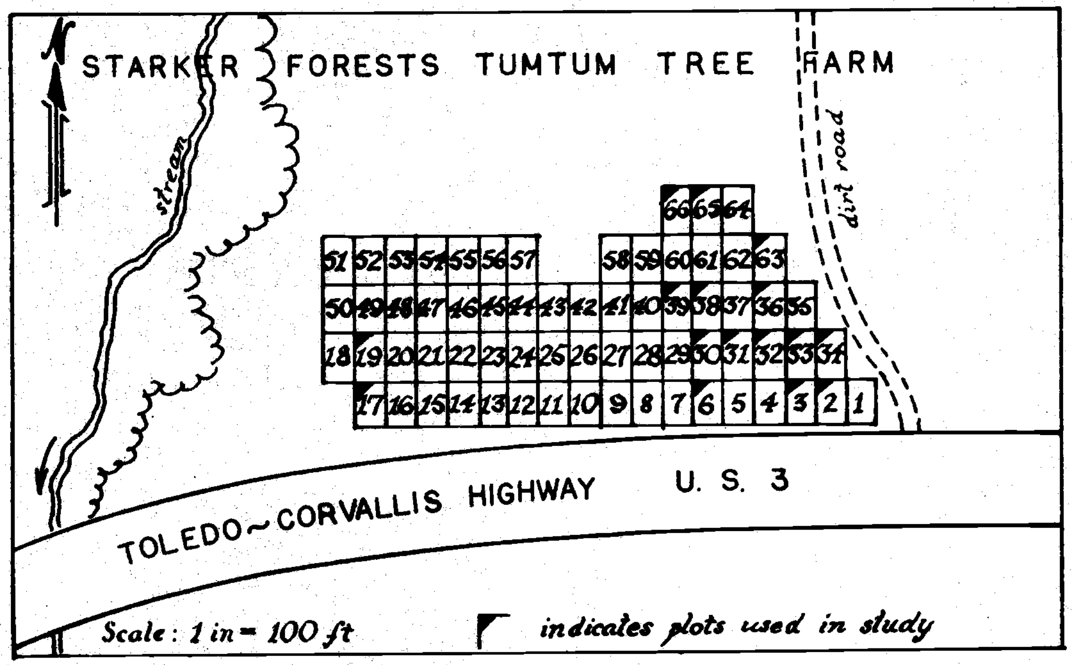

Fig. 1b. - Plan of plot layout.

on herbaceous weeds and planted Douglas-fir. A sequence of whole and split plot treatments applied over the period from spring 1968 to spring 1970 was such that each plot was effectively divided into four quadrants (Fig. 2a, 2b), designated NE, NW, SE and SW, each quadrant being occupied by vegetation whose species composition and density reflected its prior herbicide history. The plots selected for study were generally characterised by having the following vegetative covers on their quadrants:

NE quadrant: Largely weed free or having a few scattered forbs, mainly false dandelion; treated third year after planting.

NW quadrant: Dense forb cover, typically pure false dandelion; treated second and third year after planting.

SE quadrant: Dense, almost pure bent grass, with a few false dandelions and occasionally clumps of alta fescue - essentially the original pasture condition.

SW quadrant: Mixed vegetation consisting of dense annual grasses, principally silvery hairgrass (Aira caryophyllea L.) and forbs; treated the second year after planting only.

There was some variation but, by and large, the plots conformed to this format. Sixteen plots were chosen in all, consisting of eight pairs of adjacent plots. They were selected in adjacent pairs for convenience of irrigation (see later).

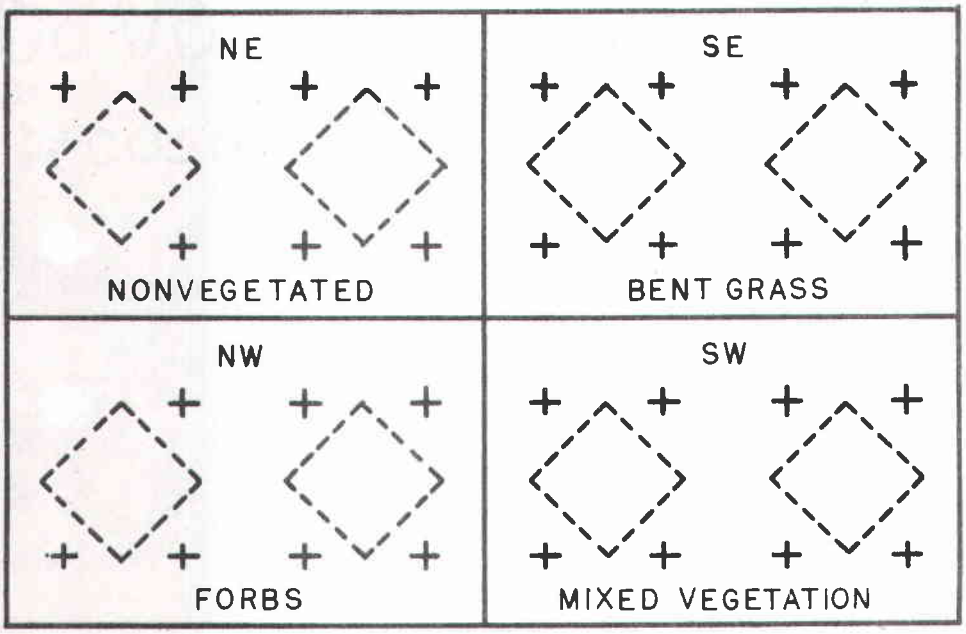

Fig. 2a.- Layout of a plot and its quadrants. Broken lines and crosses indicate position of vegetation assessment quadrats and Douglas-fir trees respectively.

Fig. 2b. - Photograph of plot 63 at the end of summer. Disposition of quadrants is the same as in Fig. 2a.

Each plot originally contained approximately 30 Douglas-fir trees, planted as 2/0 stock in four rows of seven or eight trees each in the winter of 1968. This worked out at two rows of approximately four trees each in each quadrant. At the time of this study, however, the size and number surviving per quadrant varied widely depending on the intervening treatment history and normal random fluctuation in growth and survival.

Because soil moisture depletion was already well advanced at the time data collection was commenced, it was decided to irrigate four of the eight pairs of plots to restore them to field capacity. Water was pumped from a nearby stream and applied through perforated plastic sprinkler hoses. At least six inches of water was applied as indicated by six inch tall cans scattered over each plot. Irrigation took three days and was completed on June 26, 1970.

Data Collection and Preparation

The types of data collected relevant to this report can be grouped into two broad categories: drying factors and soil moisture factors. They will be described under these two headings.

Drying Factors

These include measures of transpirational surface, location of absorptive surfaces (weed root profiles), and climate index.

Measures of Transpiration Surface

The transpirational surfaces active on the plots consisted of herbaceous vegetation (weeds) and trees.

Standing Biomass of Herbaceous Vegetation. The herbaceous vegetative cover percent on each NE and NW quadrant was estimated at the end of August using a dot grid/dry weight correlation procedure (Table 1, Appendix 2). One-yard-square quadrats were delineated by a square wooden frame having crosswires at six-inch intervals, with the intersections of the crosswires, points of attachment and corners of the wooden frame constituting a 49 point dot grid. Two systematically located quadrats (Fig. 2a) were counted on each quadrant. In order to relate these assessments to the quantity of dry matter present, 16 other quadrants were subjectively chosen on nearby, non-experimental plots having similar treatment histories (to have harvested the vegetation on the observation plots during the study would have interfered with the subsequent course of moisture depletion). Percent cover was estimated in the same manner, and all the above-ground vegetation harvested and its oven-dry weight determined. This provided the 16 data points (Table 2, Appendix 2) and the fitted curve of dry matter production per acre versus estimated percent vegetative cover shown in Fig. 3. While the polynomial chosen gave the best fit of several functions tried, its behavior in the 90-100% region is obviously anomalous. Nevertheless, since it was not required for predictions in this region, no serious error was introduced on this score.

Estimates of dry matter production based on percent cover would have been meaningless for the SE and SW plots as all had virtually 100% cover. Areas of comparable non-irrigated vegetation were chosen nearby and sampled for dry matter production in the manner just described. Five quadrats corresponding to each of the two quadrant types were

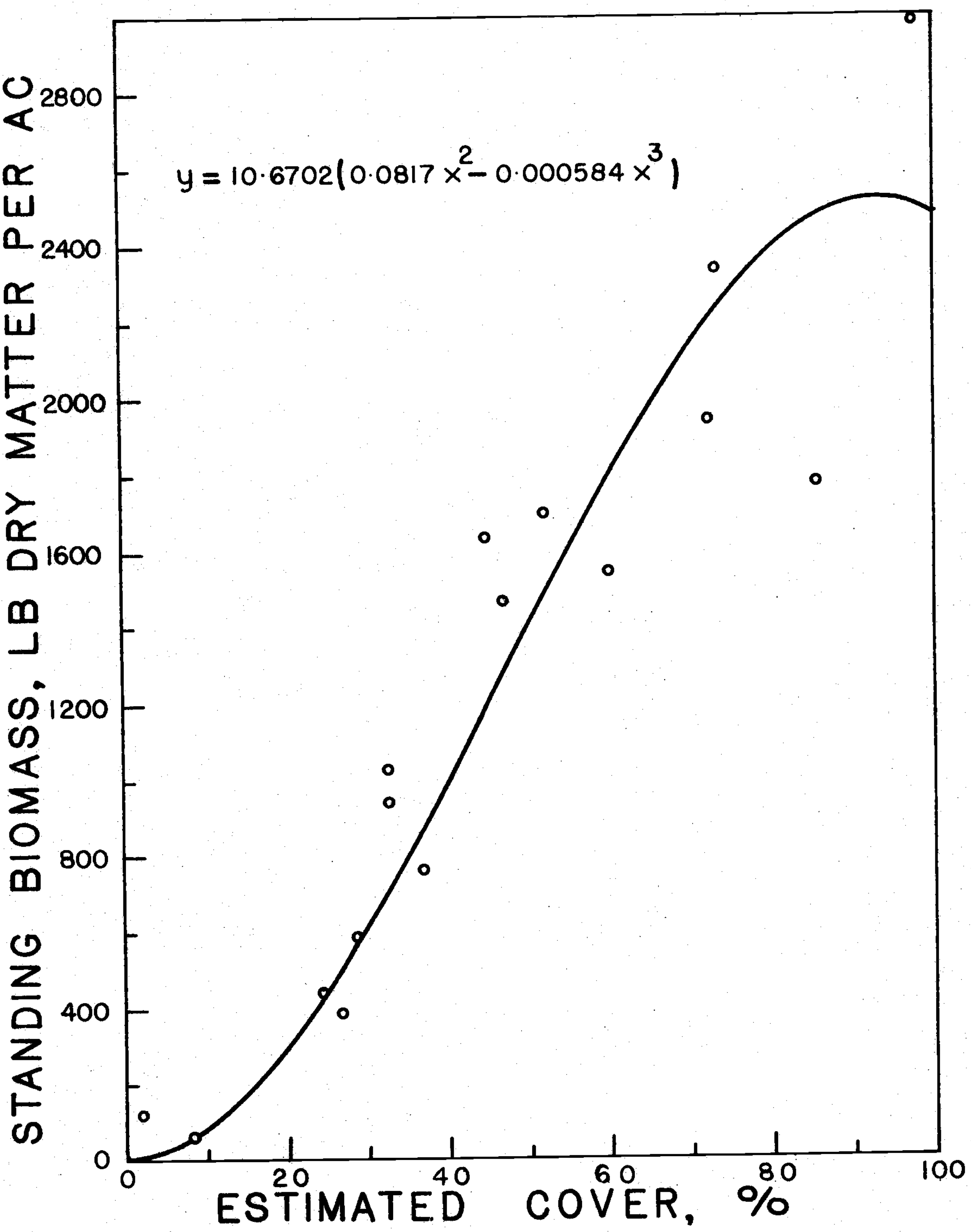

Fig. 3. - Data and fitted curve of dry matter production as a function of estimated % vegetative cover for NE and NW quadrants at end of August, 1970.

harvested and the means of the oven dry weights used as estimators of the dry matter production on all the non-irrigated SE and SW quadrants as at the time of assessment (Table 3, Appendix 2).

Ideally, dry matter production should have been assessed at times corresponding to the dates when soil moisture samples were taken (see later). This was not done and it was necessary to generate data for these dates. To do this the following assumptions were made:

(i) Except near the start and end of the summer, when climatic and other factors become overriding, cumulative dry matter production can be described by the Gompertz function

$$G(T) = B_1 e^{B_2 e^{B_3 T}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where T is the time in days since growth commenced. For B_2 and B_3 negative, B_1 is the upper asymptote ($T \to + \infty$), and zero is the lower asymptote ($T \to - \infty$).

(ii) Dry matter production commenced on March 1 (near start of the growing season for most pasture species) in the SE and SW quadrants, and March 25 (date of last herbicide treatment) in the NE and NW quadrants. In order to 'anchor' the Gompertz functions a small arbitrary cumulative dry matter production (1.0 lb/ac) had to be assumed at these dates and the curves for the nonirrigated plots forced through this point.

(iii) Standing biomass for the whole season (the upper asymptote, B_1) on the nonirrigated quadrants was 10% more than the observed maximum for each vegetation type (quadrant) as assessed on July 5, 1970[3].

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[3]Although the values assumed for the upper maxima may be in error, the

i.e. NE and NW quadrants $B_1 = 181 \times 1.1 \doteq 200$ lb/ac

SE quadrants $B_1 = 3643 \times 1.1 \doteq 4000$ lb/ac

SW quadrants $B_1 = 4240 \times 1.1 \doteq 4660$ lb/ac

Evaluation of the two remaining parameters was carried out as follows:

Letting $G(0) = 1.0$ gives

$$B_2 = \ln[G(0)/B_1] = -\ln B_1 \quad \ldots\ldots\ldots\ldots (2)$$

Since we know $G(T)$ on August 30 (date of dry matter assessment) we can find

$$B_3 = \frac{\ln\{\ln[G(T)/B_1]/B_2\}}{T} \quad \ldots\ldots\ldots\ldots (3)$$

Estimation of the standing biomass on the non-irrigated quadrants at the time of SMC assessments was then made using equation (1).

Estimation of standing biomass on the irrigated plots was based on two further assumptions:

(i) That the average standing biomass followed the curve of the corresponding nonirrigated quadrants up to the date of irrigation, but that thereafter it followed another Gompertz function passing through the mean standing biomass for the quadrant type as assessed on August 30;

(ii) That the Gompertz function for irrigated plots had upper

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concept of an upper maximum dependent on species composition and the presence of a fixed reservoir of available soil moisture, would seem to be a valid one. It was estimated that the most heavily vegetated plots in each type had reached approximately 90% of the standing biomass potential for the type for the year.

asymptotes determined by the three fixed lower points through which they pass (i.e. G_0, G_1, G_2, at T_0, T_1, T_2). This involved the solution of the equation

$$e^{B_3T_1} - e^{B_3T_2\left[\frac{\ln(G_0/G_1)}{\ln(G_0/G_2)}\right]} = \frac{\ln(G_1/G_2)}{\ln(G_0/G_2)} \quad \ldots\ldots\ldots\ldots (4)$$

for B_3. This cannot be solved explicitly for B_3 but graphical and numerical (computer) solutions were possible for the SE and SW quadrants, and these solutions when substituted back into

$$B_1 = \left[\frac{G_2}{G_0}^{e^{-B_3T_2}}\right]^{\frac{e^{B_3T_2}}{1-e^{B_3T_2}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

yielded realistic upper asymptotes (B_1). Unfortunately solutions could not be obtained in the case of the NE and NW quadrants, and upper asmyptotes of 500 lb/ac were assumed. B_2 was then determined by evaluating $B_2 = -\ln(B_1/G_1)$ where G_1 is the standing biomass predicted for the nonirrigated plots at the time of irrigation.

Biomass assessment results, parameter values, and function estimates of standing biomass at the time of SMC assessment are tabulated in Table 4, Appendix 2. The respective computer-generated curves are shown in Figs. 4 and 5. In order to account for more of the variability in the amount of soil moisture used in the NE and NW quadrants, the estimates of standing biomass generated for each at the times of SMC assessment were modified by multiplying them by the factor:

(Standing biomass on particular quadrant at time of biomass assessment) ÷ (Mean standing biomass for quadrant type at time of biomass assessment).

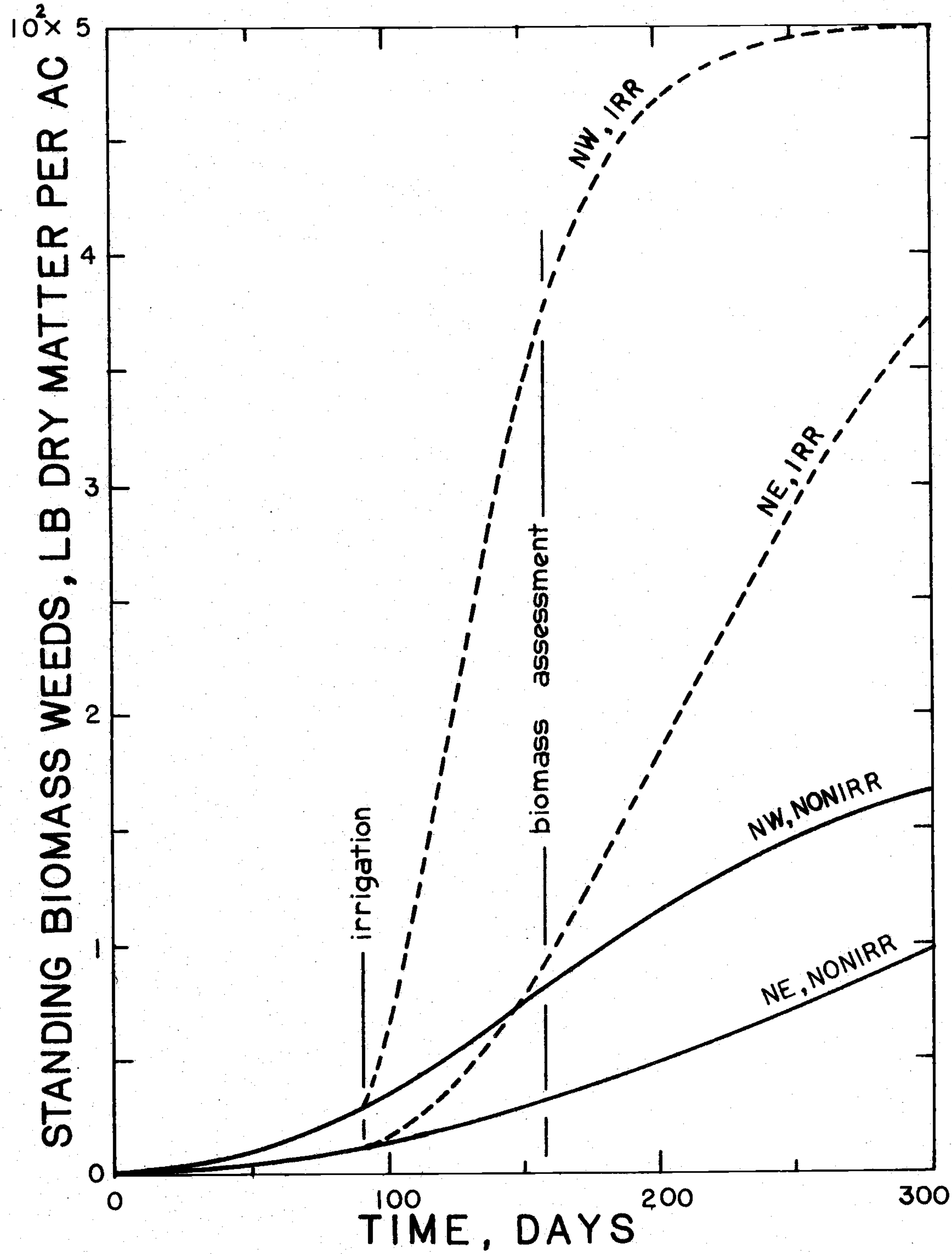

Fig. 4. - Gompertz function curves for NE and NW quadrants for estimating standing biomass (herbs) at any time since commencement of growth.

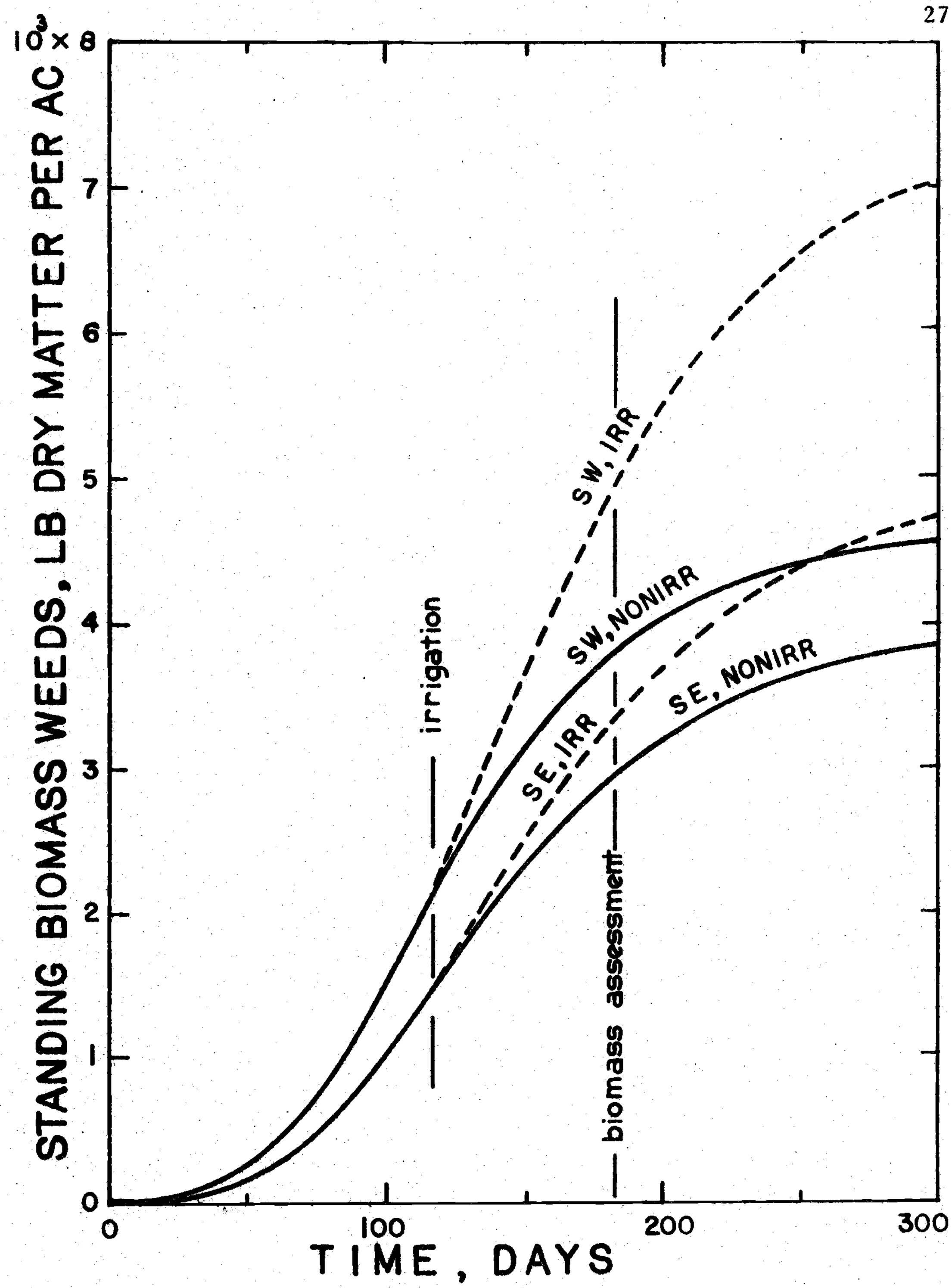

Fig. 5. - Gompertz function curves for SE and SW quadrants for estimating standing biomass (herbs) at any time since commencement of growth.

This was done on the further assumption that the variation in standing biomass of specific quadrants from the function values (assumed means) at the various times of SMC measurement was proportional to the variation existing at the time of the biomass assessment.

Standing Biomass of Trees. Since trees represented a large component of the total transpiring vegetation on many plots (much more on some than on others because of wide variation in survival and size attained) it was considered that they too could be a significant factor in soil moisture depletion. Estimates of the total mass of green foliage would undoubtedly have provided the best measure of this 'tree effect', but to have attempted this would have been too time consuming. It was decided instead to opt for total shoot fresh weight at the end of the growing season as an index. All the trees from 16 nonexperimental quadrants were harvested, measured for height and weighed (Table 5, Appendix 2). The following exponential functions relating fresh weight to height were fitted to the data for each quadrant type (Fig. 6) using a non-linear least squares curve fitting program (CURVFIT).

NE quadrants : $Y = -.28699(1.0-e^{.0307X})$

NW quadrants : $Y = -.09818(1.0-e^{.0608X})$

SE quadrants : $Y = -.02485(1.0-e^{.0931X})$

SW quadrants : $Y = -.06439(1.0-e^{.0759X})$

where X is the height of the shoot in inches and Y the predicted weight of the shoot in lbs.

The functions were then used to estimate the total tree fresh weight per acre on each experimental quadrant based on the height measurements of all the trees present at the end of the 1970 growing

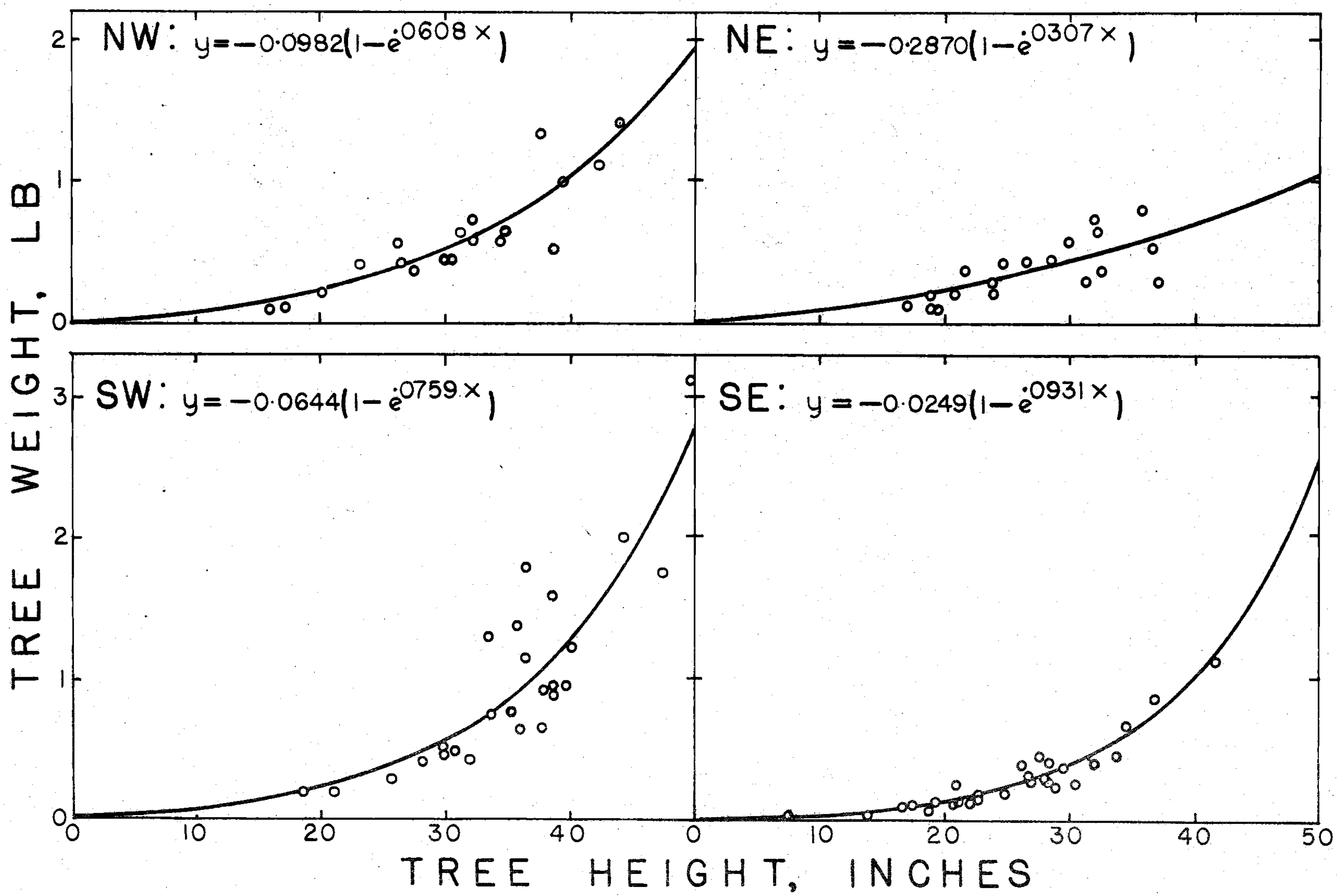

Fig. 6.-Relationships between Douglas-fir tree height and fresh weight for each of the four quadrant types.

season (Table 6, Appendix 2). The effect of irrigation on tree height (if any) was ignored. Also, it was not feasible to derive estimates of fresh weight at the times of the SMC assessments as was done for the herbaceous vegetation.

Location of Absorptive Surfaces

One of the factors determining the depth from which moisture is lost, and the shape of the soil moisture profile, is undoubtedly the root distribution profile.

It was thought that a knowledge of this might help to explain species effects on the pattern of soil moisture depletion. Twenty-six, five-inch diameter, 36 inch deep soil cores were extracted by means of coring tube driven by a hydraulic ram mounted on a pick-up truck (Fig. 7a). Five cores were taken in each of the following vegetation types: Bent grass, forbs, alta fescue and velvet grass. Six cores were withdrawn from the mixed vegetation type corresponding with SW quadrants. The cores were cut up into six-inch segments (Fig. 7b), and the total root content of each segment extracted by a laborious washing and sieving process. The extracted roots were then oven dried and weighed. Because there were undoubtedly significant differences in root losses during the extraction procedure between species, and also because mere root mass is not necessarily a good indicator of absorptive capacity, the data points were each expressed as a percent of total root mass for each core. In order to magnify the differences at greater depths the data is plotted on semi-log scales (Fig. 8). Data means and their standard errors are listed in Table 7, Appendix 2.

Fig. 7a. - Hydraulic coring rig used to extract soil cores for root distribution study.

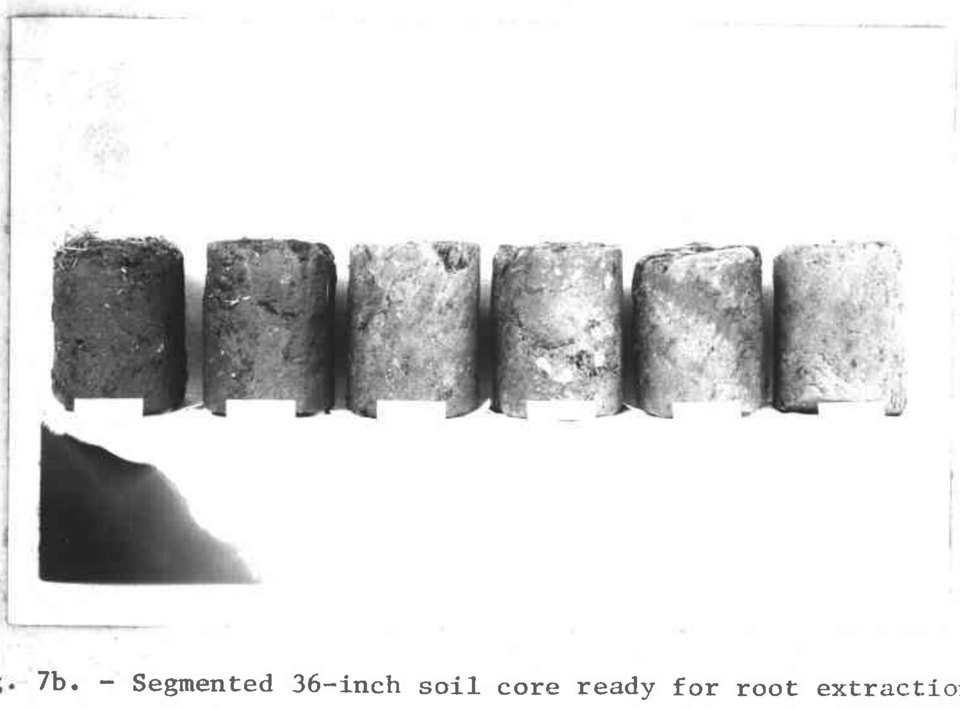

Fig. 7b. - Segmented 36-inch soil core ready for root extraction.

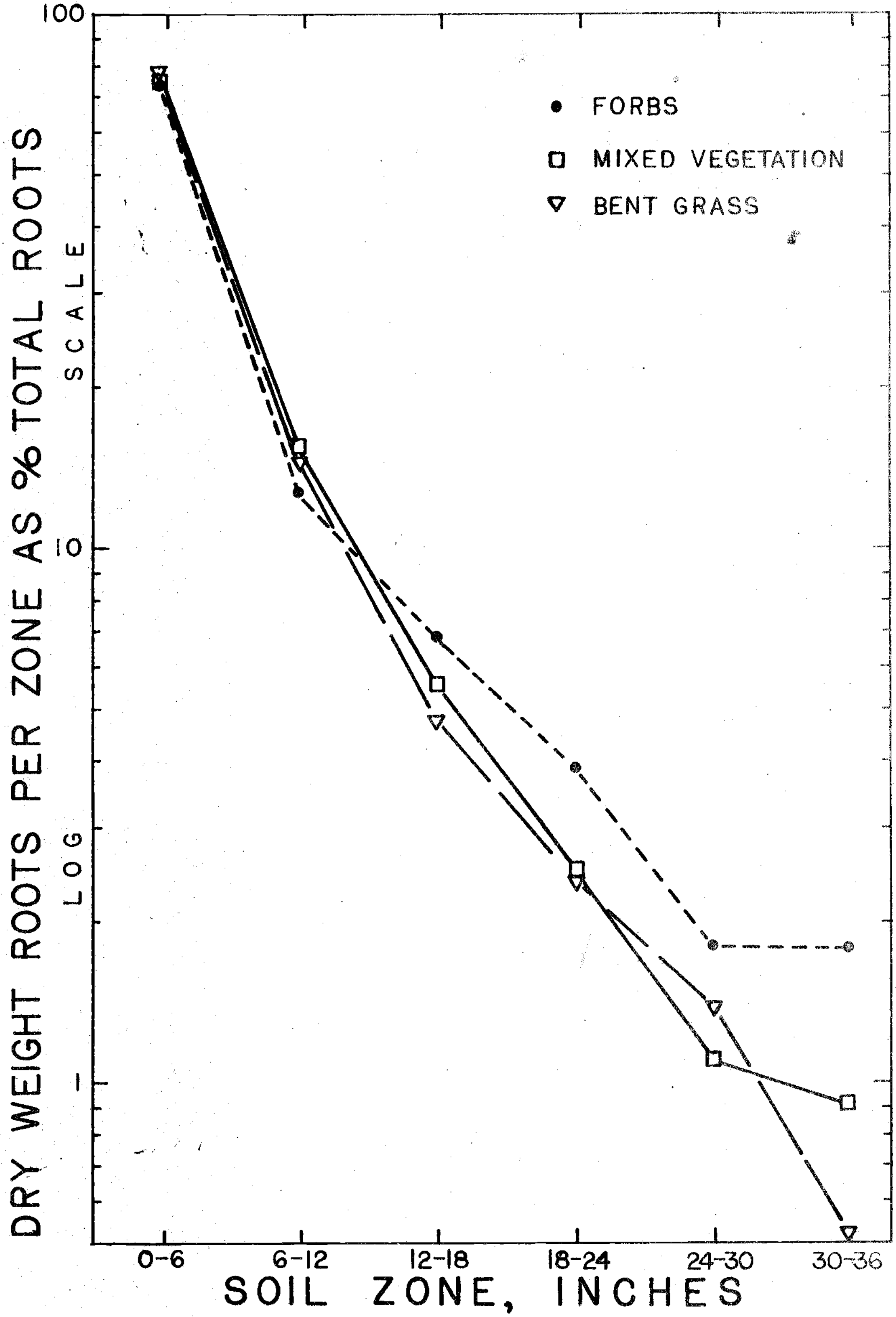

Fig. 8 -Replicate means of percent weed roots plotted against soil depth for forbs, bent grass, and mixed vegetation.

Climate Index

An integrated measure of the total evaporative forces acting on a site during a season is provided by the cumulative open-pan evaporation. It was decided to make use of the records kept at Hyslop Farm, a part of the O.S.U. campus, five miles NE of Corvallis. Although situated approximately 18 miles due east of the experimental area, and in the Willamette Valley, it was considered that, while conditions there would not duplicate those existing on the experimental area, at least they would fairly closely parallel them throughout most of the summer.

A plot of cumulative open-pan evaporation and fitted Gompertz function for 157 days after the last significant spring rains is shown in Fig. 9. The data are presented in Table 8, Appendix 2.

Soil Moisture Factors

The characterization of the soil moisture profiles involved the determination of SMC, FC, WP and bulk density (BD).

Soil Moisture Profiles

Gravimetric soil moisture determinations were made from samples extracted by means of a 3/4 inch-inside-diameter, hand-driven, core sampler at depths of 3-6, 9-12, 18-21 and 33-36 inches.

Sampling was done on June 29-July 3, July 24-25, Aug. 11-15, Sept. 4-5, 1970. Five sub-sample holes were driven per quadrant on the first sampling, and two holes per quadrant on the three subsequent samplings. All quadrants in all plots were sampled. The holes were located at random within a central strip approximately two feet wide down each quadrant. Each hole was loosely refilled with soil and plugged with a

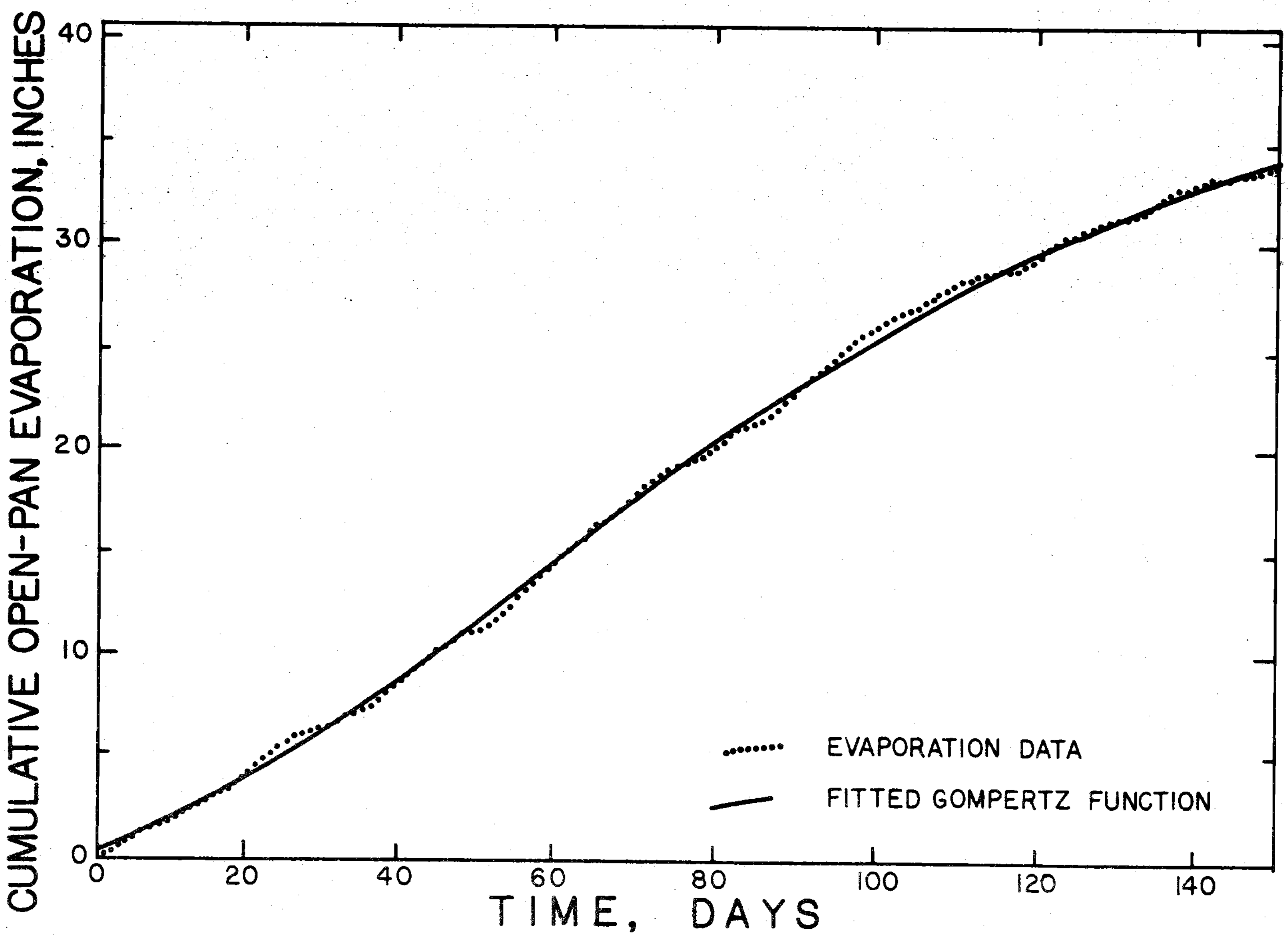

Fig. 9. - Cumulative open pan evaporation. Data derived from Hyslop Farm meteorological records.

wooden peg to minimize drying effects introduced by the holes, and also to make sure holes in subsequent samples were located at least a foot from pre-existing holes. Samples drawn from the same depth in the same quadrant were composited for moisture content determination.

Determination of the total amount of soil moisture used at any given time requires a knowledge of the starting moisture content or field capacity of the soil. Further soil samples were taken from each level at each quadrant by the method just described. Sampling was done during the winter of 1971-72 at a time when the profile was judged to be at field capacity.

The replicate means and standard errors for specific SMC are tabulated in Tables 9 and 10, Appendix 2.

Permanent Wilting Point

The gravimetric determination of soil moisture percent, in effect, gives the percent soil mass due to free water, capillary water and hydroscopic water, i.e. it includes water held in the soil below wilting point which is not generally considered available to higher plants. Correction for this is therefore necessary. Samples were collected in the same manner described above, except that three cores were drawn per quadrant. Wilting coefficients were determined using a Soil Moisture Equipment Co., 15 bar ceramic plate extractor operated at 220 psi. Four determinations were made using four subsamples from each of the 64 composite samples. The means of these determinations for each of the 16 plots, and the overall means for each depth (Tables 11 and 13, Appendix 2) are plotted on Fig. 10.

The overall effect of depth on permanent wilting point was

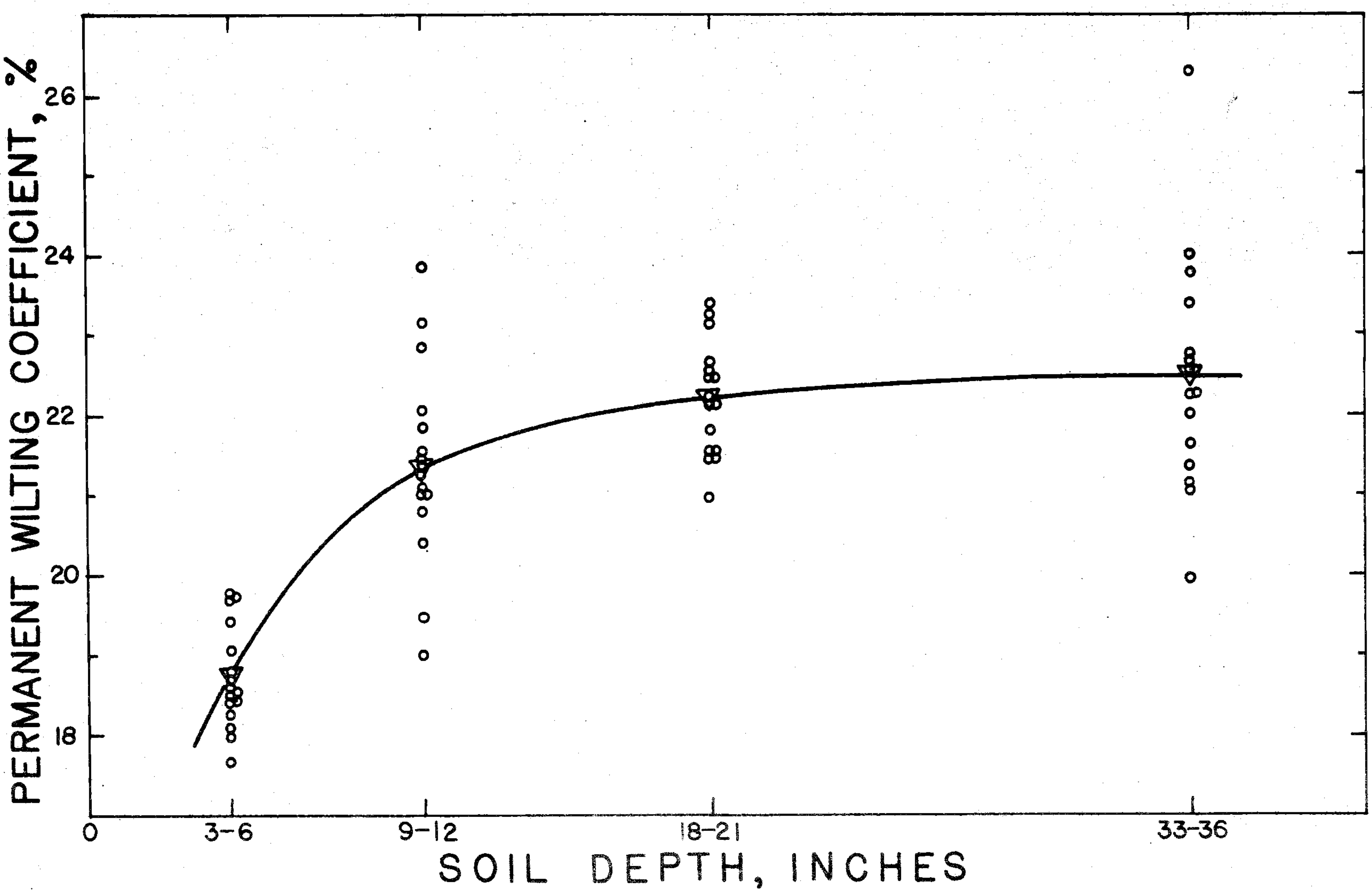

Fig. 10. - Variation of perm. wilting coeff. with soil depth; plotted data, means, and hand-fitted curve.

significant at the 0.01 level (Table 12, Appendix 2). However, only the differences between the 3-6 inch mean and the other means were significant (0.01 level; Table 13, Appendix 2).

Because of the high degree of variability in wilting point from quadrant to quadrant at the same depth, and the close agreement between the four determinations on each sample, it was decided to use the individual quadrant means for each level to correct each of the SMC percent determinations to 'available' SMC percent, i.e.:

(available SMC percent) = (SMC percent) - (WP percent)

Bulk Density

Bulk density of the soil was determined so that the amount of water stored in the soil at any one time, or the rate of water use could be expressed in absolute terms. Single sample points were located at random, one in each of a random selection of nine of the sixteen study plots. Using a three-inch-inside-diameter, hammer-driven, core sampler and a six-inch diameter post hole borer, four bulk density samples corresponding to depths of 3-6, 9-12, 18-21 and 33-36 inches were obtained at each sample point. The bulk density of each sample and the means for each soil depth (Table 14, Appendix 2) are plotted in Fig. 11.

The overall effect of depth on bulk density was significant at the 0.01 level (Table 15, Appendix 2), though only the differences between the 33-36 inch mean and the other means were significant (0.05 level, Table 14, Appendix 2). The bulk density mean for each level was used to calculate the specific SMC corresponding to each moisture content percent determination at that level according to the relation:

Specific SMC = (SMC percent) x (bulk density).

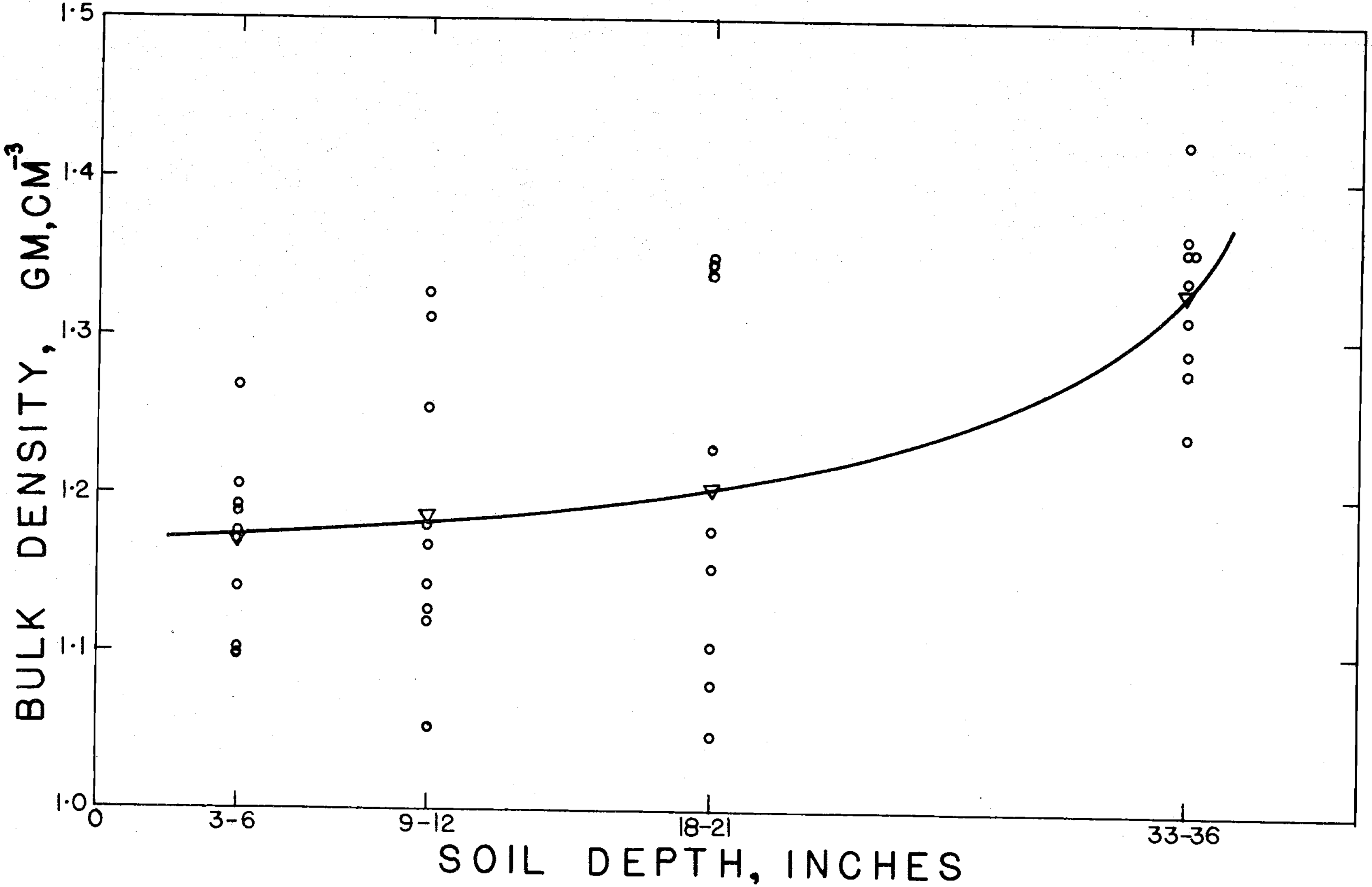

Fig. 11. - Variation of bulk density with soil depth; plotted data, means, and hand-fitted curve.

DATA ANALYSES AND RESULTS

The main objectives of the data analyses were:

(i) the graphical depiction of the soil moisture withdrawal process using the response surface method;

(ii) the development of a mathematical model(s) which would accurately portray response of the system to changes in the independent variables;

(iii) to enable the elucidation of facts and the drawing of inferences concerning system behavior and implications for early plantation management.

General Remarks

The data for the irrigated and nonirrigated plots were dealt with separately. In the case of the nonirrigated plots the data associated with plots 38 and 39 were deleted because they contained a sizeable grapeleaf blackberry (*Rubus vitifolius* C.& S.) component. The presence of the blackberry may have been responsible for some anomalous soil moisture values associated with these plots.

The dependent variables of interest were specific SMC (Y_1) and specific soil moisture used (Y_2). The use of Y_2 (derived from the former according to the relation: $Y_2 = FC - Y_1$) as the dependent random variable had the advantage that noise due to different starting moisture levels (variations in FC) was eliminated while it could still be used to give estimates of Y_1 ($Y_1 = FC - Y_2$). A disadvantage was that the variance of all the Y_2 values, except those corresponding to $X_1 = 0$, was approximately double that of the corresponding Y_1 values.

Response Surface Representation of the Data

Preliminary data analysis involved plotting the replicate means of Y_1 and Y_2 in three dimensions against open-pan evaporation (X_1) and soil depth (X_3) (Figs. 12-15). The replicate means and their standard deviations are tabulated in Tables 9, 10, 16 and 17, Appendix 2.

At a later point in the analysis it was decided to plot specific available SMC, and specific available SMC summed over depth, against X_1 and X_3 for the nonirrigated plots. The latter provided surfaces which described the total amount of soil moisture in the profile in inches above any X_3 for any X_1 and any quadrant type (Figs. 16 and 17). These data are tabulated in Tables 18 and 19, Appendix 2.

Mathematical Modelling Attempts

The primary objectives of modelling this data were threefold:

(i) the determination and description of functional relationships between the response variable (Y_1 or Y_2) and the factors which were assumed *a priori* to control soil moisture depletion in the soil-plant-atmosphere system;

(ii) to enable some determination of the relative importance of these factors with respect to soil moisture depletion;

(iii) to provide models which portray the system behavior with accuracy sufficient to allow interpolation of soil moisture values for use in a subsequent study of the effect of soil moisture levels on tree moisture stress and growth.

It was decided to confine model fitting attempts to the data from the nonirrigated plots first, then apply the same models to the data

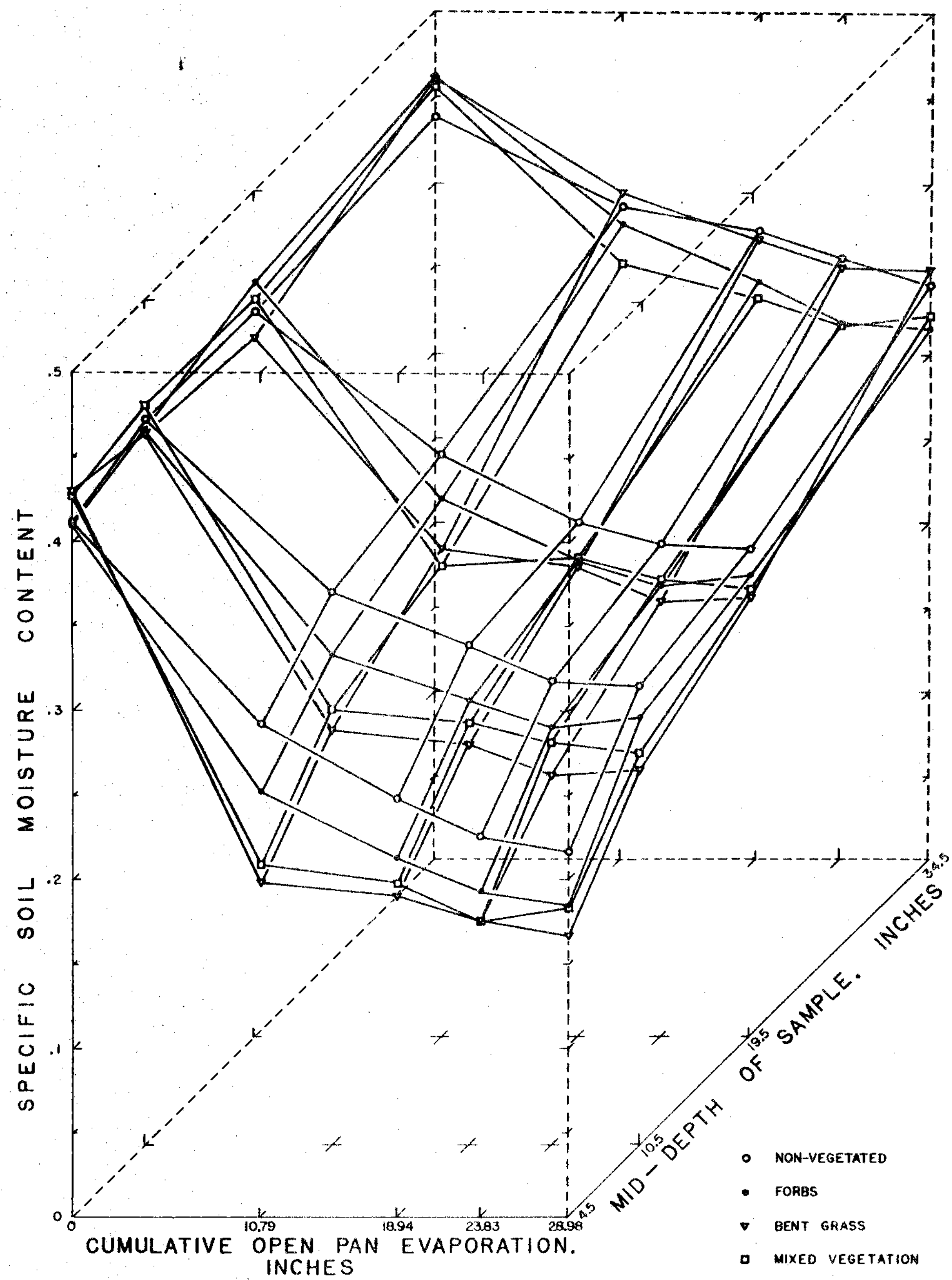

Fig. 12. - Response surface of specific SMC formed by data means (six reps) from nonirrigated plots.

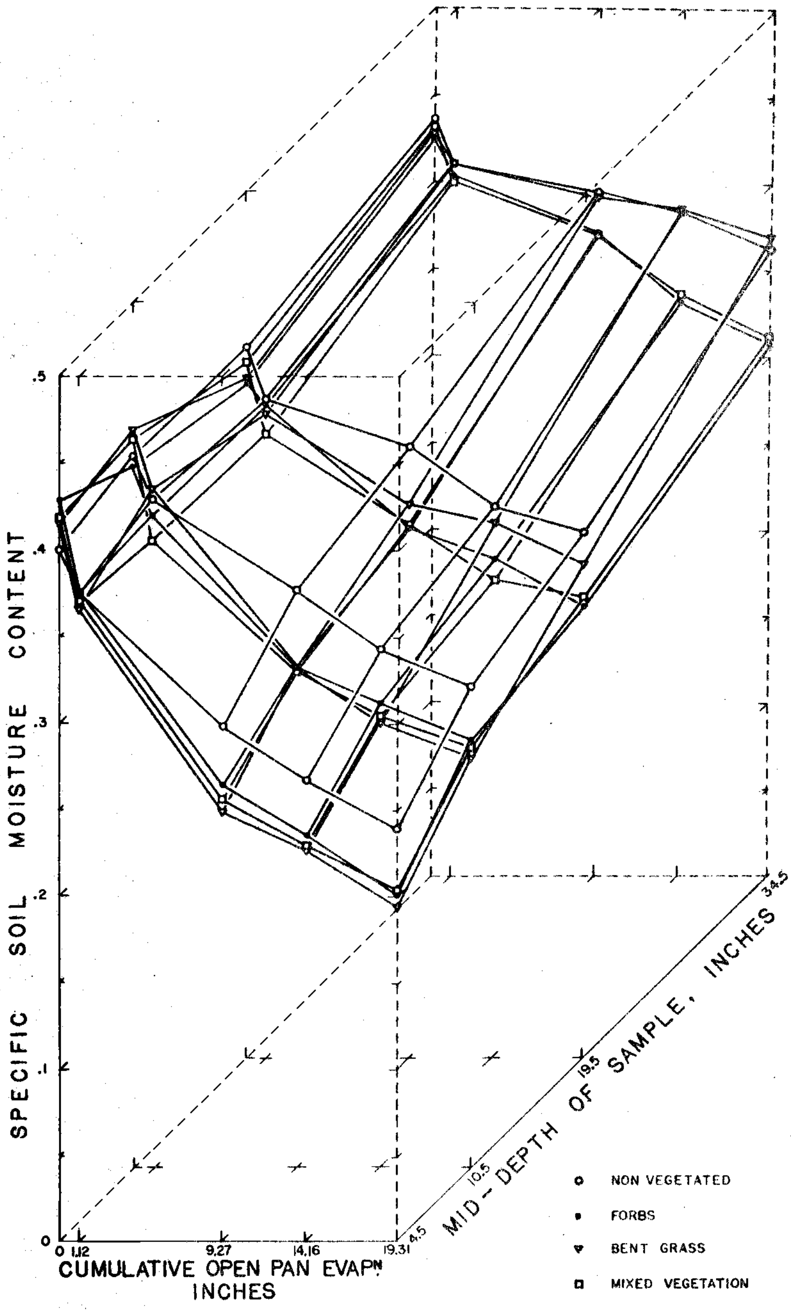

Fig. 13. - Response surface of specific SMC formed by data means (eight reps) from irrigated plots.

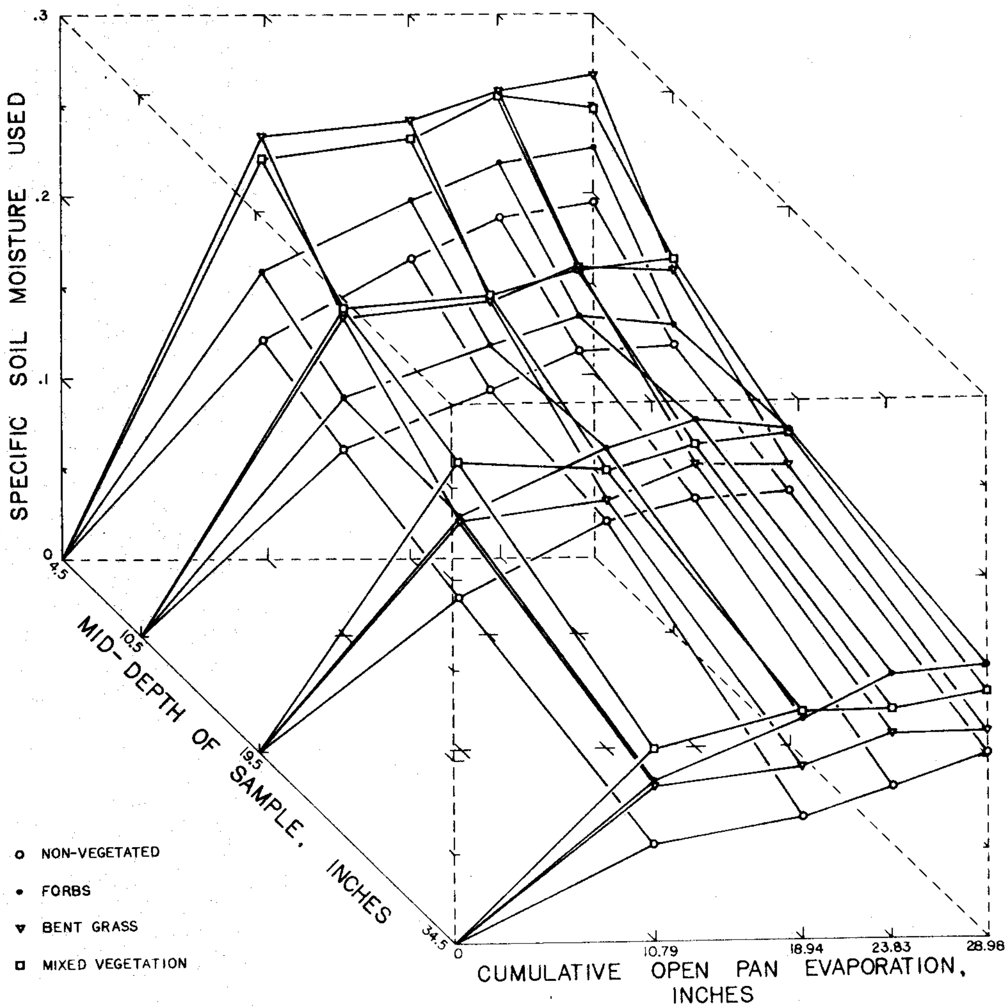

Fig. 14. - Response surface of specific soil moisture used formed by data means (six reps) from nonirrigated plots.

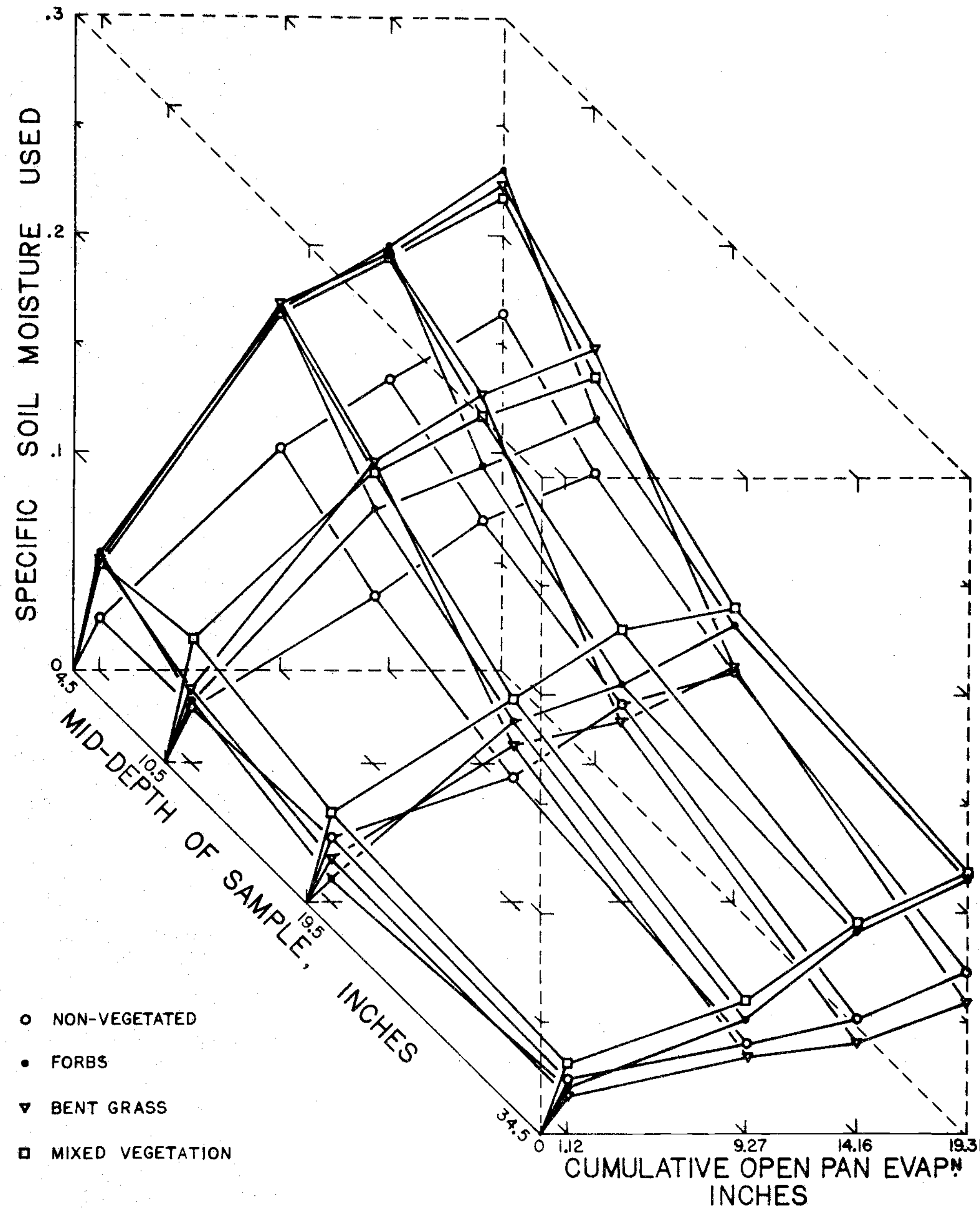

Fig. 15. - Response surface of specific soil moisture used formed by data means (eight reps) from irrigated plots.

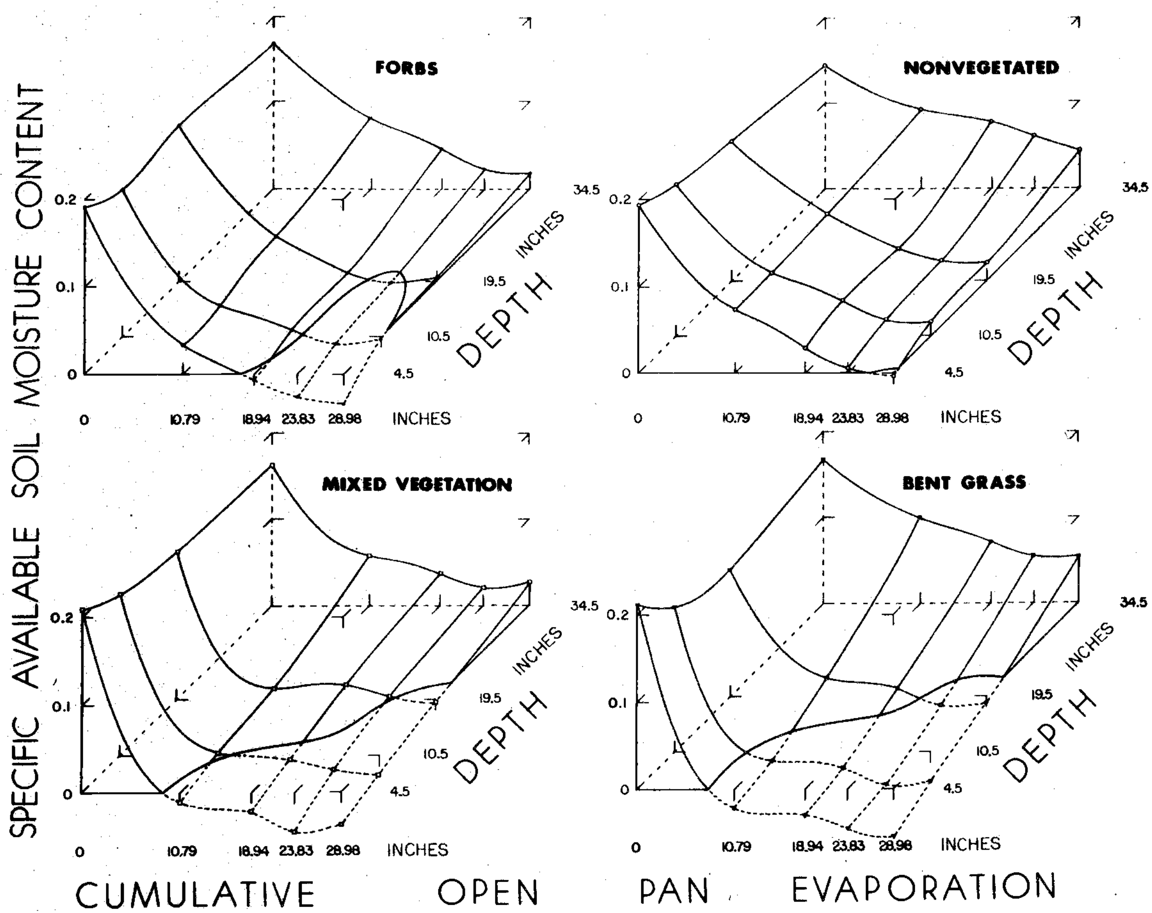

Fig. 16. - Response surfaces of specific available SMC formed by data means (six reps) for the nonirrigated plots. The heavier curved lines in the horizontal planes represent the change from supra- to sub-wilting point conditions, and portray the descent of the PWP fronts as the summer progressed. The broken curved lines indicated negative soil moisture availability.

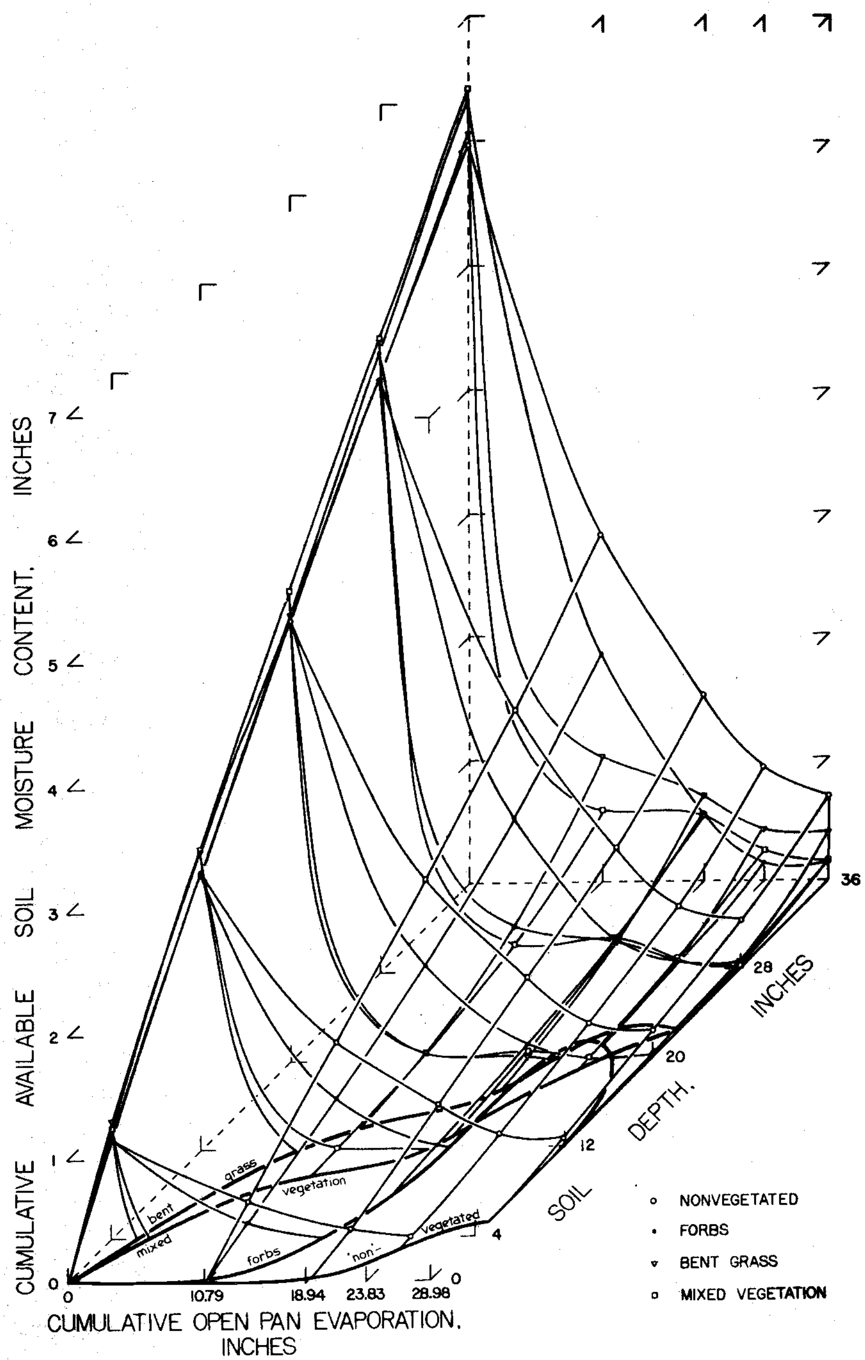

Fig. 17. - Response surfaces showing total available soil moisture in the profile above any depth for any cumulative open-pan evaporation. Heavy curved lines in the horizontal plane portray descent of PWP front for each vegetation type.

from the irrigated plots, and, finally, by comparing corresponding coefficients try to gain some insight into the causal relationships involved in the soil moisture depletion process.

Initially it was assumed that the evaporation and transpiration components of the rate of soil moisture depletion were related to cumulative evaporation, soil depth, standing biomass (X_4) and fresh weight of trees (X_6) by simple exponential functions of the form

$Y' = \beta_1 e^{-\beta_2 X}$ the exponential decay curve

$Y' = \beta_3(1.0-e^{-\beta_4 X})$ the monomolecular growth curve;

and also linearly related to the rate of evaporation (X_2)

$Y' = \beta_5 + \beta_6 X_2$

where Y' in each case is the rate component of soil moisture depletion due to evaporation or transpiration relative to change in the appropriate independent X variable.

These were regarded as simple first order, linear, differential equations, which, when solved and added, yielded a moisture depletion function that included various exponential, linear and quadratic terms. It was hoped to use the CURVFIT non-linear least squares curve fitting program to fit this model, or one similar to it incorporating certain interaction terms as well; but this had to be abandoned because of the difficulty of determining satisfactory starting values for the parameters. Instead, multiple linear regression was used with various transformed variables, including square-, cube- and fourth-root terms to approximate the exponentials, and also interaction terms involving cumulative evaporation and vegetation, cumulative evaporation and depth, and root distribution and depth. Dummy variables, X_7, X_8, X_9, were included to allow for the expression of vegetation type or quadrant effects and (quadrant) x (vegetation) interactions. The simple correlation coefficients of each of these with the dependent variable and among themselves, were obtained and used to make an initial selection of variables to go into the various models subsequently investigated. The correlation coefficients of the variables investigated are shown in Table 20, Appendix 2.

An early attempt was made to isolate the effects of physical and biological (vegetation) factors by fitting a 'physical effects' model whose terms consisted of various functions of cumulative evaporation, the rate of cumulative evaporation and depth, to the data for the nonirrigated NE quadrants. This was done on the assumption that the small vegetation component on most of these quadrants would play a relatively minor role in moisture removal and that the great bulk of the moisture loss would be attributable to the physical factors alone. The regression of the 'physical effects' model using the nonirrigated plot data had an $R^2 = 0.71$. On the further assumption that the 'physical effects' model would be valid under the other vegetation conditions it was then used to determine the residuals of specific SMC used on the NW, SE and SW quadrants after removal of variation due to the physical factors. A 'biological effects' model was then used in an attempt to explain the residual variation in terms of vegetation and (vegetation) x (physical factors) interactions. The results were disappointing. Only ten percent of the residual (or about three percent of the original) variation could be explained by the 'biological effects' model. This may have been due to a combination of factors, including: underestimating the effect of the small amount of vegetation on the NE quadrants; the fact that cumulative evaporation and standing biomass, and depth and root distribution are highly correlated; failure of the 'physical effects' model to apply to heavily vegetated plots; and finally, excessive noise in the residuals.

This attempt to fit separate 'physical' and 'biological effects' models was subsequently abandoned in favor of an 'overall' model approach in which physical and biological variables and their interactions were included in the same model.

Commencing with the basic model

$$Y_2 = \beta_{1.0} + \beta_{1.1}X_1 + \beta_{1.2}X_2 + \beta_{1.3}X_3^{-1} + \beta_{1.4}X_4 + \beta_{1.5}\ln X_5 + \beta_{1.6}X_6 + \beta_{1.7}X_7 + \beta_{1.8}X_8 + \beta_{1.9}X_9 + \beta_{1.10}X_1X_4 + \beta_{1.11}X_1X_6 + \beta_{1.12}X_4X_7 + \beta_{1.13}X_4X_8 + \beta_{1.14}X_4X_9 + \varepsilon \qquad \text{Model 1}$$

the regress mode of SIPS (Statistics Instruction Programming System) was used to explore the possibility of improving the fit by introducing various of the transformed variables already described. This led eventually to the formulation of two further models:

$$Y_2 = \beta_{2.0} + \beta_{2.1}X_1^{\frac{1}{2}} + \beta_{2.2}X_2 + \beta_{2.3}X_3 + \beta_{2.4}(X_1/X_3)^{\frac{1}{2}} + \beta_{2.5}X_4^{\frac{1}{2}} + \beta_{2.6}\ln X_5 + \beta_{2.7}X_6 + \beta_{2.8}X_7 + \beta_{2.9}X_8 + \beta_{2.10}X_9 + \beta_{2.11}X_1X_4 + \beta_{2.12}X_1X_6 + \beta_{2.13}X_4X_7 + \beta_{2.14}X_4X_8 + \beta_{2.15}X_4X_9 + \varepsilon \qquad \text{Model 2}$$

and

$$Y_2 = \beta_{3.0} + \beta_{3.1}X_1 + \beta_{3.2}X_1^{\frac{1}{2}} + \beta_{3.3}X_2 + \beta_{3.4}X_3 + \beta_{3.5}(X_3-10)^{\frac{1}{3}} + \beta_{3.6}X_4 + \beta_{3.7}X_4^{\frac{1}{2}} + \beta_{3.8}\ln X_5 + \beta_{3.9}X_6 + \beta_{3.10}X_7 + \beta_{3.11}X_8 + \beta_{3.12}X_9 + \beta_{3.13}X_1X_4 + \beta_{3.14}X_1X_6 + \beta_{3.15}X_4X_7 + \beta_{3.16}X_4X_8 + \beta_{3.17}X_4X_9 + \varepsilon \qquad \text{Model 3}$$

The estimated values of the coefficients, their standard errors and Students t-statistics, and the R^2 statistic for these three models are shown in Tables 21 and 22, Appendix 2. Figs. 18 and 19 show the response surfaces predicted from Model 3. The combined correlation matrix for the irrigated and nonirriaged plots for the variables in Model 3 is shown in Table 23, Appendix 2.

Although Model 3 has somewhat lower R^2 values than Model 2, it displays the dynamic characteristics of the two systems better. Also, Model 3 is preferable in that terms involving depth (X_3) are relegated to a low level of significance in favor of the more 'causally' explicable terms involving cumulative evaporation (X_1), standing biomass (X_4), and root distribution (X_5).

The normal statistical lack of fit test could not appropriately be applied to these models for two reasons:

(i) the X_4 and X_6 variables were not fixed for all replicates in each replicate set;

(ii) there were marked differences in the variances of the replicate sets. In particular, the method of deriving Y_2 resulted in all sets corresponding to $X_1 = 0$ having zero variance.

DISCUSSION OF RESULTS

The use of multiple linear regression described in the previous section has clearly exemplified some of the problems inherent in such an approach. In particular, the presence of such highly correlated variables as cumulative evaporation and standing biomass, standing biomass and quadrant, and soil depth, root distribution and quadrant in

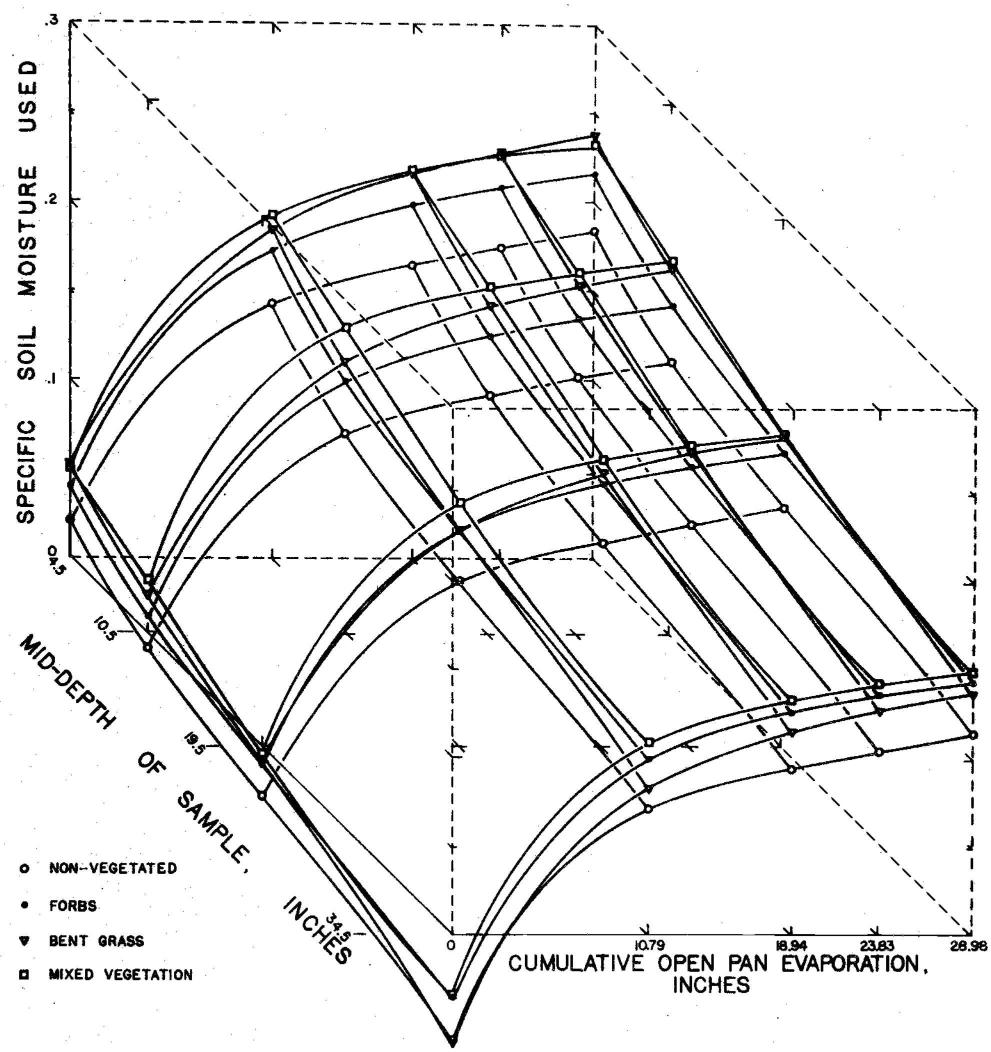

Fig. 18. - Response surface of specific soil moisture used formed by means (six reps) of predicted values using model 3 for the nonirrigated plots.

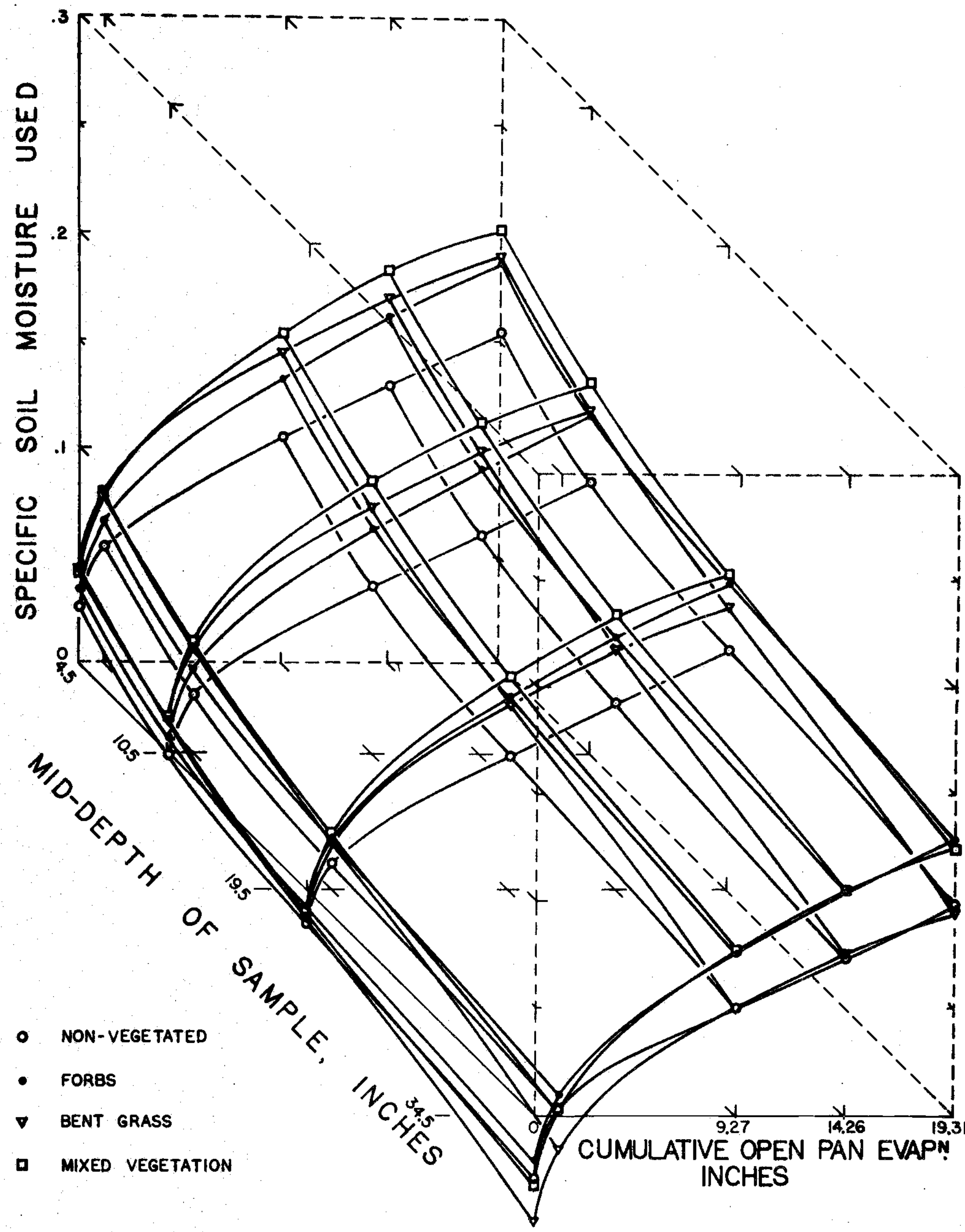

Fig. 19. - Response surface of specific soil moisture used formed by means (eight reps) of predicted values using model 3 for the irrigated plots.

the same regression made it almost impossible to separate out the effect of these components individually. It is apparent that the amount of variation attributed by the regression to any of these depends upon the form in which they occur in the regression equation, and the presence or absence, and form, of the correlated variable(s).

Despite the relatively high R^2 values obtained, superimposition of Fig. 18 on Fig. 14 and Fig. 19 on Fig. 15 reveal some serious discrepencies in fit in certain regions, so that these models must be regarded as inadequate. It may, however, be observed that the characteristics of the response surfaces described by the data have, in a general way, been preserved in those described by Model 3. It is probable that by forcing through the origin and some refinement of this model further improvement in both accuracy and behavior could be attained, but this could not be pursued at this juncture.

In view of these deficiencies in the models it would seem safer at this point to use the plots of the data means, etc., directly (Figs. 14, 15, 16 and 17) as the primary source of information about system behavior.

Firstly, it is apparent that there are significant vegetation type (quadrant) effects experienced at all depths and persistent in time (cumulative evaporation is also a measure of time). Furthermore, the data for both irrigated and nonirrigated plots give clear indications that the moisture withdrawal patterns of the three vegetation types are distinctly different. Whereas bent grass (SE quadrant) rapidly depletes available soil moisture from the top 12 inches or so of soil, its demands on soil moisture relative to that of the pure forb and mixed forb-grass vegetation progressively decline with depth thereafter. Interestingly, the total amount of available soil moisture remaining in the pure forb and mixed vegetation soil profiles at the end of the season was identical (Fig. 17). On the irrigated plots moisture used by the bent grass at the lower levels actually falls below that of the 'nonvegetated' quadrants (Fig. 15). This is almost certainly due to the fact that recharging the profile caused a greater response in growth of transpirational surface on the 'nonvegetated' quadrants than on the already fully occupied bent grass quadrants where, additionally, transpiration was probably declining following post-flowering aestivation.

Moisture use by the mixed vegetation appears almost identical to that of the bent grass down to about 12 inches but remains characteristically high at the lower levels also. Similarly the pure forbs, although exhibiting a somewhat lower moisture demand at the upper levels earlier in the season (presumably attributable to the absence of a shallow-rooting grass component), come on strongly at greater depths and later in the season to the point where water use is comparable with (Fig. 15) or even exceeds (Fig. 14) that of the mixed vegetation. The slightly reduced rate of later season moisture use by the mixed vegetation may be attributable in part to some protection afforded the persistent forbs by the aestivated, shallow-rooted grass component.

The reason for the characteristic mid-season 'trough' in the rate of soil moisture use by the mixed vegetation, and to a lesser extent the bent grass, on the nonirrigated quadrants is less explicable. The fact that there is no hint of it in the pure forb plots suggests that it is probably associated with some phenological characteristic of the grass component.

It is unfortunate that lack of soil moisture data for the earlier part of the season prevents more accurate definition of this region of the response surface for the nonirrigated plots. It is apparent that the dynamics of soil moisture withdrawal on the irrigated plots are significantly different from those on the nonirrigated plots so that data from the former cannot be used to supplement the latter. The rate of moisture use during the first ten inches of open-pan evaporation is obviously less on the irrigated than on the nonirrigated plots, suggesting that later season withdrawal is not determined simply by soil moisture availability and standing biomass but is also conditional on the state of the vegetation. Thus, given a well established plant cover, weather conditions corresponding to near maximum rates of open-pan evaporation and a newly-charged soil profile, one would expect a rate of moisture withdrawal in excess of that experienced during a comparable period earlier in the season. That this did not occur implies a lowering of the transpirational efficiency of the biomass which is consistent with the observed aestivation of the grass and partial aestivation of the forbs. This may be linked with the mid-season 'trough' noted earlier for the SE and SW quadrants of the nonirrigated plots.

The substantial moisture losses evident in the non- or lightly vegetated NE quadrants require some explanation. Several possibilities exist. Compensatory surface evaporation plus transpiration by the small amount of weed and tree vegetation present are undoubtedly reflected here. The work of Hewlett and Hibbert (1963) suggests that losses due to continuing unsaturated flow may be significant. Finally, the smallness of the quadrants (8 ft x 13.6 ft) may have resulted in significant lateral movement in response to horizontal moisture gradients induced by high rates of moisture withdrawal in neighboring, more heavily vegetated areas. The importance of the last possibility is questionable. Firstly, restriction of sampling to the central two foot strip left a three foot buffer zone on all sides. Secondly, a consideration of the flow equation (Slatyer, 1967):

$$\frac{dV}{dt} = k.A.(\psi_1 - \psi_2)$$

where $\frac{dV}{dt}$ is the volume of water per unit time passing through an area A perpendicular to the direction of flow under a water potential difference $\psi_1 - \psi_2$ in a soil with conductivity k; and also the probable relative values of ψ_1 and ψ_2 for horizontal and vertical transport, indicated that horizontal transport is likely to be small compared with vertical transport as long as flow is in the liquid phase only. Once capillary conductivity with the soil surface is lost the situation becomes less clear, and may well be reversed. In any case, any lateral flows would act to minimize differences between vegetation types, so that more effective isolation would serve only to increase the significance of the observed differences. It would seem reasonable to interpret the major part of the nontranspired moisture loss from the NE quadrants in terms of surface evaporation and unsaturated flow drainage, especially the latter.

Regarding the smallness of the apparent net saving in soil moisture towards the end of the season as a consequence of weed control, it would appear that these results tend to support the conclusions of Lambert et al. (1971). They found that although weed control in a young pine plantation resulted in a large decrease in evapotranspirational losses (about 44%) this was mostly compensated for by a 61% increase in drainage, so that the increase available to the trees was quite small. It would seem important to recognize, however, that weed control results in much more favorable soil moisture conditions early in the season when young trees are most vulnerable and are making maximum growth, and that although towards the end of the season the overall effect of weed control may be the conservation of only a minor component of the soil moisture which would have been transpired by the weeds, it is precisely this component which represents the difference between only light or moderate, temporary, diurnal tree moisture stress, and the severe, unrelieved moisture stress which results in lowered photosynthetic efficiency or death through dehydration.

The lines of intersection of the specific available SMC surfaces (Fig. 16) and the cumulative available SMC surfaces (Fig. 17) with the horizontal plane representing PWP, appear to have important implications for tree survival and growth. These lines portray the descent of the PWP front in response to vegetation type and cumulative open-pan evaporation. In particular they indicate the rate of vertical root extension necessary for trees to have continual access to available soil moisture. If it is assumed that the average maximum depth of effective roots at the commencement of the summer drought is six inches, it appears that under heavy bent grass and mixed forb-grass communities rates of downward root extension of approximately 0.67 and 0.56 inches per inch of open-pan evaporation respectively, would be required. These correspond to 0.17 and 0.14 inches per day. Under optimum conditions Douglas-fir roots growing in loose perlite appear to be capable of a maximum growth rate of about 0.15 inches per day (Lavender, 1972). Under field conditions soil resistance and the effects of recurrent severe plant moisture stress could be expected to reduce this by at least 50% which is well below that required.

With pure forbs the early-season soil moisture situation is somewhat better (Fig. 16). Nevertheless, towards the end of the summer the PWP front descends very rapidly to approximately the same level as that under the bent grass and forb-grass communities (Fig. 17) so that a similar overall rate of root extension would be necessary. The trees are less likely to be subject to excessive moisture stress early in the season and consequently higher rates of root growth can be expected at this time; but under field conditions this is still likely to be inadequate. The rise in the PWP front which occurs at the end of the season under the pure forbs (Figs. 16 and 17) is difficult to interpret but may be related to reduced transpirational efficiency of the forbs plus a slow upward migration of soil moisture from greater depths.

Under nonvegetated or sparsely vegetated conditions the PWP front descends only about five inches by the end of the summer. This is a level to which the roots of even the weakest seedlings, given an adequate prior moisture supply, should reach.

It is acknowledged that the standard 15 bar estimate of PWP probably does not in fact represent the limit of soil moisture availability for Douglas-fir. Nevertheless, the amount of additional soil moisture represented by the range 15-24 bars, for instance, is very small at these moisture tensions (especially in sandy soils), so that the above conclusions would seem still to be valid. It is therefore apparent that all three of the vegetation types considered represent very hostile environments into which to attempt to seed or transplant Douglas-fir.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Failure to come up with satisfactory mathematical models of sufficient predictive accuracy has unfortunately precluded a proper investigation of the functional relationships among the dependent and independent variables, or a quantitative assessment of the relative importance of the various independent variables in the moisture withdrawal process. Nonetheless, certain conclusions may be drawn directly from the data regarding the impact of vegetation manipulation on soil moisture.

It is evident that not only the quantity but also the type of herbaceous weed vegetation present on the site has a profound effect on the amount and source of transpired soil moisture, and hence on the amount and source of soil moisture available to young trees.

It appears that the vertical profiles at any given time are influenced by quite minor differences in root distribution and to prior sequential changes in the patterns of root absorptive activity. On the other hand, the temporal profiles at any given depth are no doubt responsive to the phenological characteristics of the vegetation type.

This study shows that in areas characterized by summer drought, vegetative covers of dense pure forbs, bent grass, or a mixture of forbs and annual grasses all make heavy demands on the moisture resources of the upper soil profile. They consequently represent hostile ecosystems for young trees whose vertical root growth cannot keep up with the descent of the PWP front while severe moisture stress conditions exist. Furthermore, the persistent, deep-rooted forbs also make heavy moisture demands on, and raise the moisture tension levels in, the lower soil profile as well. This is likely to be reflected in elevated moisture stresses and reduced growth even in well-established, deeper-rooted trees. (Data relative to this last point are to be presented in a subsequent dissertation.) There is some evidence that, on this site at least, bent grass makes relatively low moisture demands on the lower soil profile and may consequently represent a less unfavorable ecosystem than heavy forb cover for well-established, deep-rooted trees.

The study suggests that it may be advantageous, in terms of moisture availability, to aim for almost complete vegetation control during the first several years of Douglas-fir establishment in an 'old field' situation. The necessity for good first year weed control under similar conditions has been well demonstrated locally by Newton (1964) and is widely accepted. But current chemical weed control practices involving a single application of atrazine alone, or (to a lesser extent) a mixture of atrazine and 2,4-D, applied soon after planting, while usually achieving good first year weed control, actually tend to create a situation favoring heavy infestations of forbs in the second or third year thus perpetuating high summer moisture stress conditions. Heavy forb infestations can bring in their train additional problems associated with an improved habitat for deer and small burrowing mammals. The below- and above-ground implications of all this in terms of moisture availability, tree survival and growth, and stand uniformity may be of substantial importance to foresters and Christmas tree growers working with droughty sites.

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APPENDIX I

Description of Some Terms Used

Bulk density (BD): Weight of oven dry soil per unit volume of undisturbed moist soil. Usually expressed as gm cm^{-3}.

Soil moisture content (SMC): The total weight of water (not including chemically bound water) in a soil expressed as a percent of the oven dry weight of the soil.

Specific SMC: The volume of water per unit volume of undisturbed soil = (SMC%/100)(BD).

Specific available SMC: The volume of available soil water (i.e. that held above PWP) per unit volume of soil = [(SMC% - PWP%)/100](BD).

Saturation point (SP): A normally temporary condition following prolonged heavy rain, irrigation or flooding when all the pore space within the profile is occupied by water.

Field capacity (FC): Gravitational drainage is responsible for emptying the larger soil pores. When this has occurred, but no additional moisture loss has occurred through evaporation or transpiration, the soil is said to be at field capacity. An arbitrary standard water potential which approximates this has been set at 1/3 bars. It is generally considered that most soils attain FC several days after gravitational drainage commences, though there is evidence that slow gravitational drainage may proceed for much longer than this.

Permanent wilting point (PWP): Below FC moisture depletion occurs through evaporation from the soil directly and indirectly through transpiration by plants. As this proceeds, the water menisci retreat into the smaller and smaller pores of the soil. This continues to the point where the water pressure deficits developed at the water absorbing surfaces of the roots are permanently exceeded by the increasing forces of retention developed in the soil water. This is called the permanent wilting point and is indicated by the failure of the vegetation to regain turgor following normal diurnal wilting. At this point the residual soil water is considered to be present as a thin film around the soil particles and any water wedges at the points of contact of the soil particles are very small. The PWP has been arbitrarily standardized at 15 bars.

Hygroscopic coefficient (HC): Below PWP capillary conductivity is virtually zero, moisture movement is in the vapor phase only and water loss is very slow. At equilibrium in a saturated atmosphere when the surface films have evaporated, and the only remaining soil moisture is that adsorbed to the soil particles, and chemically bound water, the SMC is said to be described by the hygroscopic coefficient. At this stage the water potential is about 31 bars.

Chemically bound water: At, and near, the soil surface, the atmospheric moisture content will often drop well below saturation so that even some hygroscopic water will be lost. When all the hygroscopic water has been lost (as when a soil is oven dried at 105°C), only chemically bound water is considered to remain.

APPENDIX 2

<u>Note</u>: Standard errors of means in Appendix 2 are calculated according to the formula:

$$s_{\bar{x}} = \frac{1}{\sqrt{n}} \cdot \sqrt{\sum_{i=1}^{n} \frac{(x_i - \bar{x})^2}{n-1}}$$

where n is the number of observations, x_i is the i-th observation, and $\bar{x}$ is the mean of the n observed values.

TABLE 1. ESTIMATED PERCENT FORB COVER ON NE AND NW QUADRANTS AS AT AUGUST 30, 1970. ESTIMATES BASED ON POOLED RESULTS FROM TWO ONE-YARD-SQUARE, 49-POINT DOT GRID QUADRATS PER QUADRANT.

	Nonirrigated			Irrigated		
Quad-rant	Plot no.	% cover	Equivalent standing biomass lb/ac	Plot no.	% cover	Equivalent standing biomass lb/ac
NE	6	7.1		2	20.4	
	30	7.1		3	15.3	
	31	4.1		17	7.1	
	32	9.2		19	16.3	
	36	9.2		33	14.3	
	63	0		34	2.0	
	--	--		65	3.1	
	--	--		66	7.1	
	Mean	6.11	31.1	Mean	10.70	92.2
	Std. error	1.44		Std. error	2.39	
NW	6	15.3		2	23.5	
	30	13.3		3	17.4	
	31	7.1		17	18.4	
	32	14.3		19	37.8	
	36	5.1		33	25.5	
	63	5.1		34	15.3	
	--	--		65	17.4	
	--	--		66	25.5	
	Mean	10.03	81.4	Mean	22.60	373.2
	Std. error	1.95		Std. error	2.58	

TABLE 2. DATA FOR PERCENT COVER/STANDING BIOMASS RELATIONSHIP FOR NE AND NW QUADRANTS AS AT AUGUST 30, 1970. PLOTTED ON FIGURE 3.

No. dot grid hits out of 49	Equivalent %	Standing biomass (ODW) gm/sq yd.	lb/ac.
1	2.04	11.3	120.57
4	8.16	5.8	61.89
12	24.48	41.2	439.61
13	26.53	36.5	389.46
14	28.57	54.9	585.79
16	32.65	96.0	1024.34
16	32.65	88.4	943.25
18	36.73	71.5	762.92
22	44.89	153.4	1636.81
23	46.93	137.2	1463.95
13*	52.00	159.2	1698.70
15*	60.00	144.6	1542.91
35	72.41	182.1	1943.04
36	73.46	219.0	2336.77
42	85.71	166.4	1775.52
48	97.95	279.3	2980.19

*Number of hits out of 25.

TABLE 3. DATA FOR ESTIMATING STANDING BIOMASS ON NONIRRIGATED SE AND SW QUADRANTS AS AT AUGUST 30, 1970.

Quadrant (Veg. type)	Sample number	Standing biomass (ODW) gm/sq yd.	lb/ac.
SE	1	236.7	
(Bent grass)	2	341.4	
	3	240.2	
	4	296.2	
	5	280.4	
	Mean	278.99	2977.0
	Std. error	19.34	206.4
SW	1	380.7	
(Forb/grass)	2	397.4	
	3	280.2	
	4	379.0	
	5	352.7	
	Mean	358.00	3819.9
	Std. error	20.72	221.1

TABLE 4. BIOMASS ASSESSMENT RESULTS, PARAMETER VALUES AND FUNCTION ESTIMATES OF STANDING BIOMASS AS AT TIMES OF SMC ASSESSMENT. FIGURES IN PARENTHESES ARE NUMBERS OF DAYS (T) SINCE GROWTH ASSUMED TO COMMENCE.

Quadrant	Mean cover Aug. 30	Equivalent standing biomass (lb dry matter/ac)	Coefficients			Function estimates of standing biomass (lb dry matter/ac)			
			B_1	B_2	B_3	June 30	July 25	Aug. 13	Sep. 9
Nonirrigated									
NE	6.11	31.1	200	-5.29832	-.006622	12.3 (97)	18.8 (122)	24.9 (141)	33.4 (164)
NW	10.03	81.4	200	-5.29832	-.011227	33.6 (97)	52.0 (122)	67.4 (141)	86.3 (164)
SE	---	2977.0	4000	-8.29405	-.018224	1629.9 (122)	2263.8 (147)	2674.2 (166)	3069.5 (189)
SW	---	3819.9	4660	-8.44677	-.020488	2328.8 (122)	3075.2 (147)	3516.3 (166)	3908.8 (189)
Irrigated									
NE	10.70	92.2	500	-3.79869	-.012266	14.0 (97)	36.1 (122)	62.3 (141)	104.0 (164)
NW	22.60	373.2	500	-2.80346	-.034245	47.1 (97)	183.3 (122)	296.2 (141)	394.0 (164)
SE	---	3360.0	5031	-8.52337	-.016667	1648.4 (122)	2410.9 (147)	2943.7 (166)	3491.4 (189)
SW	---	4970.0	7472	-8.91892	-.016860	2389.1 (122)	3536.3 (147)	4341.1 (166)	5169.0 (189)

TABLE 5. DATA USED TO ESTABLISH TREE HEIGHT/FRESH WEIGHT RELATIONSHIPS FOR EACH QUADRANT TYPE.

NE		NW		SE		SW	
Height (in)	Fresh weight (gm)	Height (in)	Fresh weight (gm)	Height (in)	Fresh weight (gm)	Height (in)	Fresh weight (gm)
18.8	47.5	27.5	168.5	27.0	121.3	33.5	582.0
32.5	168.0	32.3	336.4	22.0	54.7	29.9	236.2
32.0	335.9	16.1	40.3	28.9	103.6	35.3	344.0
35.8	358.6	44.0	638.0	24.7	78.1	37.7	289.6
23.9	94.7	20.2	93.5	20.6	47.6	18.6	80.0
17.0	52.7	17.3	47.0	13.8	13.1	25.7	128.0
19.5	47.3	34.5	254.0	7.8	15.6	39.7	438.0
28.5	204.7	31.2	280.8	30.4	118.5	44.2	904.5
37.0	131.6	42.3	505.4	26.6	143.8	35.7	628.5
32.3	292.3	39.4	451.7	27.5	206.6	30.7	223.1
21.5	173.3	30.1	204.3	29.5	168.5	38.7	437.7
18.8	83.0	26.5	190.3	28.2	183.6	38.7	399.2
24.8	194.3	26.0	251.1	34.5	303.1	28.4	187.0
26.5	195.5	23.2	182.3	17.4	48.9	38.5	721.6
29.9	258.3	34.9	286.5	22.6	76.3	47.5	794.8
36.6	241.6	30.5	201.4	32.0	178.3	29.7	212.0
31.3	134.9	38.5	233.0	21.0	53.6	33.7	341.6
23.9	132.0	37.6	607.6	36.8	383.0	37.9	416.3
20.8	90.1	32.3	264.9	27.9	134.3	32.0	191.7
				16.5	40.7	49.9	1409.0
				19.2	59.3	40.1	558.7
				41.5	513.0	36.0	293.9
				33.7	208.8	36.5	814.5
				26.1	177.6	36.5	522.4
				22.6	63.8	21.1	91.2
				28.0	127.6		
				18.8	32.6		
				24.8	117.3		
				20.7	111.7		

TABLE 6. FUNCTION ESTIMATES OF TREE FRESH WEIGHT PER ACRE FOR EACH OF THE QUADRANTS.

Plot no.	Quad-rant	Trees /ac.	Fresh weight lb/ac.	Plot no.	Quad-rant	Trees /ac.	Fresh weight lb/ac.
2	NE	544	1319	6	NE	326	526
	NW	544	2002		NW	435	830
	SE	762	1244		SE	870	1575
	SW	870	4502		SW	653	1681
34	NE	544	747	30	NE	544	652
	NW	435	764		NW	762	1757
	SE	326	428		SE	762	742
	SW	653	2061		SW	870	2701
3	NE	544	1309	31	NE	544	785
	NW	544	1366		NW	653	2651
	SE	653	3494		SE	653	1180
	SW	653	1903		SW	870	2627
33	NE	218	434	32	NE	544	758
	NW	109	233		NW	435	1689
	SE	870	1121		SE	762	1564
	SW	653	1365		SW	544	2320
17	NE	762	1595	36	NE	653	1014
	NW	544	2371		NW	653	1768
	SE	653	664		SE	762	1170
	SW	653	1499		SW	762	1969
19	NE	544	769	63	NE	435	710
	NW	762	1769		NW	435	1003
	SE	762	429		SE	653	323
	SW	762	2710		SW	544	1238
65	NE	544	793	38	NE	653	1048
	NW	653	1360		NW	653	3218
	SE	425	417		SE	870	2482
	SW	870	2061		SW	762	2932
66	NE	326	407	39	NE	435	683
	NW	435	1048		NW	544	1197
	SE	218	113		SE	544	597
	SW	653	1803		SW	870	2476

TABLE 7. REPLICATE MEANS ($\overline{X}_5$) AND THEIR ESTIMATED STANDARD ERRORS FOR ROOT WEIGHTS AND PERCENT ROOT WEIGHTS (X_5) FOR FIVE VEGETATION TYPES.

Vegetation type	No. reps (n)	Depth (in)	Mean weight roots (gm)	Std. error of mean	Mean percent root weight	Std. error of mean
Forbs	5	0-6	6.746	0.464	73.04	2.72
		6-12	1.213	0.228	12.70	1.61
		12-18	0.626	0.106	6.85	1.15
		18-24	0.358	0.077	3.84	0.75
		24-30	0.162	0.046	1.80	0.54
		30-36	0.170	0.041	1.77	0.32
Bent grass	5	0-6	6.563	0.625	76.72	3.21
		6-12	1.288	0.236	14.26	1.96
		12-18	0.439	0.090	4.76	0.76
		18-24	0.219	0.049	2.37	0.45
		24-30	0.122	0.036	1.37	0.32
		30-36	0.045	0.010	0.52	0.10
Forb/ grass	6	0-6	6.801	0.536	74.58	1.68
		6-12	1.368	0.077	15.41	1.41
		12-18	0.500	0.044	5.54	0.43
		18-24	0.229	0.040	2.46	0.32
		24-30	0.101	0.014	1.10	0.13
		30-36	0.080	0.013	0.91	0.18
Velvet grass	5	0-6	6.487	1.522	66.67	3.50
		6-12	1.783	0.287	19.89	1.49
		12-18	0.654	0.069	7.71	1.07
		18-24	0.257	0.069	2.84	0.46
		24-30	0.124	0.031	1.61	0.54
		30-36	0.091	0.029	1.28	0.62
Alta fescue	5	0-6	8.955	0.271	62.96	3.27
		6-12	2.825	0.415	19.39	2.01
		12-18	1.068	0.195	7.33	1.06
		18-24	0.833	0.071	5.79	0.31
		24-30	0.453	0.062	3.14	0.39
		30-36	0.201	0.032	1.40	0.21

TABLE 8. CUMULATIVE OPEN-PAN EVAPORATION (COPE) DATA DERIVED FROM HYSLOP FARM METEOROLOGICAL RECORDS. DAY NUMBER 1 IS THE FIRST DAY AFTER THE LAST SIGNIFICANT SPRING RAINS.

Day no.	COPE (in)	Day no.	COPE (in)	Day no.	COPE (in)
1	.159	54	12.486	107	27.553
2	.333	55	12.837	108	27.791
3	.565	56	13.192	109	28.134
4	.828	57	13.559	110	28.320
5	1.073	58	13.932	111	28.527
6	1.267	59	14.279	112	28.592
7	1.364	60	14.612	113	28.791
8	1.509	61	14.947	114	28.892
9	1.673	62	15.371	115	28.975
10	1.795	63	15.855	116	29.027
11	2.043	64	16.202	117	29.051
12	2.318	65	16.299	118	29.159
13	2.515	66	16.611	119	29.356
14	2.754	67	16.963	120	29.664
15	2.895	68	17.363	121	29.922
16	3.076	69	17.718	122	30.254
17	3.268	70	18.000	123	30.599
18	3.553	71	18.318	124	30.797
19	3.967	72	18.639	125	30.947
20	4.264	73	18.939	126	31.071
21	4.551	74	19.076	127	31.246
22	4.884	75	19.284	128	31.379
23	5.153	76	19.426	129	31.597
24	5.422	77	19.581	130	31.597
25	5.715	78	19.811	131	31.670
26	5.978	79	20.109	132	31.800
27	6.064	80	20.397	133	31.885
28	6.242	81	20.670	134	32.022
29	6.356	82	20.941	135	32.225
30	6.440	83	21.173	136	32.625
31	6.690	84	21.286	137	32.971
32	6.812	85	21.505	138	33.134
33	6.891	86	21.767	139	33.241
34	7.045	87	22.004	140	33.335
35	7.258	88	22.303	141	33.455
36	7.391	89	22.702	142	33.615
37	7.763	90	23.127	143	33.789
38	8.121	91	23.492	144	33.916
39	8.431	92	23.830	145	33.944
40	8.653	93	24.125	146	34.029
41	8.972	94	24.478	147	34.126
42	9.310	95	24.768	148	34.222
43	9.668	96	25.075	149	34.322
44	10.057	97	25.374	150	34.372
45	10.110	98	25.663	151	34.486
46	10.439	99	25.894	152	34.586
47	10.628	100	26.154	153	34.734
48	10.789	101	26.358	154	34.954
49	10.883	102	26.614	155	35.267
50	11.048	103	26.815	156	35.467
51	11.348	104	26.940	157	35.551
52	11.694	105	27.032		
53	12.062	106	27.380		

TABLE 9. REPLICATE MEANS ($\bar{y}_{1i}$) AND THEIR ESTIMATED STANDARD ERRORS FOR SPECIFIC SMC (Y_1); NONIRRIGATED PLOTS.

Quad-rant	Depth, X_3 (in)	Cumulative open-pan evaporation, X_i, (inches)				
		0	10.79	18.94	23.83	28.98
NE	3-6	.411 (.005)	.292 (.016)	.248 (.021)	.225 (.016)	.216 (.018)
	9-12	.429 (.011)	.327 (.011)	.296 (.012)	.274 (.008)	.271 (.010)
	18-21	.429 (.016)	.345 (.007)	.305 (.009)	.292 (.009)	.289 (.007)
	33-36	.438 (.015)	.386 (.015)	.372 (.013)	.356 (.016)	.339 (.011)
NW	3-6	.409 (.006)	.252 (.006)	.213 (.007)	.193 (.004)	.185 (.006)
	9-12	.422 (.013)	.290 (.008)	.263 (.005)	.247 (.005)	.253 (.005)
	18-21	.446 (.019)	.319 (.011)	.282 (.007)	.267 (.004)	.273 (.007)
	33-36	.462 (.025)	.376 (.018)	.342 (.015)	.318 (.016)	.314 (.012)
SE	3-6	.429 (.010)	.199 (.007)	.190 (.010)	.175 (.008)	.166 (.005)
	9-12	.420 (.016)	.245 (.010)	.237 (.013)	.218 (.009)	.221 (.012)
	18-21	.413 (.009)	.289 (.003)	.278 (.007)	.258 (.002)	.260 (.004)
	33-36	.461 (.019)	.394 (.021)	.366 (.019)	.350 (.019)	.349 (.017)
SW	3-6	.427 (.004)	.209 (.005)	.198 (.003)	.175 (.003)	.183 (.004)
	9-12	.437 (.009)	.257 (.006)	.250 (.010)	.238 (.007)	.232 (.009)
	18-21	.436 (.014)	.279 (.005)	.284 (.009)	.271 (.005)	.265 (.003)
	33-36	.456 (.014)	.352 (.008)	.332 (.012)	.316 (.008)	.322 (.010)

TABLE 10. REPLICATE MEANS ($\overline{y}_{1i}$) AND THEIR ESTIMATED STANDARD ERRORS FOR SPECIFIC SMC (Y_1); IRRIGATED PLOTS.

Quad-rant	Depth, X_3 (in)	Cumulative open-pan evaporation, X_1 (inches) 0	1.12	9.27	14.16	19.31
NE	3-6	.400 (.007)	.376 (.007)	.298 (.010)	.267 (.007)	.238 (.011)
	9-12	.411 (.007)	.386 (.007)	.334 (.012)	.300 (.008)	.278 (.011)
	18-21	.410 (.011)	.380 (.007)	.353 (.010)	.319 (.008)	.304 (.011)
	33-36	.436 (.008)	.410 (.005)	.395 (.012)	.383 (.009)	.361 (.011)
NW	3-6	.429 (.018)	.375 (.007)	.264 (.004)	.235 (.008)	.200 (.005)
	9-12	.405 (.009)	.377 (.008)	.289 (.008)	.269 (.010)	.247 (.008)
	18-21	.389 (.006)	.377 (.004)	.306 (.005)	.288 (.009)	.261 (.006)
	33-36	.424 (.009)	.403 (.007)	.371 (.014)	.331 (.006)	.307 (.005)
SE	3-6	.415 (.010)	.365 (.008)	.248 (.013)	.225 (.013)	.193 (.008)
	9-12	.426 (.016)	.392 (.012)	.288 (.014)	.257 (.011)	.236 (.010)
	18-21	.392 (.011)	.372 (.011)	.320 (.009)	.309 (.008)	.285 (.006)
	33-36	.428 (.009)	.410 (.012)	.391 (.012)	.385 (.011)	.368 (.013)
SW	3-6	.418 (.011)	.370 (.006)	.255 (.008)	.229 (.006)	.202 (.006)
	9-12	.420 (.013)	.362 (.013)	.287 (.011)	.261 (.006)	.243 (.007)
	18-21	.401 (.006)	.360 (.003)	.308 (.009)	.276 (.003)	.267 (.003)
	33-36	.431 (.009)	.399 (.010)	.370 (.011)	.335 (.004)	.311 (.006)

TABLE 11. MEANS AND STANDARD ERRORS OF MEANS OF WILTING POINT (WP) FROM FOUR DETERMINATIONS MADE ON SUB-SAMPLES DRAWN FROM SINGLE COMPOSITE SAMPLES DRAWN FROM EACH PLOT AND SOIL LEVEL.

Plot no.	Depth (in)	Mean WP %	Standard error	Equivalent specific SMC	Standard error
6	3-6	18.09	.26	.212	.003
	9-12	22.83	.29	.271	.003
	18-21	22.67	.47	.272	.006
	33-36	22.22	.29	.295	.004
30	3-6	18.50	.26	.217	.003
	9-12	21.47	.26	.255	.003
	18-21	22.22	.48	.267	.006
	33-36	22.54	.28	.299	.004
31	3-6	18.43	.19	.216	.002
	9-12	20.79	.58	.247	.007
	18-21	22.54	.36	.271	.004
	33-36	21.04	.56	.279	.007
32	3-6	19.42	.54	.227	.006
	9-12	20.98	.45	.249	.005
	18-21	21.54	.50	.259	.006
	33-36	21.37	.92	.284	.012
36	3-6	19.06	.28	.223	.003
	9-12	22.06	.56	.262	.007
	18-21	22.46	.40	.270	.005
	33-36	23.38	.29	.310	.004
63	3-6	18.58	.33	.218	.004
	9-12	20.94	.37	.248	.004
	18-21	22.12	.34	.266	.004
	33-36	22.74	.36	.302	.005
38	3-6	18.80	.33	.220	.004
	9-12	21.53	.36	.255	.004
	18-21	23.12	.43	.278	.005
	33-36	26.28	.45	.349	.006
39	3-6	18.44	.35	.216	.004
	9-12	21.07	.40	.250	.005
	18-21	23.38	.36	.281	.004
	33-36	23.77	.37	.316	.005

(Continued)

TABLE 11. (Continued)

Plot no.	Depth (in)	Mean WP %	Standard error	Equivalent specific SMC	Standard error
2	3-6	18.69	.16	.219	.002
	9-12	21.39	.32	.254	.004
	18-21	21.43	.13	.258	.002
	33-36	21.99	.33	.292	.004
34	3-6	19.74	.32	.231	.004
	9-12	23.85	.32	.283	.004
	18-21	23.24	.50	.279	.006
	33-36	22.54	.21	.299	.003
3	3-6	18.24	.09	.214	.001
	9-12	20.39	.13	.242	.002
	18-21	21.81	.16	.262	.002
	33-36	22.21	.23	.295	.003
33	3-6	19.66	.67	.230	.008
	9-12	23.14	.19	.274	.002
	18-21	21.55	.34	.259	.004
	33-36	21.61	.43	.287	.006
17	3-6	17.98	.14	.211	.002
	9-12	18.98	.13	.225	.002
	18-21	20.95	.12	.252	.001
	33-36	21.15	.11	.281	.001
19	3-6	17.66	.13	.207	.002
	9-12	19.46	.10	.231	.001
	18-21	21.43	.11	.258	.001
	33-36	19.93	.17	.266	.002
65	3-6	18.37	.11	.215	.001
	9-12	21.82	.18	.259	.002
	18-21	22.48	.19	.270	.002
	33-36	23.99	.14	.319	.002
66	3-6	19.71	.24	.231	.003
	9-12	21.23	.21	.252	.002
	18-21	22.11	.16	.266	.002
	33-36	22.65	.27	.301	.004

TABLE 12. ANALYSIS OF VARIANCE FOR WILTING POINT DATA.

Source of variation	Sums of squares	Degrees of freedom	Mean squares	F	F (.01, 3, 60)
Depth	140.876	3	46.96	40.8	4.13
Replication (Replication) x (Depth)	68.968	60	1.150		
Total	209.844	63			

TABLE 13. OVERALL MEANS FOR WILTING POINT FOR EACH DEPTH, AND SIGNIFICANCE TEST FOR DIFFERENCES.

Depth (in)	Overall means	Differences between means	Significance
3-6	18.71		
9-12	21.37	2.66	* *
18-21	22.19	.82	NS
33-36	22.46	.27	NS

$LSD = t_{(\alpha;\ d.f.)} \cdot \sqrt{2(MSE)/n}$

$LSD_{.05} = 2.00\sqrt{2(1.150)/4} = 1.52$

$LSD_{.01} = 2.66\sqrt{2(1.150)/4} = 2.02$

TABLE 14. BULK DENSITY DETERMINATIONS.

Soil depth (in)	Plot no.	Bulk density	Mean	Standard error	Differences between means	Significance
3-6	6	1.099				
	19	1.188				
	30	1.206				
	32	1.192				
	33	1.169				
	34	1.101				
	39	1.140				
	63	1.268				
	65	1.176	1.171	.018		
9-12	6	1.051				
	19	1.311				
	30	1.142				
	32	1.180				
	33	1.167				
	34	1.254				
	39	1.118				
	63	1.126				
	65	1.327	1.186	.031	.015	NS
18-21	6	1.104				
	19	1.348				
	30	1.176				
	32	1.228				
	33	1.153				
	34	1.347				
	39	1.047				
	63	1.080				
	65	1.338	1.202	.040	.016	NS
33-36	6	1.354				
	19	1.422				
	30	1.337				
	32	1.355				
	33	1.238				
	34	1.364				
	39	1.291				
	63	1.313				
	65	1.278	1.328	.018	.126	*

$LSD_{.05} = t_{(.05,\ 32)} \sqrt{2(MSE)/n} = 2.04 \sqrt{2(.007133)/4} = 0.122$

See Table 15 for MSE

TABLE 15. ANALYSIS OF VARIANCE FOR BULK DENSITY DATA.

Source of variation	Sums of squares	Degrees of freedom	Mean squares	F	F (.01, 3, 32)
Depth	.13953	3	.046511	6.521	4.46
Replication (Replication)x (Depth)	.22826	32	.007133		
Total	.36779	35			

TABLE 16. REPLICATE MEANS ($\bar{y}_{2i}$) AND THEIR ESTIMATED STANDARD ERRORS FOR SPECIFIC SMC USED (Y_2); NONIRRIGATED PLOTS.

Quad-rant	Depth, X_3 (in)	Cumulative open-pan evaporation, X_1 (inches)				
		0	10.79	18.94	23.83	28.98
NE	3-6	0 (0)	.119 (.020)	.163 (.025)	.186 (.020)	.194 (.022)
	9-12	0 (0)	.102 (.017)	.134 (.020)	.155 (.016)	.158 (.015)
	18-21	0 (0)	.083 (.014)	.124 (.019)	.136 (.021)	.139 (.021)
	33-36	0 (0)	.052 (.006)	.066 (.009)	.082 (.012)	.100 (.009)
NW	3-6	0 (0)	.157 (.009)	.196 (.010)	.216 (.007)	.224 (.007)
	9-12	0 (0)	.131 (.010)	.159 (.009)	.175 (.010)	.169 (.013)
	18-21	0 (0)	.127 (.014)	.164 (.018)	.179 (.020)	.173 (.019)
	33-36	0 (0)	.087 (.022)	.120 (.023)	.144 (.027)	.148 (.024)
SE	3-6	0 (0)	.231 (.012)	.239 (.016)	.255 (.011)	.263 (.012)
	9-12	0 (0)	.175 (.017)	.183 (.021)	.201 (.019)	.199 (.022)
	18-21	0 (0)	.124 (.011)	.135 (.014)	.155 (.009)	.153 (.012)
	33-36	0 (0)	.084 (.028)	.094 (.025)	.111 (.024)	.112 (.023)
SW	3-6	0 (0)	.218 (.006)	.229 (.005)	.252 (.006)	.245 (.008)
	9-12	0 (0)	.180 (.011)	.187 (.014)	.200 (.012)	.205 (.013)
	18-21	0 (0)	.157 (.013)	.152 (.010)	.165 (.014)	.171 (.013)
	33-36	0 (0)	.104 (.015)	.123 (.016)	.124 (.021)	.134 (.016)

TABLE 17. REPLICATE MEANS ($\bar{y}_{2i}$) AND THEIR ESTIMATED STANDARD ERRORS FOR SPECIFIC SMC USED (Y_2); IRRIGATED PLOTS.

Quad-rant	Depth, X_3 (in)	Cumulative open-pan evaporation, X_1 (inches)				
		0	1.12	9.27	14.16	19.31
NE	3-6	0 (0)	.024 (.005)	.102 (.014)	.133 (.013)	.163 (.017)
	9-12	0 (0)	.025 (.004)	.077 (.014)	.111 (.009)	.133 (.014)
	18-21	0 (0)	.030 (.011)	.057 (.011)	.091 (.010)	.106 (.014)
	33-36	0 (0)	.026 (.005)	.042 (.008)	.053 (.007)	.075 (.009)
NW	3-6	0 (0)	.054 (.012)	.165 (.018)	.194 (.014)	.229 (.015)
	9-12	0 (0)	.028 (.006)	.116 (.010)	.136 (.011)	.158 (.009)
	18-21	0 (0)	.011 (.005)	.083 (.006)	.100 (.006)	.127 (.007)
	33-36	0 (0)	.022 (.008)	.053 (.012)	.093 (.011)	.117 (.008)
SE	3-6	0 (0)	.050 (.008)	.168 (.011)	.190 (.007)	.222 (.006)
	9-12	0 (0)	.034 (.006)	.138 (.007)	.169 (.010)	.190 (.012)
	18-21	0 (0)	.020 (.006)	.072 (.013)	.083 (.007)	.108 (.011)
	33-36	0 (0)	.018 (.005)	.036 (.003)	.042 (.006)	.060 (.006)
SW	3-6	0 (0)	.048 (.006)	.163 (.012)	.189 (.011)	.216 (.014)
	9-12	0 (0)	.058 (.013)	.133 (.012)	.159 (.011)	.177 (.014)
	18-21	0 (0)	.041 (.004)	.093 (.009)	.125 (.005)	.135 (.006)
	33-36	0 (0)	.033 (.006)	.061 (.004)	.097 (.010)	.120 (.010)

TABLE 18. REPLICATE MEANS FOR SPECIFIC AVAILABLE SMC (Y_3); NONIRRIGATED PLOTS.

Quad-rant	Depth, X_3 (in)	Cumulative open-pan evaporation, X_1 (inches)				
		0	10.79	18.94	23.83	28.98
NE	3-6	.192	.073	.029	.006	-.003
	9-12	.174	.072	.041	.019	.016
	18-21	.161	.077	.037	.024	.021
	33-36	.143	.091	.077	.061	.044
NW	3-6	.190	.033	-.006	-.026	-.034
	9-12	.167	.035	.008	-.008	-.002
	18-21	.178	.051	.014	-.001	.005
	33-36	.167	.081	.047	.023	.019
SE	3-6	.210	-.020	-.029	-.044	-.053
	9-12	.165	-.010	-.018	-.037	-.034
	18-21	.145	.021	.010	-.010	-.008
	33-36	.166	.099	.071	.055	.054
SW	3-6	.208	-.010	-.021	-.044	-.036
	9-12	.182	.002	-.005	-.017	-.023
	18-21	.168	.011	.016	.003	-.003
	33-36	.161	.057	.037	.021	.027

TABLE 19. SPECIFIC AVAILABLE SMC (a) AND CUMULATIVE AVAILABLE SMC (b) DERIVED FROM SMOOTHED CURVES OF SPECIFIC AVAILABLE SMC EVALUATED AT FOUR INCH INTERVALS OF SOIL DEPTH. CUMULATIVE AVAILABLE SMC WAS APPROXIMATED BY SUMMING THE AREAS OF TRAPEZOIDS AND TRIANGLES.

		Cumulative open-pan evaporation (inches)									
Quad-	Depth	0		10.79		18.94		23.83		28.98	
rant	(in)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
NE	0	.210	0	.075	0	.008	0	-.009	0	-.026	0
	4	.194	.808	.073	.296	.027	.070	.005	.004	-.005	0
	8	.180	1.556	.072	.586	.039	.202	.015	.044	.010	.015
	12	.170	2.256	.073	.876	.041	.362	.021	.116	.018	.071
	16	.165	2.926	.075	1.172	.039	.522	.022	.202	.020	.147
	20	.160	3.576	.078	1.478	.037	.674	.024	.294	.020	.227
	24	.155	4.206	.081	1.796	.039	.826	.027	.396	.021	.309
	28	.150	4.816	.084	2.126	.047	.998	.035	.520	.023	.397
	32	.145	5.406	.088	2.470	.063	1.218	.049	.688	.035	.513
	36	.142	5.980	.093	2.832	.087	1.518	.070	.926	.050	.683
NW	0	.218	0	.033	0	-.024	0	-.045	0	-.075	0
	4	.192	.820	.033	.132	-.008	0	-.028	0	-.038	0
	8	.172	1.548	.035	.268	.003	.002	-.014	0	-.012	0
	12	.167	2.226	.039	.416	.010	.028	-.005	0	.001	>0
	16	.174	2.908	.043	.580	.013	.074	-.002	0	.006	.014
	20	.178	3.612	.052	.770	.013	.126	-.001	0	.004	.034
	24	.177	4.322	.060	.996	.016	.184	.002	.003	.002	.046
	28	.173	5.022	.068	1.250	.022	.260	.006	.019	.003	.056
	32	.169	5.706	.076	1.538	.036	.376	.015	.059	.010	.082
	36	.166	6.376	.084	1.858	.054	.556	.028	.145	.025	.152

Continued on next page

TABLE 19. (Continued)

Quad- rant	Depth (in)	Cumulative open-pan evaporation (inches) 0 (a)	0 (b)	10.79 (a)	10.79 (b)	18.94 (a)	18.94 (b)	23.83 (a)	23.83 (b)	28.98 (a)	28.98 (b)
SE	0	.265	0	-.025	0	-.033	0	-.047	0	-.066	0
	4	.215	.960	-.021	0	-.030	0	-.044	0	-.055	0
	8	.178	1.746	-.015	0	-.024	0	-.040	0	-.042	0
	12	.159	2.420	-.005	0	-.014	0	-.033	0	-.030	0
	16	.148	3.034	.007	.007	-.002	0	-.022	0	-.018	0
	20	.145	3.620	.022	.065	.012	.020	-.008	0	-.007	0
	24	.146	4.202	.037	.183	.025	.094	.008	.007	.006	.005
	28	.151	4.796	.055	.367	.041	.226	.026	.075	.021	.059
	32	.159	5.416	.080	.637	.059	.426	.043	.213	.040	.181
	36	.169	6.072	.114	1.025	.078	.700	.061	.421	.064	.389
SW	0	.236	0	-.023	0	-.032	0	-.064	0	-.053	0
	4	.210	.892	-.012	0	-.022	0	-.046	0	-.038	0
	8	.191	1.694	-.003	0	-.012	0	-.032	0	-.025	0
	12	.179	2.434	.003	.003	-.002	0	-.018	0	-.013	0
	16	.172	3.136	.008	.025	.008	.013	-.006	0	-.007	0
	20	.168	3.816	.012	.065	.017	.063	.004	.003	-.022	0
	24	.165	4.482	.018	.125	.025	.147	.011	.033	.003	.003
	28	.164	5.140	.028	.217	.031	.259	.016	.089	.008	.025
	32	.162	5.792	.044	.361	.035	.391	.020	.161	.016	.073
	36	.160	6.436	.067	.583	.038	.537	.022	.245	.024	.153

TABLE 20. SIMPLE CORRELATION COEFFICIENTS OF THE ORIGINAL AND SOME OF THE TRANSFORMED VARIABLES WITH THE TWO DEPENDENT VARIABLES Y_1 AND Y_2.

Variable	Nonirrigated All data Y_1	Nonirrigated All data Y_2	Nonirrigated Plots 38,39 omitted Y_2	Irrigated All data Y_1	Irrigated All data Y_2
X_1	-.571	.593	.717	-.753	.770
Days	-.558	.586			
$X_1^{1/2}$	-.586	.610	.771	-.769	.786
$X_1^{1/3}$	-.589	.614			.777
$X_1^{1/4}$	-.590	.616			.765
$X_1^{-1/2}$		-.555			
$X_1^{-1/4}$		-.601			
X_2	.346	-.359	-.566	.575	-.588
$X_2^{1/2}$	.345	-.357			-.582
$X_2^{1/3}$	.345	-.357			-.581
$X_2^{1/4}$	.344	-.356			-.580
X_3	.522	-.378	-.360	.414	-.358
$X_3^{1/2}$	.522	-.388			-.369
$X_3^{1/3}$	.520	-.390			-.371
$X_3^{1/4}$	.519	-.391			
X_3^{-1}			.094		.352
$(X_3-10)^{1/3}$			-.358		-.364
X_4	-.256	.281	.299	-.328	.362
$X_4^{1/2}$	-.225	.249	.269	-.299	.334
$X_4^{1/3}$	-.220	.243			.334
$X_4^{1/4}$	-.219	.243			.336
X_5	-.346	.356			.337
X_5^{-1}	.394	-.270			
LnX_5	-.500	.380	.356	-.326	.371
X_6	-.050	.113	.169	-.064	.087
$X_6^{1/2}$	-.055	.119			

(Continued)

TABLE 20. (Continued

	Nonirrigated			Irrigated	
	All data		Plots 38,39 omitted	All data	
	Y_1	Y_2	Y_2	Y_1	Y_2
$X_6^{1/3}$	-.056	.120			
$X_6^{1/4}$	-.057	.121			
X_7			.014	-.061	.038
X_8			.057	-.002	.001
X_9			.115	-.078	.104
$X_1 \div X_3$	-.683	.616			.819
$(X_1 \div X_3)^{1/2}$			.849		.899
$X_1^{3/2} \div X_3^{1/2}$	-.690	.634			.849
$X_4X_1 \div X_3$	-.494	.492			
$X_4^{1/4}X_1 \div X_3$	-.633	.605			
$X_6X_1 \div X_3$	-.554	.537			
$X_6^{1/4}X_1 \div X_3$	-.675	.621			
$(X_4X_1 \div X_3)^{1/2}$					.734
$X_4^{1/3}(X_1 \div X_3)^{1/2}$					.806
X_4X_7			.120	-.270	.279
X_4X_8			.160	-.126	.132
X_4X_9			.189	-.217	.245
X_1X_4			.449	-.501	.529
$(X_1X_4)^{1/2}$					.622
X_1X_6			.641	-.573	.598
$X_1X_3X_4$		.084			
$X_1X_3X_6$		.032			

Table 21. Coefficients, standard errors (SE), Student's t values and R^2 values for the three regression models fitted to the data from the nonirrigated plots. There were 480 data points (excluding plots 38, 39). The dependent variable was Y_2, specific soil moisture used.

Independent variable	Model 1 Coefft. ($\times 10^3$)	Model 1 SE ($\times 10^3$)	Model 1 t	Model 2 Coefft. ($\times 10^3$)	Model 2 SE ($\times 10^3$)	Model 2 t	Model 3 Coefft. ($\times 10^3$)	Model 3 SE ($\times 10^3$)	Model 3 t
x_o	-10.538			-77.542			-51.784		
x_1	4.2799	.5035	8.500				-6.7621	3.3036	-2.047
$x_1^{1/2}$				0.94032	3.05850	0.307	56.518	20.525	2.754
x_2				306.358	36.967	8.287	-19.710	174.362	-0.113
x_3^{-1}	-1.2478	11.2118	-0.111						
x_3				-0.24839	0.43919	- .566	-0.30346	0.46642	-0.651
$(x_3-10)^{1/3}$							-1.1728	2.8947	-0.405
$(x_1/x_3)^{1/2}$				50.706	6.143	8.254			
x_4	0.0045529	0.0236472	0.193				0.56615	0.28019	2.021
$x_4^{1/2}$				8.0964	1.1276	7.180	5.2996	1.9698	2.690
$\ln x_5$	21.807	1.536	14.202	6.2830	3.7917	1.657	18.083	4.987	3.626
x_6	-0.011283	0.007762	-1.454	-0.0065758	0.0058393	-1.126	-0.0081523	0.0062275	-1.309
x_7	17.240	9.391	1.836	16.410	7.040	2.331	27.518	9.112	3.020
x_8	35.149	12.701	2.767	-171.435	28.151	-6.090	-88.872	53.023	-1.676
x_9	125.710	34.035	3.694	-120.373	36.171	-3.328	-42.773	59.417	-0.720
x_4x_7	0.0004513	0.0865109	0.005	-0.34180	0.09023	-3.788	-0.72756	0.20502	-3.549
x_4x_8	-0.0021712	0.0245172	-0.089	-0.066812	0.011241	-5.943	-0.60825	0.26786	-2.271
x_4x_9	-0.35678	0.027582	-1.294	-0.089312	0.014861	-6.010	-0.62903	0.26791	-2.348
x_1x_4	-0.0000140	0.0002277	-0.061	0.0001954	0.0001712	1.141	0.0002050	0.0001870	1.096
x_1x_6	0.0001472	0.0003628	4.058	0.0011696	0.0002741	4.268	0.0012489	0.0002923	4.272
R^2		.711			.840			.820	

Table 22. Coefficients, standard errors (SE), Students t values and R^2 values for the three regression models fitted to the data from the irrigated plots. There were 640 data points. The dependent variable was Y_2, specific soil moisture used.

Independent variable	Model 1 Coefft. (x 10^3)	Model 1 SE (x 10^3)	Model 1 t	Model 2 Coefft. (x 10^3)	Model 2 SE (x 10^3)	Model 2 t	Model 3 Coefft. (x 10^3)	Model 3 SE (x 10^3)	Model 3 t
x_0	-20.638			-12.165			-15.975		
x_1	5.5258	0.3888	14.211				-1.8197	1.9361	-0.940
$x_1^{1/2}$				-0.81915	2.21579	-0.370	28.113	6.379	4.407
x_2				-36.749	68.955	-0.533	-166.362	155.101	-1.073
x_3^{-1}	-26.330	47.100	-0.559						
x_3				0.071088	0.313812	0.227	0.53034	0.37965	1.397
$(x_3-10)^{1/3}$							2.4473	2.6171	0.935
$(x_1/x_3)^{1/2}$				79.522	5.175	15.366			
x_4	0.19445	0.03691	5.269				-0.019682	0.077106	-0.255
$x_4^{1/2}$				3.5096	0.5240	6.697	3.8831	1.3329	2.913
$\ln x_5$	19.790	2.442	8.106	4.2285	2.7043	1.564	25.370	4.772	5.317
x_6	-0.0011075	0.0024713	-0.448	-0.0007980	0.0020243	-0.394	-0.0009903	0.0023895	-0.414
x_7	13.304	4.882	2.725	2.1703	3.9696	0.547	0.60029	6.70705	0.090
x_8	-153.442	23.298	-6.586	-134.537	30.391	-4.427	-137.778	42.479	-3.243
x_9	-221.056	31.837	-6.943	-170.315	41.474	-4.107	-181.274	55.795	-3.249
x_4x_7	-0.067113	0.035643	-1.883	-0.0058670	0.0180694	-0.325	0.0047824	0.0454853	0.105
x_4x_8	-0.082996	0.035657	-2.328	0.011809	0.015821	0.746	0.030652	0.065555	0.468
x_4x_9	-0.086934	0.036003	-2.415	0.014051	0.015526	0.905	0.033109	0.067361	0.492
x_1x_4	-0.0029344	0.0003916	-7.494	-0.0008710	0.0004796	-1.816	-0.0009422	0.0005728	-1.645
x_1x_6	0.0002621	0.0002142	1.224	0.00022133	0.0001750	1.265	0.0002431	0.0002071	1.173
R^2		0.795			0.861			.809	

Table 23. Combined correlation matrix for model 3 based on 480 data points from nonirrigated plots (above diagonal) and 640 data points from irrigated plots (below diagonal).

Variable	$x_1^{1/2}$	$\ln x_5$	x_4	x_6	x_2	x_1	$x_4^{1/2}$	x_7	x_8	x_9	x_3	$(x_3-10)^{1/3}$	x_1x_4	x_1x_6	x_4x_7	x_4x_8	x_4x_9	Y_2
$x_1^{1/2}$	1.0000	0	.1950	0	.6263	.9665	.1375	0	0	0	0	0	.4471	.7026	.1307	.1171	.1082	.7707
$\ln x_5$	0	1.0000	-.1014	-.0062	0	0	-.1108	.0686	-.1156	-.0217	-.9417	-.9389	-.0756	-.0036	.0487	-.1018	-.0210	.3562
x_4	.3114	-.0895	1.0000	.3563	.0345	.2183	.9750	-.5067	.4519	.5753	0	0	.8916	.3924	-.3478	.5854	.6106	.2985
x_6	0	-.0026	.3365	1.0000	0	0	.3565	.1944	-.2454	.5916	0	0	.2586	.5842	.0556	-.1577	.5728	.1690
x_2	-.7297	0	-.2801	0	1.0000	.4092	.0274	0	0	0	0	0	.1086	.2975	.0105	.0194	.0210	.5663
x_1	.9726	0	.3214	0	-.8570	1.0000	.1531	0	0	0	0	0	.4883	.7269	.1497	.1314	.1206	.7167
$x_4^{1/2}$	.2652	-.1022	.9726	.3233	-.2272	.2702	1.0000	-.5212	.5073	.6012	0	0	.8105	.3314	-.3221	.5517	.6139	.2694
x_7	0	.0686	-.4775	-.0070	0	0	-.4614	1.0000	-.3333	-.3333	0	0	-.3745	.1135	.7102	-.2936	-.3227	.0135
x_8	0	-.1156	.3032	-.2380	0	0	.4141	-.3333	1.0000	-.3333	0	0	.3431	-.1434	-.2367	.8808	-.3227	.0571
x_9	0	-.0217	.7016	.5238	0	0	.6626	-.3333	-.3333	1.0000	0	0	.4168	.3456	-.2367	-.2936	.9682	.1153
x_3	0	-.9471	0	0	0	0	0	0	0	0	1.0000	.8990	0	0	0	0	0	-.3604
$(x_3-10)^{1/3}$	0	-.9536	.0001	0	0	0	.0001	0	0	0	.8990	1.0000	0	0	0	0	0	-.3579
x_1x_4	.5543	-.0570	.8678	.2186	-.5577	.5899	.7660	-.3008	.1906	.4524	0	0	1.0000	.5713	-.2532	.5358	.5287	.4486
x_1x_6	.6666	-.0014	.4586	.5558	-.5874	.6853	.3874	-.0039	-.1323	.2912	0	0	.6227	1.0000	.1486	-.0113	.4669	.6411
x_4x_7	.2655	.0444	-.2613	.0097	-.2430	.2758	-.1953	.6472	-.2157	-.2157	0	0	-.1442	.1978	1.0000	-.2085	-.2292	.1199
x_4x_8	.1664	-.1087	.3648	-.2235	-.1488	.1714	.4455	-.3131	.9393	-.3131	.0001	.0002	.3333	-.0400	-.2027	1.0000	-.2843	.1598
x_4x_9	.1701	-.0203	.7803	.4905	-.1523	.1753	.6924	-.3121	-.3121	.9634	0	0	.6571	.4677	-.2020	-.2932	1.0000	.1889
Y_2	.7863	.3709	.3617	.0871	-.5876	.7696	.3342	.0378	.0010	.1040	-.3583	-.3640	.5292	.5984	.2791	.1322	.2448	1.0000