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Title The Influence of Herbaceous Vegetation on Coniferous Seedling Habitat in Old Field Plantations

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Plantation failures on abandoned pasture lands and old clearcuts are associated frequently with heavy stands of herbaceous vegetation. The competitive influence of the vegetation has been described as the causative factor of mortality, but quantitative estimates of vegetation influence are lacking. The development of chemicals with promise for selectivity in conifer plantations has made it possible to create a range of vegetation conditions which makes quantitative study possible. This thesis undertakes to analyze the changes in some factors of the environment which occur as the function of vegetation manipulation, particularly moisture availability.

Aerially-sprayed grassy south slopes near Corvallis, Oregon, supporting vegetation densities ranging from devegetated to fully-stocked stands, were sampled intensively for moisture depletion in relation to the amount of vegetation surviving the herbicide effects. It was shown that the rate of depletion of moisture was the direct

function of the amount of vegetation. Evaporation from the soil surface of devegetated plots accounted for moisture loss which was important in terms of tension only in the surface six inches. Abundant moisture remained within the root zones of planted seedlings below six-inch depth. Fully vegetated plots were completely depleted of available moisture in the surface 36 inches by June 23, and depletion occurred at equal rates throughout the soil profile. Late spring rains contributed nothing to available moisture supplies after May 17. The year 1962, the season under study, was later in this respect than average.

Mathematical models were constructed which permitted prediction of moisture depletion rates on the basis of vegetation, climate and soil parameters. Models were derived for prediction of the amount of moisture available at any given time, on the basis of vegetation, drainage, and soil depth; and for prediction on a general basis of the moisture depletion rate which is likely to occur at any time, and under any conditions of vegetation and soil, when qualified by meteorological data. The former equation may be used on a given date during the period of rapid drying, and on a particular site, to predict the amount of moisture remaining as the function of vegetation. Qualification by soil depth was not as important as consideration of drainage, which was an indication of considerable unsaturated moisture flow into and away from devegetated areas, in particular. The latter equation is more complex, but affords a prediction of the moisture depletion pattern over the entire drying period as the function of vegetation, soils, potential evaporation, and date. Cubic expression of date gave a reasonable approximation of combined meteorological phenomena, and greatly simplified the equation.

Calculation of the energy budget during the period of rapid vegetation development indicated that fully occupied stands of herbaceous vegetation were utilizing 82 percent of the net radiation in transpiration, and that 92 percent or more of the total moisture loss occurred through the transpiration process. Removal of the vegetation may divert substantial energy into sensible heat, which may cause localized soil surface heating during the drying period. The period of maximum soil-heating damage occurs during the season when little moisture is available for cooling in fully-vegetated sites, hence the significance of heat budget manipulation may be minor.

In consideration of the amount of moisture conserved, it is likely that drought conditions can be avoided for at least one season with proper evaluation of vegetation conditions and proper chemical amelioration thereof. The habitat improvement was evidenced by the general initiation of lammas growth of Douglas-fir seedlings, and by greatly increased survival and vigor on all coniferous species tested. The principles herein developed were verified by good survival and vigor on sites distributed throughout western Oregon where plantations had failed three or more times previously.

While chemical control of drought conditions through vegetation manipulation is shown to be a powerful tool in reforestation, it must be recognized that solution of the drought problem will not overcome difficulties not related to vegetation.

THE INFLUENCE OF HERBACEOUS VEGETATION ON CONIFEROUS SEEDLING HABITAT IN OLD FIELD PLANTATIONS

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INTRODUCTION

Grassy openings in conifer forests are a subject of interest to foresters and botanists. Foresters view these openings as areas which should be productive and which present formidable reforestation problems; botanists regard the stability of vegetation thereon as evidence of natural successional conditions approaching climax, and find them interesting from the standpoint of successional differences from forest types. Foresters have been willing to devote a disproportionate amount of their reforestation efforts to this type, despite inherently low relative productivity, and on numerous occasions have been known to spend excessive amounts to afforest such areas. The stability of the herbaceous cover is also of interest to range, wildlife, and watershed managers from the standpoints of forage supplies, soil stabilization, and water utilization.

Despite the combined attentions of research workers in the above fields, working in cooperation and individually, no reasonable quantitative measure of environment, based on vegetation, has been associated with the absence of conifers. Moreover, the close similarity of the vegetation conditions in the stable forest opening to those in clearcut forest areas on which reforestation efforts have failed, suggests the stabilizing influence of the herbaceous cover, whether in natural openings or on deforested sites.

The present study resulted from evidence in previous work by the author illustrating that seedling environment may be the most important factor in establishment, and that the success of seedlings in dominating a site is related to their ability to obtain the moisture and nutrients necessary for survival during the brief period of establishment. This thesis undertakes to examine some of the environmental conditions associated with herbaceous cover on grassy plantation sites, with an analysis of the relationships between the vegetation and some of the factors which may cause mortality, particularly drought.

The emphasis in this work has been directed toward a characterization of the drought conditions which prevail as the function of the use of water by herbaceous vegetation. It was felt at the outset that the condition of drought was damaging to conifer seedlings from the standpoints of the degree of droughtiness, and perhaps just as important, a qualitative characterization of the dynamics of drought onset. Both evaluations have been approached from the point of view that the vegetation conditions may have an important bearing on moisture conditions as a causative influence.

In the past there has not been great incentive to study the quantitative influence of vegetation on seedling habitat because there has been no practical method of applying results. The practice of scalping the ground around planted seedlings has been interpreted as a method of reducing the competition for moisture by associated herbs, but has not been consistently successful in creating conditions favorable for seedling survival. Other methods of vegetation reduction have been used, with cultivation being the most successful, and possibly the only practice which has been consistently practical. On wild land situations, the point of view has generally been that grass cover exists as an unavoidable nuisance, to be overcome only through long persistence and some element of good luck.

In recent years the development of chemicals with which herbaceous vegetation can be manipulated shows promise of weed control in conifer plantations on field sites. For the first time it has become pertinent to study the quantitative relationships between vegetation and environment for the practical reason that a range of ecological conditions may now be created as the function of the herb cover surviving the herbicide effects.

The studies presented in this thesis have been conducted in the vicinity of the Willamette Valley, near Corvallis, Oregon. The conclusions drawn from the field studies should have direct application in other areas of similar climatic and soil situations, and should be conceptually pertinent over a much wider range of conditions. The use of climatic data, and the conversion of all data to absolute quantities has been done to facilitate the process of interpretation outside the range of conditions herein encountered.

REVIEW OF LITERATURE

Analyses of the conditions responsible for mortality of conifer seedlings have taken many forms. Drought and heat have probably received the greatest amount of specific attention as causes of mortality. Quantitative analysis of the heat problem has been undertaken on numerous occasions (1; 9; 16; 21; 23; 24; 25; 37; 39; 42; 48; 51; 59; 64; 75; 86; 89; 90; 91). Drought has perhaps received more attention, but the characterization of the problem with causes and effects has been largely qualitative and speculative. Considerable effort has been made to relate the uses of water to vegetative cover according to cover type for watershed streamflow prediction (41; 50; 80; 83; 104), but these studies have estimated water use differences between fully-stocked cover types. Moreover, the studies which have undertaken to analyze the relationship between the use of water through transpiration and that which is lost to evaporation (100) have not related water use to the quantity of transpiring plant material. An estimate of this type would be desirable for reliable measurement of the effects of vegetation manipulation.

Relationship of Physical Factors to Moisture Use

The relationship between the physical environment and the use of water has been studied by a number of investigators (61; 76; 77; 104). The two factors which have received the greatest attention in this approach have been the influence of solar radiation on evapotranspiration (32; 95; 99; 100; 107), and the rate of water loss as the function of the amount of available moisture within the rooting zone (3; 13; 82).

Penman points out that the amount of evapotranspiration may be predicted according to the equation:

$$ET = \frac{H}{1 + \beta}$$

when ET is expressed in millimeters of evapotranspiration per day, H is the net radiation per day in langleys, and β is Bowen's ratio, which is an empirical expression of the influence of relative humidity, temperature gradient above ground, and vapor pressure gradient (77, p. 133). He points out that this expression fits experimental data better in late than in early summer, but points out also that the failure of this equation to predict moisture loss amounts to a relatively small proportion of the estimate, and the comparison of this equation with others in reference to experimental data illustrates its usefulness. Thornthwaite (as quoted by Smith (93)) expresses the total evapotranspiration in terms of air temperature and latitude, but also uses a so-called "F" factor which qualifies the moisture loss as the function of the amount of available moisture. This relationship fitted Smith's experimental data better than Penman's equation, but still predicts moisture loss on the questionable basis that the difficulty of removing moisture from the soil is the inverse linear function of the amount of available moisture within reach of the plant roots.

Lowry (61) reviews the relationship between the availability of water and rate of loss, and points out that most of the experimental evidence of this relationship has been established at low moisture tensions and under laboratory conditions. He further adds that the evaporation rate may not show a linear decrease with decreasing soil moisture, and, in fact, estimates appear to be normalized by the equation:

$$\frac{h}{h^*} = \left(\frac{\Delta W_s}{\Delta W_m}\right) \div \left(\frac{\Delta W_s}{\Delta W_m}\right)^* \qquad \text{(Lowry, 1962, eq. 7)}$$

when $\frac{h}{h^*}$ is an evaporation rate correction factor dependent only on soil moisture, W_s is the soil moisture content as percent of moisture at field capacity, and W_m is the amount of water under the experimental conditions (atmometer) at time "t". The asterisk represents "standard conditions" arbitrarily established. With this equation, field estimates of evaporative soil moisture loss are converted to "normalized" conditions on a predictable basis. When field data were applied to the standard, evaporation was related to moisture content in such a way that evaporation rate increased with increases in moisture in a positively curvilinear log log relationship, with relatively little deviation from the empirical curve.

Evaporative losses of water appear to represent a variable proportion of the total water loss. Under California conditions Veihmeyer (104) found that fruit trees removed eight inches of water from a given soil in a six-week period, while the same soil was characterized by an evaporative loss of water of 3.375 inches during a four-year period. While Veihmeyer concluded that evaporation amounted to a small proportion of the total loss, the American Society of Agricultural Engineers reported that the transpiration losses under average conditions might amount to 20-50 percent of the total loss, the remainder being accounted for by direct evaporation (2). Beyond this, it was indicated that the ratio of evaporation to transpiration increased with increases of temperature and wind velocity, although soil depth was not discussed. Briggs and Shantz (17) found that the water losses from soil were correlated with a number of physical factors independent of vegetation, with the following factors explaining variation as indicated:

Factor	Percent corr. with water loss
Gross solar radiation	50
Wet-bulb depression	79
Temperature	64
Open-pan evaporation	72
Wind velocity	26

Obviously, some of these factors are correlated with others, and no multiple correlation was used to assign to each factor the amount specifically contributed. It was shown that different crops could have variable influence on the drying rate, however, and this difference presumably would have its effect through variations in efficiency of interception and utilization of physical forces for water extraction.

The relation of evaporation to transpiration on some of the California reforestation problem areas has been shown to vary considerably according to season, with a maximum of transpiration-evaporation ratio occurring in July when 87 percent of the loss is transpirational (21). This estimate probably reflects the early loss of nearly all moisture in the surface soil from which much of the evaporation would take place. Evaporation from the deeper layers would appear to involve long diffusion distances which would reduce the rate of loss from this cause.

The Role of Vegetation in Evapotranspiration

The classical equations of evapotranspiration generally make the assumption that the forces of the physical environment are acting upon a soil-vegetation complex in which vegetative conditions are static and in condition to utilize the radiant energy for transpiration uniformly over the entire site. In view of the modified conditions involved in the present study, it is difficult to interpret these expressions in terms of partially-occupied sites and under situations in which vegetation is constantly developing. The lack of fit of the equations which pertain to fully-stocked sites is illustrated in some degree by several workers approaching the relationship from different standpoints. Tanner (99) has pointed out that the efficiency of radiant energy in producing evapotranspiration from a corn field is roughly the same over a relatively large range of numbers of plants per unit area, with consistent inverse relationships in the amount of water transpired per plant. Piemeissel (79) illustrated the same general relationship with cheatgrass in Idaho. While these workers have illustrated the constancy of total moisture use in line with the classical equations mentioned above, their approach implies that the amount of moisture used must at some point be limited by the number of plants when the amount per plant reaches the physiological maximum. The physiological maximum concept may have been demonstrated in the work of Bay and Boelter (10) who showed that forest stands did not utilize as much water after thinning as before, with the implication that one might expect the stand to utilize water more completely as it approached full stocking. It is logical that this would follow in forest stands, and the same concept appears to prevail for understocked stands of herbaceous vegetation, as in the report of Hyder and Sneva (44) pertaining to the spacing of range grasses, and other range studies (54; 57).

It may be speculated that the microsites under the influence of the residual plants, where plant populations have been artificially limited, may be characterized by the same equations as would pertain to fully-stocked stands. However, there is considerable evidence that several factors may influence estimates of water use under field conditions of this type, especially where chemical manipulation of vegetation is involved. In contrast to the soil physics concept that negligible amounts of moisture move in unsaturated soil, there is increasing evidence that sufficient movement occurs to bias vegetation-moisture use estimates (40; 72; 74; 81). Furthermore, Smith and Buchholtz have found that the application of the herbicide atrazine to vegetation reduces the transpirational efficiency of the plant by as much as 50 percent shortly after application (92). Lassen et al. (53, p. 29) have also shown that reduced plant vigor in general will reduce the rate of spread of individual plant influence. Selectivity of herbicides has been shown to create conditions more favorable for certain groups of plants while serving to limit the development of more susceptible groups with no appreciable change in total plant production, but a distinct change in distribution of production among species (54). In such instances as this, the zone of influence of the physical factors of the environment which must act through the plant will be modified by the distribution of the plant roots (20), hence will be limited by the ability of the modified plant cover to fully reoccupy the site. Moreover, the composition of the vegetative cover may have substantial influence on root distribution (20, p. 108).

When the role of vegetation is reduced by some artifical manipulation of plant populations, the role of evaporation must increase in relation to total water loss. Moreover, there is likely to be some change in the total evaporation rate, partly as the function of the accumulation of organic matter acting as a mulch and partly as the result of the greater amount of water remaining in the soil due to the lack of utilization by vegetation, hence steeper vapor pressure gradient. It is also shown that the mulch effect is restricted to the immediate surface, and it can be expected that diffusion gradients within the soil will be responsible for control of drying rates due to evaporation (4). The atypical condition represented by chemically-treated herbaceous cover presents a further difficulty with respect to the relationship of vegetation density to soil moisture. Losses due to unsaturated flow as mentioned in the work of Robins et al., and others (72; 74; 81) are sufficient to present some difficulty in determination of the amount of water used specifically by vegetation and evaporation. If work is being done in situations where hillside moisture can flow downslope in an unsaturated state, and if the water content is maintained at relatively low tension, then the bias on the downslope estimates should be the reverse of that of the upper slopes from which the subsurface flow originated (40). The difficulty of determining accurately the amount of water involved in such movement is evident in the lack of published information.

Characterization of Drought

The idea of drought connotes lack of moisture or lack of rainfall. The physical description of the onset of drought and variability of drought conditions as the function of local vegetation are matters of profound importance, yet have received little attention. In view of the apparent importance of the nature of drought conditions in the response of plants, this subject cannot be overlooked in a study of this sort.

The work of Shirley and Meuli with pine seedlings has shown that seedlings may become conditioned to high moisture stress to some extent by periodic exposure to varying degrees of soil moisture tension (87), and also by exposure to different nutrient levels (88). Their work has not been entirely supported by the work of Lavender, however, who has indicated that environmental conditions are likely to mask any such drought resistance in Douglas-fir as that which

Shirley and Meuli introduced in pines (55). The response of field-planted Douglas-fir seedlings to soil drying has been discussed by Youngberg (110; 111) who pointed out that drought conditions are responsible for considerable mortality of seedlings when Douglas-fir is planted on certain soil and vegetation combinations. Both Youngberg and Owen (75) described soil drying curves typical of the natural conditions under study in this thesis. Both related mortality to drought, in general, but Owen pointed out that much drought mortality occurred in June and October, with lesser amounts in intermediate periods. The early-season mortality is speculated to be the result of the rapid drying of the soil in combination with the active physiological condition of the seedlings. Shirley and Meuli (87) also noted that the study of drought resistance should be conducted at a time later than the period of maximum growth rate because of the general critical need for water during this period. Apparently, in Owen's work, the seedlings which were able to reach physiological hardiness were able to tolerate considerable drought until late in the summer after they had been exposed to conditions of high moisture stress for some months.

While it has been shown that the time of drought onset may have an important effect on seedlings, the rate of drying may also be important in the manner in which seedlings are permitted to attain gradually the condition of physiological hardiness. Owen pointed out that the drying rate of soil under an oak cover was slower than that of a grass cover, but that it reached the same minimum or lower. While the minimum soil moisture conditions persisted for a slightly shorter period due to the later date of reaching this stage, the seedlings planted under these conditions survived relatively well despite the exposure to prolonged drought (75, p. 34, 38).

If plant response to soil drying is to be so variable in terms of physical soil measurements, it would be preferable if the drought condition could be expressed in terms which would have definite bearing on an expected plant response. Penka (76) was able to show that the drying rate of soil was related to the amount of water available to the plants, but only after the moisture had reached the difficult-to-withdraw tension. He illustrates that the use of water is linear with time until the so-called "flexure" stage at which the moisture availability becomes limiting. At this stage in the drying curve one may expect the plants to respond with reduced vegetative growth, and by the time that flexure has reached the point of no moisture loss with time, the permanent wilting point has been reached. He also points out that curves derived from the performance of crops under the influence of these drying curves will be consistent when comparisons are made with the same crop under a variety of conditions, but that the responses will vary with different crops. Lassen _et al_. (53, p. 29) found that Penka's curves were consistent with their data, and went further in showing that the drying curves were similar at deeper soil depths although the termination of drying came at a later date. The lag effect is qualified, however, by the statement that where the moisture is equally available throughout the rooting zone, the moisture removal is distributed equally throughout the zone occupied by the roots.

Water use estimates have been made which relate the consumption of water to dry weight production of plant material under certain crop conditions. The classic work of Kiesselbach with corn plants illustrates that the dry weight increment of the plant material is related to the use of water, with the conclusion that 230 to 296 units of water are required for one unit of dry weight production (49). If this and the work of Briggs and Shantz and others (17; 57; 68; 78; 94) obtain under wild herbaceous growth conditions, the reverse should also be true in that an estimate should be possible which would predict the amount of water already used from an estimate of the dry-weight production of the vegetation at any given time, and from this a measure of the amount of available moisture still remaining in the root zone should be obtainable. Moreover, if the amount of water use could be predicted on the basis that a given amount of vegetation development would require a certain amount of moisture beyond that lost to evaporation, then one might be able to predict the amount of vegetation compatible with the water needs of seedlings. In this case, the amount of water surplus would be related to the hysteresis effect discussed by de Wit (26) and might be utilized as the stocking of the total vegetation complex approaches the maximum.

Moisture Requirements of Conifer Seedlings

The moisture requirements of plants have received substantial attention with respect to the wilting point. It is acknowledged that the wilting points of various species differ substantially, and that certain species are notoriously able to persist under conditions of extreme moisture stress. Douglas-fir, Pseudotsuga menziesii (Mirb) Franco, is native to semi-arid regions as well as the more humid Douglas-fir region. The ability of this species to survive conditions of drought has received considerable attention (23; 28; 112). Douglas-fir has been regarded as a less drought-resistant species than ponderosa pine, Pinus ponderosa (Laws), (23) yet despite the lack of so-called drought-resistance, Douglas-fir has been shown to photosynthesize at extreme moisture tension (112, p. 27) and to follow ponderosa pine into arid zones of Rocky Mountain states. At once the question arises as to whether a species must be regarded as drought resistant according to an absolute standard, or whether it should be considered in comparison to those species with which it is found. If, as Zavitkovski found, some species of conifers are capable of existence without damage in conditions of moisture tensions of tens of atmospheres (112, p. 27), then it is logical that the conifers may survive if the plants with which the seedlings must share a site are incapable of utilizing all the water which is available to the conifers. This is only likely to be a reasonable assumption if 15 atmospheres may be considered an average wilting point, and may be a specific reason for the occurrence of conifers in certain vegetation types.

After the cessation of effective rainfall, which date may be reached in the "arid" regions at a later date than in some portions of the Douglas-fir region, the drought conditions in the vicinity of a seedling will be the function of the soil drying rate, and the time of recharge. These parameters will be controlled by the same general physical factors under any climatic situation, and the ability of seedlings to persist would be the function of their ability to withdraw moisture from the soil at these high tensions at a rate sufficient to maintain turgor under the influence of prevailing solar energy conditions and relative humidity. Negligible published work is available to offer insight as to the relative drought resistance of trees as the function of moisture uptake in the 15 to 60 atmosphere tension range. Differences in drought resistance of coniferous species have received considerable attention with respect to their suitability for planting on dry sites, but these differences are seldom explained on sound physiological bases, and are often attributed to morphological characteristics.

Work with drought-resistant ecotypes of Douglas-fir has been attempted by Ferrell and Woodard and Zavitkovski, with some success in the laboratory (28; 112). Genetic differences are apparently responsible for the ability of some strains of Douglas-fir seedlings to persist under extreme drought conditions for prolonged periods, and there is some suggestion that drought resistant stock may be obtainable by collecting seeds from specific provenances (112). Growth characteristics are not fully understood as they relate to drought resistance, however, and the use of these strains may not be practicable until test plantations have been observed over an extensive period.

Physiological drought resistance based on the ability of seedlings to go into dormancy when drought conditions begin have been discussed. A rather fine distinction is made between physiological drought resistance and drought evasiveness by Stone (97), who points out that the ability of a seedling to survive may be related to its capability to regenerate roots to reach water before drought conditions prevent further root development. Stone related root regeneration potential of seedlings to the time at which they were disturbed by the lifting process, and pointed out that optimum times for the lifting process could be utilized to insure physiological capability for drought evasiveness. Lavender's work generally supports the same conclusions in this respect (56).

Regardless of the relative ability of seedlings of the less drought-hardy species to evade drought, conifers are often planted in environmental situations where competing species are able to deplete the moisture supply more rapidly than the seedlings could be expected to develop roots. Under these conditions, which are common throughout western United States and elsewhere, the seedling must be able to tolerate extended periods of high moisture stress to survive. In view of the unlikelihood that drought-resistant seedlings suitable for all sites will become available in the near future, it appears that some means of conserving moisture must be found if plantations are to succeed.

Plantation Practices for Severe Sites

Problem analyses associated with planning for the restocking of sites, on which mortality has hampered efforts, have been largely directed toward tempering the moisture deficiency which appears ubiquitous in grassy situations. Moisture conservation practices have included cultivation, herbicides, mulching, scalping, and other practices aimed toward reducing transpirational losses in the vicinity of the seedling. Of all the mechanical methods of conserving moisture, cultivation appears to have the greatest promise in reducing moisture loss (1; 7; 30; 58; 64). Hermann and others (15;

38; 69) have shown that survival can be increased by the application of mulch materials, and Newton and Bradley have further illustrated that the size of the mulch may have an influence on survival (15; 69). While the general mulch effect could be construed to have an influence on other environmental factors, improved moisture conditions are logically the primary result of increasing the size of the mulched area.

In view of the inaccessibility of many forest sites and difficulty of operating heavy equipment for site preparation, cultivation and mulching have distinct limitations. Methods which are logistically more practicable have included foliage coatings for reduction of transpiration, which have generally given erratic results (66; 67); fertilization, which has often produced negative or neutral results (5; 58; 69); grazing, which may increase growth and available moisture (34; 57; 84) but which is not recommended for several years after planting; and herbicide applications for grass control (19; 70; 88), which have not only increased survival, but have greatly increased the general vigor and growth rate of the planted stock.

The use of nurse crops to afford some measure of protection from direct exposure by species of low moisture demand has been attempted under a variety of conditions. Baron's success with grasses was erratic, and it was demonstrated that the species of grass used for this purpose could have a strong influence on survival although no benefit was demonstrated from any grass (8). Numerous species of hardwoods and broom have been used as nurse crops in Europe, with the general effect of improving the fertility of the site (17) but this procedure is not usually adopted as a means of increasing survival on droughty sites. The use of mustard as a nurse crop has met with variable success in southwestern Oregon but it has been difficult to establish its applicability on any consistent basis. More often than not, the incidence of herb cover on sites designated for reforestation is regarded as a liability, and the longer the period of herb development and denser the stand, the more detrimental to seedlings (8; 21).

The Influence of Associated Vegetation on the Water Requirements of Seedlings

While the ability of various plants to survive under high moisture tensions has received considerable attention in the literature, the environmental situations which might have a very striking effect on the ability of the seedling to withstand drought have been mentioned only indirectly. Several workers have pointed out that grass may be more detrimental to seedlings than brush (21; 46; 105) without specifically qualifying the ecological conditions completely. While the suggestion is repeatedly offered that drought conditions are more severe in the grass or open than under the brush, it has also been shown that woody as well as herbaceous cover is likely to produce high moisture tensions in the rooting zones of seedlings (75; 80). In view of the relationship between the incident radiation energy and transpiration rate, it would be logical to conclude that the improved environment for seedlings under a dry-land brush type may very well be the function of the shading effect, and subsequent low transpirational stress due to reduction of incident radiant energy. This reasoning is consistent with the theory of the use of shading materials on planted seedlings, which has been moderately successful in some plantations (21; 65). The use of brush species for protection has obvious disadvantages combined with some advantages. The incidence of drought injury and heat damage is generally greatest during the first year of a plantation, and the brush cover may not develop sufficiently for the first years to offer anything but competition for moisture. Moreover, the brush may be capable of suppressing the seedlings for an extended period if it has a sufficient growth rate to reach sheltering size within a reasonable time (46). On the other hand, for some sites, the obvious advantages of site improvement from nitrogen-fixing species represents a great asset if the brush is compatible with the growth habit of the seedlings (46; 69; 71).

Influence of Herbaceous Vegetation on Microclimate

The influence of the low cover on soil temperature and air velocity have been subjects of substantial speculation and little close quantitative study. In the study by Norris (73) pertaining to soil surface temperatures under grass and brush, it was illustrated that the range of temperature fluctuation was far greater in the presence of grass than under stands of _Ceanothus velutinus_ var. _laevigatus_. The difference between the grass cover and no cover was not measured. Brawand and Kohnke (16) have reported that the soil surface temperature was much higher on an exposed soil than in the presence of grass. These reports and others (31, p. 176) would indicate the occurrence of a temperature gradient which increases toward the soil surface in the open, and which increases with vegetated conditions as the point of maximum light interception is approached from above or below. A double gradient of this type would predict that the soil surface temperature in the complete absence of any vegetative cover would exceed that found under any degree of cover whatever, and that maximum temperatures may be reached several inches above ground in an herbaceous cover. Such an environment might subject seedlings to very high transpiration stresses, particularly when moisture availability is limited.

In view of the reports which point out the difficulties of heat damage to seedlings, with a high incidence of heat girdling on exposed sites occurring in relatively cool climates with numerous species (21; 37; 42; 45; 64), the danger of soil heating on bare ground cannot be overlooked. The use of shading materials by Maguire to increase survival may have had the effect of reducing transpirational stress, or may have reduced the incidence of heat injury, or both. The shading materials doubtless had some influence on the heat gradient close to the ground, but the reduction of heat injury is suspected of being responsible for most of the improvement in view of the improved survival simply resulting from the use of heat protectors at the ground line (65).

While the reduction of herbaceous cover may increase the incident heat at the ground surface, the increased moisture near the ground surface should also have some effect on the amount of evaporation from the soil surface. Brawand and Kohnke (16) made the observation that the diffusion of moisture from the soil surface during the summer was greatest at night. If this were the case, then one could expect the daytime influence of vegetation modification to be relatively small. Probably some influence will occur, on the other hand, from the combined cooling effect of the increased reradiation and evaporation during the night in the absence of grass, with the resultant shorter duration of higher temperatures during the day. Since the heat budget has been modified by the reduction of transpiration and an increase in the amount of water for evaporation in situations of grass elimination, it should be expected that additional sensible heat gain will occur during the periods of intense sunshine. The distribution of the heat between soil and air would determine the influence on soil surface temperature.

EXPERIMENTAL DESIGN AND FIELD PROCEDURE

The Study Area

The field studies for this experiment involved a portion of a 24-acre forest opening on which plots had been established for the testing of the use of grass herbicides for conifer planting site preparation. The specific location was in the "Jackson Place" portion of the Oregon State University School of Forestry's MacDonald Forest, Section 1, T. 11S., R. 5W., W. M. The topography of the study site is characterized by rather steeply rolling hills, with short drainages flowing directly out onto the floor of the Willamette Valley. The elevation ranges between 550 and 650 feet above sea level. The overall study area is situated generally along the upper slopes of a rolling ridge (see topographic map, Fig. 1), with the concentration of sampling restricted to southerly aspects to minimize the microclimatic variability due to exposure differences. It was felt that study of south slopes would place the study effort in ecological situations of the greatest research need.

Climatically, local conditions are very similar to those of nearby Corvallis, but with slightly greater rainfall. In view of the

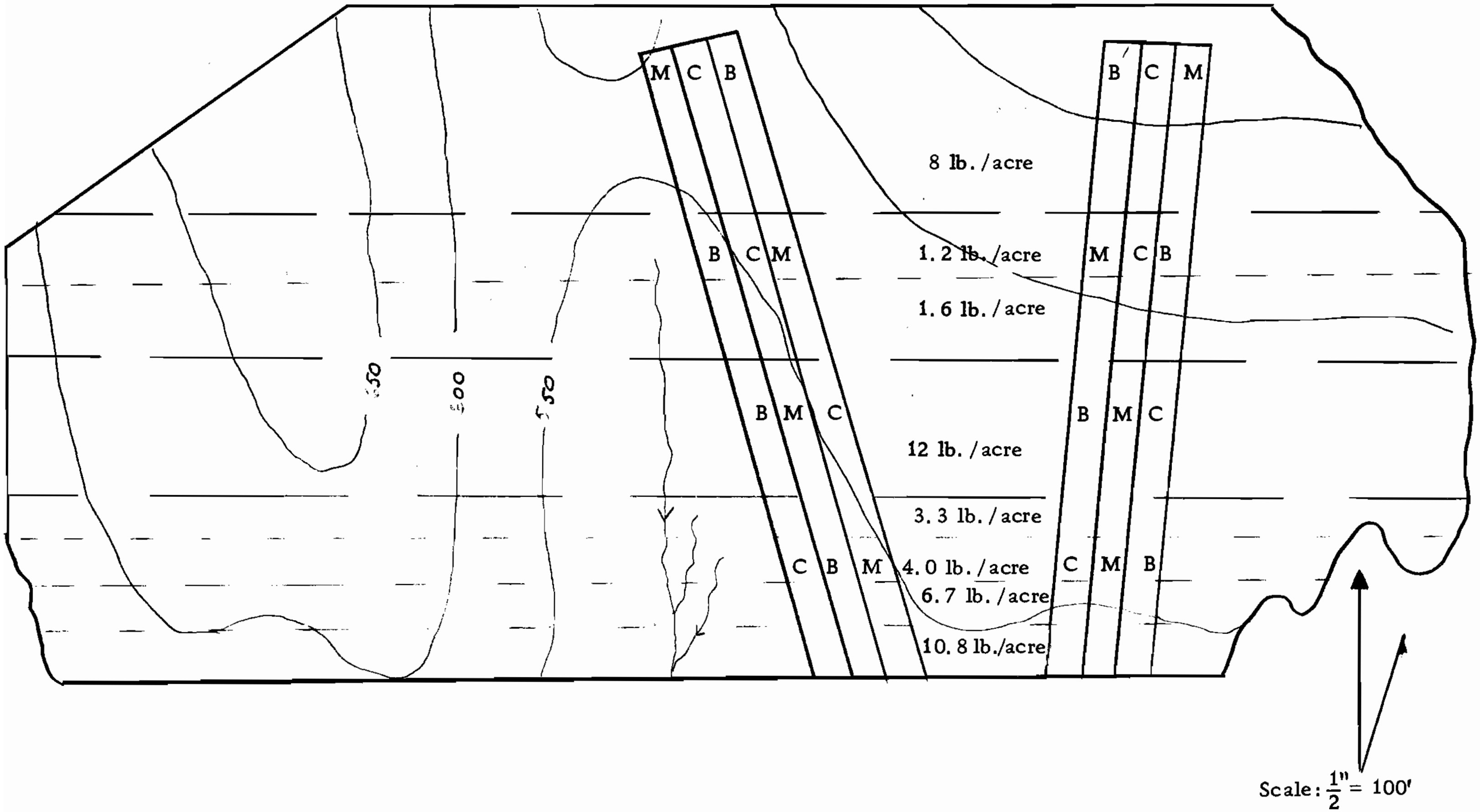

Figure 1. Plot diagram and topographic map. Jackson Place. Aerial sprayed with amizine on April 2, 1962 with active ingredient rates as shown. Subplots were mowed (M), burned (B), or left untouched (C) prior to spraying.

mean annual precipitation at Corvallis of 38 inches per year, it is estimated that the study site receives roughly 45 inches on the basis of the rain gauge observations made during the conduct of the study. Climatologically, the most significant ecological consideration in this study is that a potential moisture deficit of 14.2 inches occurs, beginning in early May and lasting into October (47, p. 22). While the mean July maximum and minimum temperatures of Corvallis are respectively 81.5 degrees F. and 52.7 degrees F. (47, p. 22) these values are regarded as very approximate. The south-slope orientation undoubtedly increased the local air temperatures, and without complete comparisons of temperatures at various levels above ground in the vicinity of the weather station and study area, it is risky to describe the average conditions in the field by extrapolation of climatological data.

Soils. The soils on which this study was conducted were generally residual and colluvial clays and clay loams derived from the Siletz River Basalt formation. The Dixonville clay loam series, shallow phase, was the most common soil, ranging into the Climax clay series toward the bottoms of some slopes. All the soils were of clay loam texture except the Climax clay, and contained moderate amounts of gravelly material derived from the decomposing basalt parent material. The profiles varied considerably over the sampling area, with depth ranging from seven to 30 inches in the Dixonville soil, and from 18 to more than 60 inches in the Climax. The range of available moisture was very similar at most of the sampling points, with about 17 percent by volume moisture available between one-third and fifteen atmospheres tension as calculated with a pressure plate. While the availability range in terms of percent was very consistent, the beginning and end points differed widely, and the bulk densities ranged from 0.90 to 1.80. In view of the difficulties in presenting the absolute moisture trends in terms of raw moisture percentages based on dry weight, all moisture values are expressed in terms of inches of water, and percent by volume.

One of the soil peculiarities of this locality was the fractured and decomposed nature of the bedrock. The basalt parent material was sufficiently weathered that roots penetrated to a considerable depth, and plants developing on soil that was apparently seven inches deep were found to be depleting moisture at depths of three feet. Moreover, this depletion from the bedrock appeared to occur at rates consistent with the depletion rates of the soil, hence the rock and soil data were considered together in the statistical treatment, after adjustment for bulk density.

Forest Potential. The classification of the site in terms of forest productivity is somewhat complicated by the patchy nature of the adjacent forested areas and unknown local history. It appears probable that the site was once forested, in view of the increasing occurrence of Oregon oak, *Quercus garryana*, with its habit of supporting an understory of Douglas-fir. There is some evidence of burned wood in the soil profile, and occasional pieces of decayed wood are to be found in the soil of the peripheral areas. Adjacent stands of Douglas-fir (Figure 2) indicate a site quality of slightly below average for Douglas-fir, or roughly site index 130.[1/] While the site is considered of relatively low productivity for Douglas-fir by local standards and is also considered as a poor risk for plantations, sites of this capability fully stocked with conifers would be considered excellent in most parts of the world, and it is felt that if they are to be considered according to their absolute potential, rather than relative to local averages, efforts at re-stocking may be justifiable.

Field Procedure

The field test of the influence of vegetation density on soil moisture involved 24 sub-plots superimposed upon the original aerial spray grass control areas. Two replications of plots were oriented across the full width of the aerial spray treatments (Figure 1). Each strip was composed of 12 plots, three in each of four aerial spray strips, representing aerial spray application rates of 1.2 to 12 pounds per

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[1/] 100-year site index.

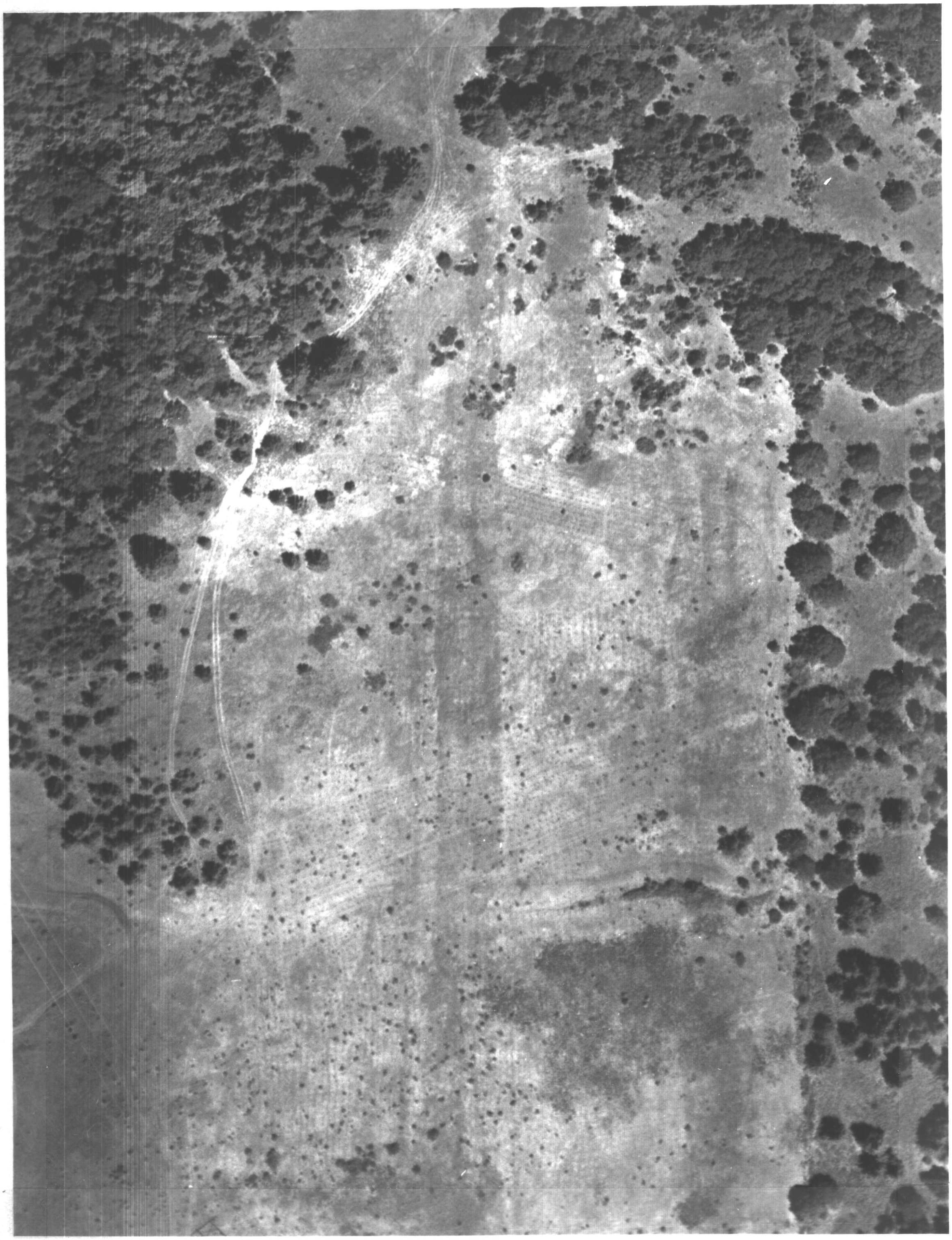

Figure 2. Aerial photograph of study area showing plantation orientation and herbicide application patterns. Scale 1:2400

acre of a mixture of amitrole[2/] and simazine[3/], with three forms of site preparation prior to spraying. Two sample points were systematically located within each sample plot. In the preliminary study regarding the aerial spraying for grass control, it was found that the site preparation treatments (i. e. burning, mowing, or leaving the dead grass unprepared prior to spraying) had no obvious influence on the vegetation density, hence these variables are not considered in the current study. Six sample points were thus situated within each replication at each application rate. 52 sample points, including four control points outside the aerial spray area, are represented in the vegetation and moisture sampling.

Soil Moisture Field Measurements. Field sampling for the determination of soil moisture depletion involved weekly soil moisture determinations at levels of zero to three, three to six, six to nine, and nine to 12 inches on all 52 sample plots during the period of maximum soil moisture drying rate on fully vegetated plots. Intervals between samplings were longer during the latter part of the season when soil moisture depletion was nearly complete in the vegetated plots. The field sampling procedure involved the location of a random distance and direction from the sample point marker.

[2/] 3-amino-1, 2, 4-triazole.

[3/] 2-chloro-4, 6-bis(ethylamino)-s-triazine.

Randomization was done once for all 52 sample points for each date of sampling. Directions were randomized among 36 choices of azimuth, and distances were randomized at one foot intervals along a ten foot radius. One sample point was observed on each plot for each day of sampling. While it is recognized that this form of randomization tends to concentrate samples toward the center of the plot, the plot center is the location which best represents average conditions throughout the area sampled in vegetation analysis.

Moisture sampling in the early portion of the season was accomplished with two instruments. The Kane-Tube sampler, a tube with an open side approximately two feet long and one inch in diameter, was used to extract sample cores. This tool proved awkward in the vicinity of rocks or on shallow soils where the decomposed basalt bedrock was too dense to penetrate. During the period of the study characterized by rapid drying, a soil auger, one inch in diameter and three feet long, was used for extraction of samples. The auger was removed from the sample hole for each three-inch sample, and the soil placed in 250 milliliter cans. The cans containing the soil samples were capped and taken back to the laboratory where they were weighed on a torsion balance for gross weight and placed in a 105 degree Centigrade oven. After drying for 48 hours, the samples were removed from the oven and weighed again. Soil moisture loss was calculated as a percent of the soil dry weight. No screening of soil samples was done, nor was any attempt made to modify the soil structure prior to drying.

Soil Samples for Tension Analysis. Soil samples for tension analysis were gathered during the season in which soil samples were taken of each soil type encountered in the study. The usual technique of gathering bulk samples, sieving for gravel particles, and analyzing with a pressure membrane apparatus illustrated that much variation was to be found in the location of the range of available moisture, but that the length of the range within which moisture was available was nearly identical on all soils. Plotting of soil moisture according to tension on semi-logarithmic paper illustrated nearly linear functions, and the curves were nearly parallel for all soils. Four points were plotted on each soil, i. e. one-third, three, five, and 15 atmospheres. All soils tested appeared to have approximately 11-14 percent moisture content available between one-third and 15 atmospheres based on dry weight of the soil. The absolute quantity of moisture available in this range of tension was not so consistent as measured with standard apparatus. Large variations in bulk density from 0. 9 to 1. 8 from one type of soil to another caused substantial variability in the laboratory estimates of absolute moisture holding capacity.

Soil moisture tension analyses appeared to have limited value in this study. While the pressure membrane samples initially taken showed a very distinct parallel range of availability for all soils, the same situation apparently did not prevail with undisturbed soils. While the bedrock of decomposing basalt would appear to have a large capacity for moisture storage according to the bulk samples taken and screened, the undisturbed samples appeared to have a much smaller storage capacity. Striking differences were observed both at one-third and 15 atmospheres. Soil moisture tension curves as derived on the pressure membrane or pressure plate with bulk soil samples screened for two-millimeters-plus fractions proved the most nearly consistent with biological drying curves derived from field measurements. Analyses of undisturbed cores and undisturbed clods gave ranges of available moisture equivalent to about half that of the bulk samples, or less. Indeed, the bulk samples indicated a smaller range of available moisture than was indicated by soil moisture field measurements.

In view of the difficulties arising in the use of the normal moisture-tension analyses, the drying curves of Penka were used to illustrate field capacity and permanent wilting point (76). The permanent wilting point was represented in Penka's work by the horizontal portion of the drying curve. In the sampling scheme used in this study, horizontal curves prevailed at nine-to-twelve inch depths in all fully-vegetated sample plots. Shallower horizons continued to show some drying tendency, but the point at which moisture fell below that of comparable but deeper soils which showed little change was taken to be the permanent wilting percentage. In the statistical equation handling a prediction of moisture depletion by a given amount of vegetation, limits were placed on the equation by entering the permanent wilting percentage of all the soils. In this way vegetation influence was not extended beyond the range in which vegetation is readily able to extract moisture.

Vegetation Analysis. In view of the objective of determining the relationship between vegetation density and soil moisture use, the aerial spray treatment rates were not considered as an independent variable. The local vegetation resulting from the spray treatments was considered more descriptive of factors conditioning the responses under study.

Analysis of the vegetation was accomplished with a point frame. The instrument consisted of a row of ten spring-loaded pins which could be lowered into the ground at roughly four-inch intervals along a straight line. The pins were sharpened at the lower end so that depression of a pin would carry the point in a line extending to the ground. The frame was oriented at an angle of 45 degrees with the ground so that any point have an equal chance of recording a hit on either a vertical or horizontal plant part (Figure 3).

At each sampling point 40 frame sets were recorded in a systematic pattern in an area 20 feet square, with the plot center as the base point for soil moisture sampling. Correlations of actual

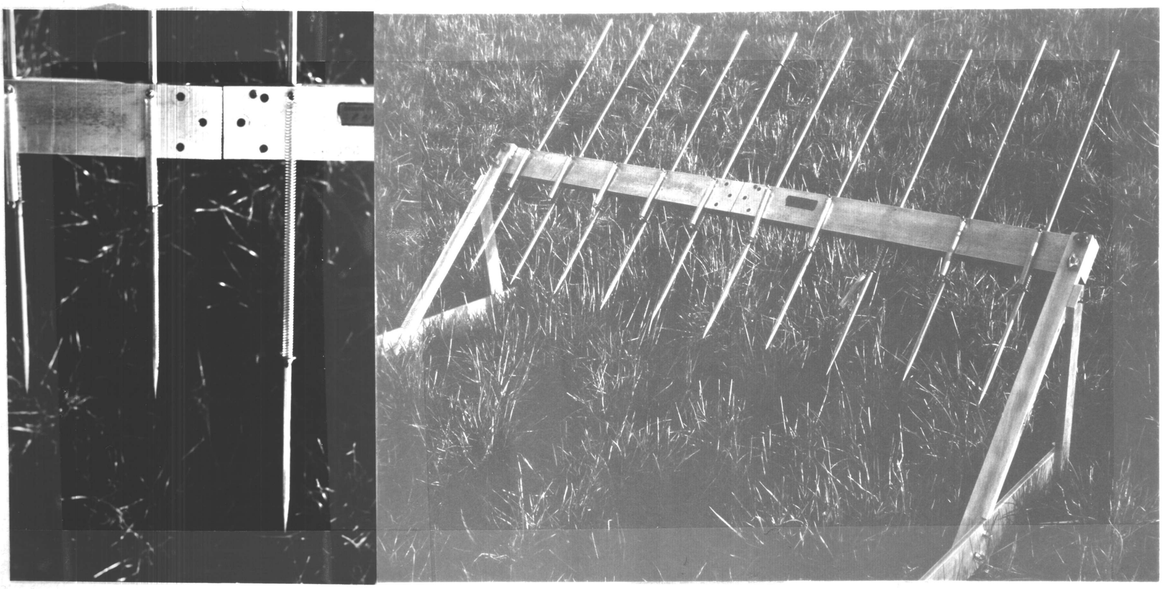

Figure 3. Point frame used for the vegetation analysis.

vegetation harvest amount, in grams dry weight per point-frame hit, were recorded in vegetation adjacent to 30 plots, but not within the area of influence of moisture sampling plots. The harvest correlations consisted of a point-frame sampling with ten systematically located settings within 1/10,000-acre plots. After recording the number of hits in each class of vegetation, all live vegetation, including the dead portions, was harvested, dried and weighed. The harvest data were related to the point frame hits according to the classes of vegetation hit by the point-frame and their frequency of occurrence. Initially, seven classes of vegetation were distinguished. However, upon examination of the raw point-frame data, it was found that, for purposes of yield estimation, the plant species could be grouped into two classes according to Table 1.

Table 1. Classes of vegetation used in analysis of herbaceous vegetation density. By species, in order of abundance.

Perennial bunch grasses	Annual grasses and forbs
Danthonia californica	Bromus carinatus
Poa spp.	Elymus caput-medusae
Elymus glaucus	Torilis nodosa
Dactylis glomerata	Bromus rigidus
Festucca rubra	Plantago lanceolata
Koeleria cristata	Daucus carota
	Cynosurus echinatus
	Prunella vulgaris
	Hypochaeris radicata
	Sherardia spp.
	Madia gracilis
	Delphinium menziesii
	Grindelia nana

While the plants grouped together here have little in common except as they are related to the ratio of hits to yield, the grouping was considered justifiable in view of the increased simplicity of yield prediction.

The yield equation used for the vegetation estimates for the moisture sampling plots predicted vegetation yield thus:

$$y = 3.229 + 0.511P + 0.452A - 0.00128P^2 + 0.00531A^2 + 0.0142AP$$

(Equation 1)

when:

y = predicted yield per acre x 10^{-4}, in grams

A = number of hits per hundred points on single-stem grasses and forbs

P = number of hits per hundred points on bunch grasses.

This equation provided an explanation for 98.2 percent of the variation in yields on the harvest correlations, hence was considered a reliable predictor for estimating vegetation density for the habitat influence study. Figure 3a illustrates predicted yields according to the above equation.

The use of this technique for measuring the vegetation provided a rapid method for obtaining a large number of observations pertaining to yield, and had the additional benefit of not disturbing the vegetation whose influence was to be studied. Inasmuch as the vegetation was measured only when nearly mature, and did not account for the

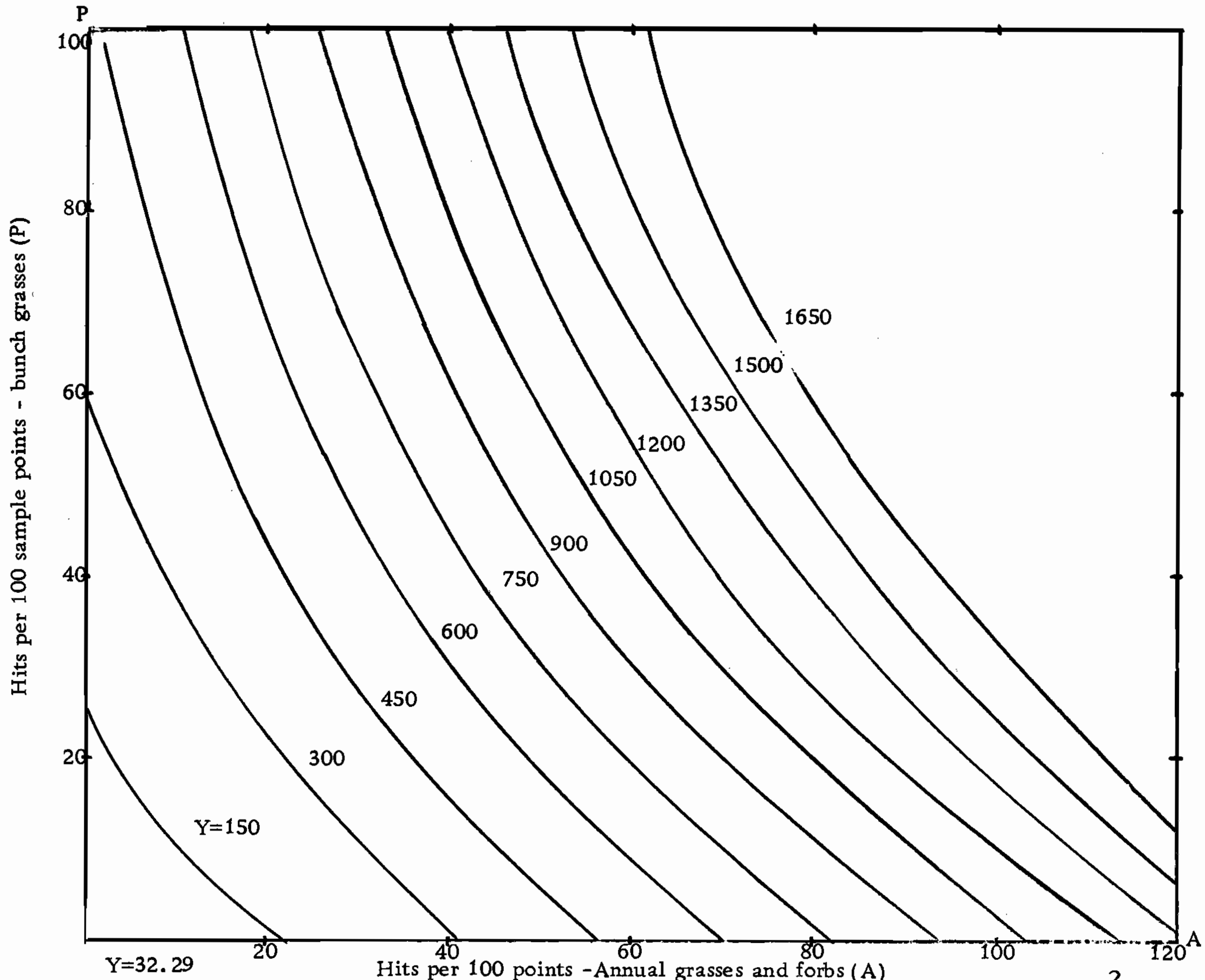

Figure 3a. Graph of equation: $Y = 32.29 + 4.52A + .0531A^2 + 5.11P - .0128P^2 + .142AP$. Lines of equal yield predict harvested weight of living vegetation. Based on relative occurrence of any plant part at a given point. Point frame oriented at 45 degrees. Vegetation classes according to Table 1.

stage of growth, periodic observations were made to follow development of vegetation by class according to seasonal changes.

Stages of growth were given a number rating (Table 9, Appendix) to provide relative quantitative estimates of the amount of each category of plants transpiring at any time based on the one vegetation analysis. The density of vegetation was assumed to have remained roughly proportional within classes during the various sampling periods, so that the basic quantitative measurements would be relatively the same over all plots throughout the sampling period. While this assumption later appeared to be only partly valid, the bias introduced is probably of little significance in habitat estimates.

The yield estimates on the 52 observation plots ranged from 36 to 1,510 kilograms per acre, representing the full range of vegetation conditions likely to be encountered in comparable grass-weed control projects. The procedure of 400 sample points on each plot, instead of 100 points, was adopted when it was found that moving from plot to plot was the major time component of the measuring job, and the error of estimate was reduced by 50 percent.

Conifer Plantations as Environmental Indicators. Fifty Douglas-fir seedlings from two seed sources were planted at each of the 48 sample points within the aerial spray treatment area before spraying. Half were of Vancouver Island seed source, and half of Corvallis origin. After treatment, 100 seedlings each of ponderosa pine, lodgepole pine, *Pinus contorta*, and Monterey pine, *Pinus radiata*, were planted across the treatment plots so that some seedlings of each species were represented in each treatment. In view of the lack of precise vegetation data in the vicinity of the pines, quantitative information was not gathered pertaining to seedling behavior as the function of vegetation control. Moreover, Monterey pine seedlings soon developed frost-damage symptoms, with 97 percent mortality within 30 days of planting.

Initially it was expected that some differences would become apparent between Douglas-fir seed sources regarding ability to utilize improved habitat. These differences, if any, were ultimately masked by other factors, largely heat and herbicide damage, and the value of the Douglas-fir plantations for tests of genetic differences or as indicators of environment was virtually eliminated.

Derivation of Observations Used in Statistical Analysis

When preliminary analyses of the experimental data failed to demonstrate a clear relationship between soil moisture depletion rate and vegetation density, it was determined that other sources of variation should be tested so that the main independent variable, vegetation density, could explain a significant portion of the residual variation in moisture conditions.

Moisture Loss per Day. The absolute water loss per day was calculated for each sampling point, for each time interval and for all depths. Each sample point was visited at weekly intervals during the period of rapid drying, followed by somewhat longer intervals during the dryer part of the season when less change would be expected. After conversion to absolute moisture loss per day, the loss per day was expressed as the function of vegetation density. The low simple correlation in this relationship further verified the need for qualifying parameters which would enable the prediction of a more accurate estimate of soil moisture content based on time of year and vegetation density. The following sources of variation will be discussed separately as they are handled in the statistical analyses.

Meteorological Data. Potential open-pan evaporation estimates were based on data from the Corvallis College Station (103). Open-pan evaporation, expressed in inches per day, was felt to be the best indicator of combined relative humidity and temperature. Gross incoming solar radiation, as recorded on an Eppley pyroheliometer, was expressed in langleys per day. Evaporation and radiation data used in this study were daily averages derived from totals for the periods between sample dates.

Precipitation per day was determined in four standard rain gauges placed systematically within the experimental area. Rain gauges were checked after each storm; the precipitation per day used in the experimental data was derived from the total amount of rainfall between observations. The time-lapse since the last rainfall equal to or greater than 0. 25 inches is expressed in days. The precipitation record is described in Table 5, Appendix.

Soil Depth. Soil-depth observations represent the average of several measurements to bedrock or 36 inches at each sample point. Soil data is summarized in Table 6, Appendix.

Drainage. Estimates of drainage class were made subjectively. During the first growing season following treatment, and also in the beginning of the second season, it was noticed that vegetation development in the vicinity of some of the sample-points was atypical. The apparent abundance of moisture in these locations, combined with the local development of vegetation, led to the assumption that moisture movement in the areas or through them was contributing to vegetation development beyond the normal expectation.

After the onset of fall rains it was noted that in certain of the plots water was apparently perched on a dense clay horizon which was restricting drainage and directing the flow of water through the soil in the depth zone of nine to 15 inches. On other plots it was noted that while drainage was apparently satisfactory, there was evidence of unsaturated flow from adjacent plots where low vegetation density had retained moisture which was still present at low tension, and apparently able to move relatively readily through the unsaturated profile. Many plots were not under the influence of either of these conditions, and were typical of well-drained upland conditions. Three plots had been subjected to considerable gopher activity and had been exposed to atypical aeration, hence had dried out prematurely.

On the basis of these groups as determined by field examination, and from the observation of the moisture depletion curves, the plots were grouped into four drainage classes according to Table 2.

Table 2. Soil conditions associated with drainage classes.

Drainage Class	Soil Condition
1	Soil with evidence of clay pan, or located in concave, base of slope. Poor drainage.
2	Soil downslope from devegetated plot, or adjacent to poorly-drained soil.
3	No source of later moisture movement. Well-drained, average conditions.
4	Soil disturbed by gopher or vehicle activity, causing atypical ventilation.

STATISTICAL ANALYSIS

While field measurements of soil moisture extended from April to October, 1962, those observations which were apparently meaningful from the standpoint of seedling environment were those which began at the time measurements indicated drying rates exceeding those of replenishment from precipitation. Preliminary analyses of the observations indicated that no significant rate of drying was occurring after June 23, hence this was the last period of observation generally used for the statistical analysis; observations in one soil depth were analyzed through August 10 for verification. Observations taken later in the summer illustrated rapid recharge rates with the onset of fall rains, but these changes would not be expected to influence the observable vigor of seedlings. The last effective rain occurred on May 17 as evidenced by the onset of drying between May 12 and May 19, 1962. Moisture observations from weekly sampling through June 23 constituted the main series of data for analysis. During the summer, moisture samples at three additional dates, July 7, July 21, and August 10 were analyzed to verify rates of change. At each sampling, a total of 208 observations were recorded on the 52 sample points at four depths. The total number of observations during this period was

2,080, of which 1404 were used for statistical analyses. The observations from the surface three inches of soil were not analyzed here, due to moisture changes too rapid to be properly described by weekly sampling. An International Business Machines 1620 computer was used to analyze the data with a standard multiple regression stepwise program. The stepwise regression program processed the data so that the machine output included the sums of squares and cross products, standard deviations of each variable, averages of each variable, correlation matrix, and test of the effects of the independent variables on the dependent variable. The latter was computed in steps, so that the variable explaining the greatest percentage of total variation was tested by itself, followed by a test of the most important two variables, and so on, until all variables were expressed in the final output of each analysis. Combinations of variables and ratios were processed as single variables.

Complete analyses of the data were made from two distinct approaches. For estimates under local conditions the model given in Equation 2 predicted available moisture on any given date on the basis of vegetation and soil characteristics. From a conceptual standpoint Equation 3 was more meaningful, but far more complex. This model related the loss of moisture from different horizons of the soil to the amount and composition of vegetation, as qualified by environmental conditions and time of exposure, expressed here as the function of date. The following discussion describes the mechanics of both types of analysis, with the advantages and limitations of each.

Available Moisture According to Date and Vegetation

This analysis had the advantage of simplicity and local applicability under field conditions. After a substantial number of trial-run analyses, it was concluded that the most important variables for explaining the amount of moisture at any given date were, in order of importance, the ratio of vegetation density to soil depth, vegetation only, expressed in kilograms of dry weight per acre; soil drainage class; and the interaction of vegetation and soil moisture drainage. The data was segregated into 52-observation groups, representing each soil depth within each date. For each date and soil depth, soil moisture was predicted according to the equation:

$$Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4 \qquad \text{(Equation 2)}$$

When: Y = Moisture available, percent by volume

B_0 = constant term

X_1 = vegetation kilograms/acre

X_2 = drainage class

X_3 = vegetation/soil depth in inches

X_4 = vegetation x drainage class

This equation explained up to 67 percent of the variation in observed moisture content, depending on the range of conditions encountered.

Before the onset of drying, the vegetation effect did not have a significant influence, hence it is to be expected that this expression would predict most accurately during the period of rapid drying, when the vegetation effect is greatest and when the greatest range of residual moisture occurs.

Moisture Loss per Day

In contrast to the above analysis, the expression of moisture loss per day at any time, based on a single equation, required variables which qualified the moisture loss at any given date, as well as those which qualified the site and vegetation. The result is a more complex equation, as seen thus:

$$Y=B_0+B_1X_1+B_2X_2+B_3X_3+B_4X_4+B_5X_5+B_6X_6+B_7X_7+B_8X_8 \quad \text{(Equation 3)}$$

When: Y = soil moisture loss per day, percent by volume

B_0 = constant term

X_1 = $(\text{date})^2$ x vegetation kilograms/acre

X_2 = vegetation x moisture available, percent by volume

X_3 = $(\text{date})^3$

X_4 = (vegetation/soil depth) x evaporation x drainage

X_5 = vegetation x moisture available x evaporation

X_6 = vegetation x composition (percent annuals)

X_7 = $(\text{days since precipitation} \geq 0.25 \text{ inches})^2$

X_8 = vegetation

This equation predicts the rate of moisture loss at any or all depths under a variety of conditions before the conditions occur, while Equation 2 is subject to climatic influence of unknown quantity. The above model represents the best fit of a large number of combinations of variables that were tested. In view of the subjectivity of the selection of variables from each analysis, and possible chance in selecting some variables which fit the data due to chance, the final equation given above should be regarded as descriptive, and not as a test of significance of any specific variable.

In stepwise multiple regression analyses, if one factor explains some of the variation already explained by another, the less important of the two will be relegated to a much lower order of importance if judged only by the "T" ratio. Examination of the correlation matrix illustrated the importance of each of the variables expressed in the above equation. The correlation matrix for the six-to-nine inch soil depth for the period May 12 to June 23 is given in the Appendix, Table 7. Equation 3 was derived from step eight of a 14-step analysis.

It is of interest to compare the results of the equation cited above with that of the data when segregated by date and fitted to the following:

$$Y=B_0+B_1X_1+B_2X_2+B_3X_3+B_4X_4+B_5X_5+B_6X_6+B_7X_7+B_8X_8+B_9X_9$$

(Equation 4)

When: Y = soil moisture loss per day, percent by volume

B_0 = constant term

X_1 = vegetation x moisture available, percent by volume

X_2 = vegetation x drainage

X_3 = $(\text{vegetation})^2$

X_4 = drainage

X_5 = moisture available, percent by volume

X_6 = vegetation x composition factor (percent annuals)

X_7 = vegetation $\div$ soil depth

X_8 = vegetation

X_9 = $(\text{moisture available})^2$

While the above equation very closely predicts the rate of moisture loss on the individual dates of rapid drying, it fails to predict more closely than Equation 3 the amount of moisture actually lost over an extended period when one plot is followed through several weeks' predictions in sequence (Table 3).

Table 3. Examples of soil moisture loss per day and predicted residual available moisture when: (a) moisture loss is predicted in one equation for the entire period, and (b) when moisture loss is calculated for each date. (Equations 3 and 4).

	Plot 1902 - 1510 Kg/Acre 9-12 inch depth					Plot 2301 - 62 Kg/Acre 9-12 inch depth				
	Equation (3) a.		Equation (4) b.		Actual moist. avail. % vol.	Equation (3) a.		Equation (4) b.		Actual moisture available
Date	Predicted loss/day of moisture % by vol.	Predicted available residual moisture % by vol.	Predicted moisture loss by date % by vol. (da)	Predicted available % vol. moisture by date		Predicted loss/day % by vol.	Predicted resid. available moisture % vol.	Predicted moisture loss by date % by vol.	Predicted available by date % vol.	
May 12	.3331	20.28	-.2991	20.28	21.71	-.1034	17.32	-.1251	17.32	15.24
May 19	.4687	17.00	1.0354	13.03	14.82	-.0204	17.46	.3141	15.11	13.80
May 26	.6151	12.70	.5862	8.93	11.83	.1776	16.22	-.2351	16.76	12.00
Jun 10	.2675	8.96	.3982	6.14	6.63	.2563	19.81	.0362	16.51	13.56
Jun 16	.3951	6.40	.8893	.02	3.12	.1554	18.72	-.0807	17.07	10.92
Jun 23	.7544	1.12	.1942	-1.34	1.72	.3645	16.17	.5126	13.48	10.85

RESULTS

In all approaches to the fitting of field data to the above models, it was apparent that vegetation has a very strong influence on the rate of moisture loss, and that there is striking moisture conservation from the complete removal of vegetation. Figure 4 illustrates the predicted moisture available at three soil depths as the function of time, with the vegetation influence removed. This figure reveals the moisture conservation in the absence of vegetation, and the moisture gradient with depth. Figure 5 illustrates the predicted moisture available within the three-to-12 inch soil depth as the function of date and vegetation, while Figures 6 and 7 illustrate the parallel depletion rates to 36 inches when the soil profile is fully occupied by roots.

Vapor Pressure Gradient

Without specific measurements of relative humidity in the soil, there is indirect evidence in the study of the distance through which vapor pressure gradients are effective in moisture loss from the soil. Figure 4 illustrates the differences in predicted available soil moisture in three soil zones when evaporation is the only source of

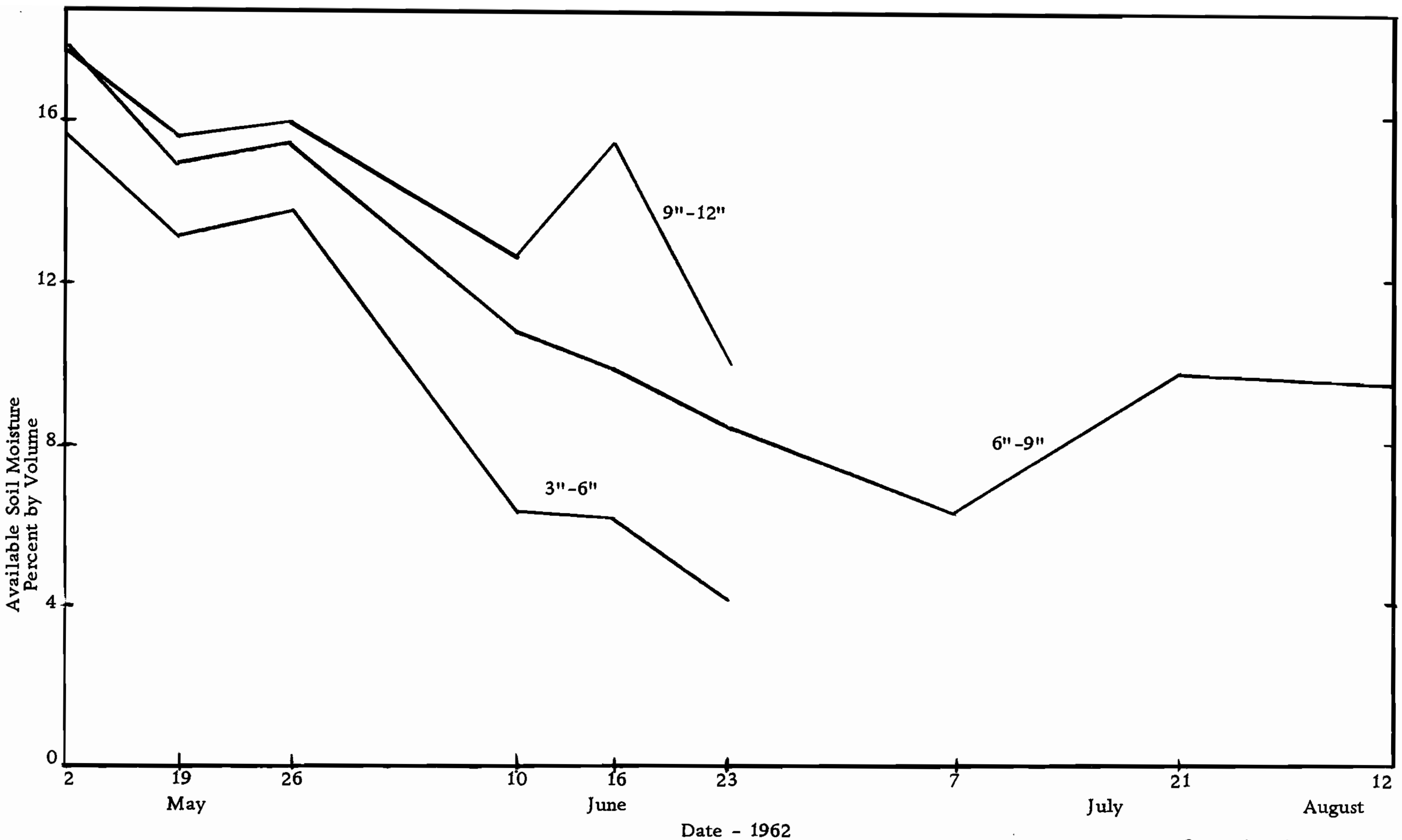

Figure 4. Predicted available moisture with complete vegetation control @ 3-6, 6-9, and 9-12-inch depths in well-drained soil.

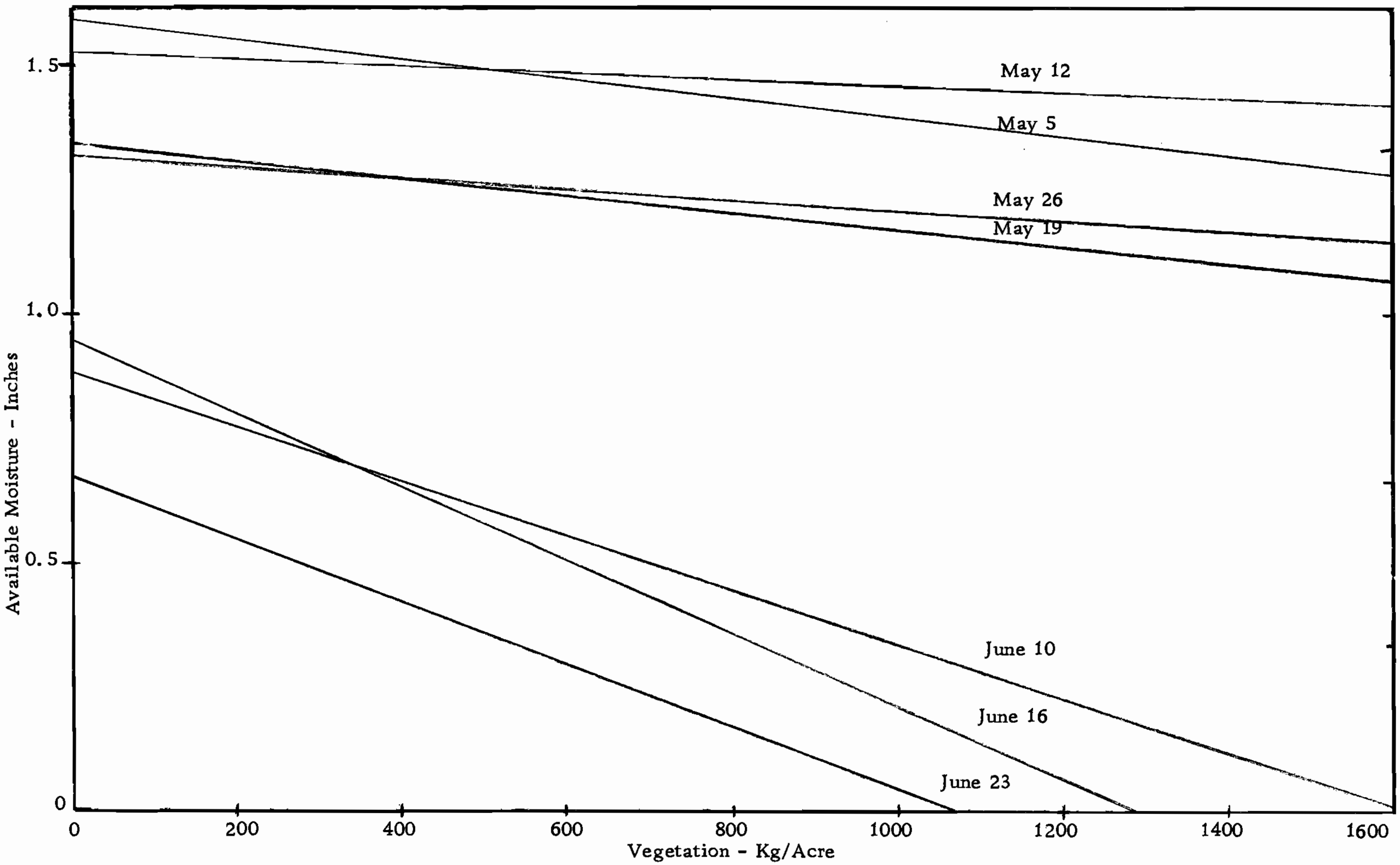

Figure 5. Available soil moisture, in inches, in the 3-12 inch zone of soil as the function of vegetation and date. 1092 observations.

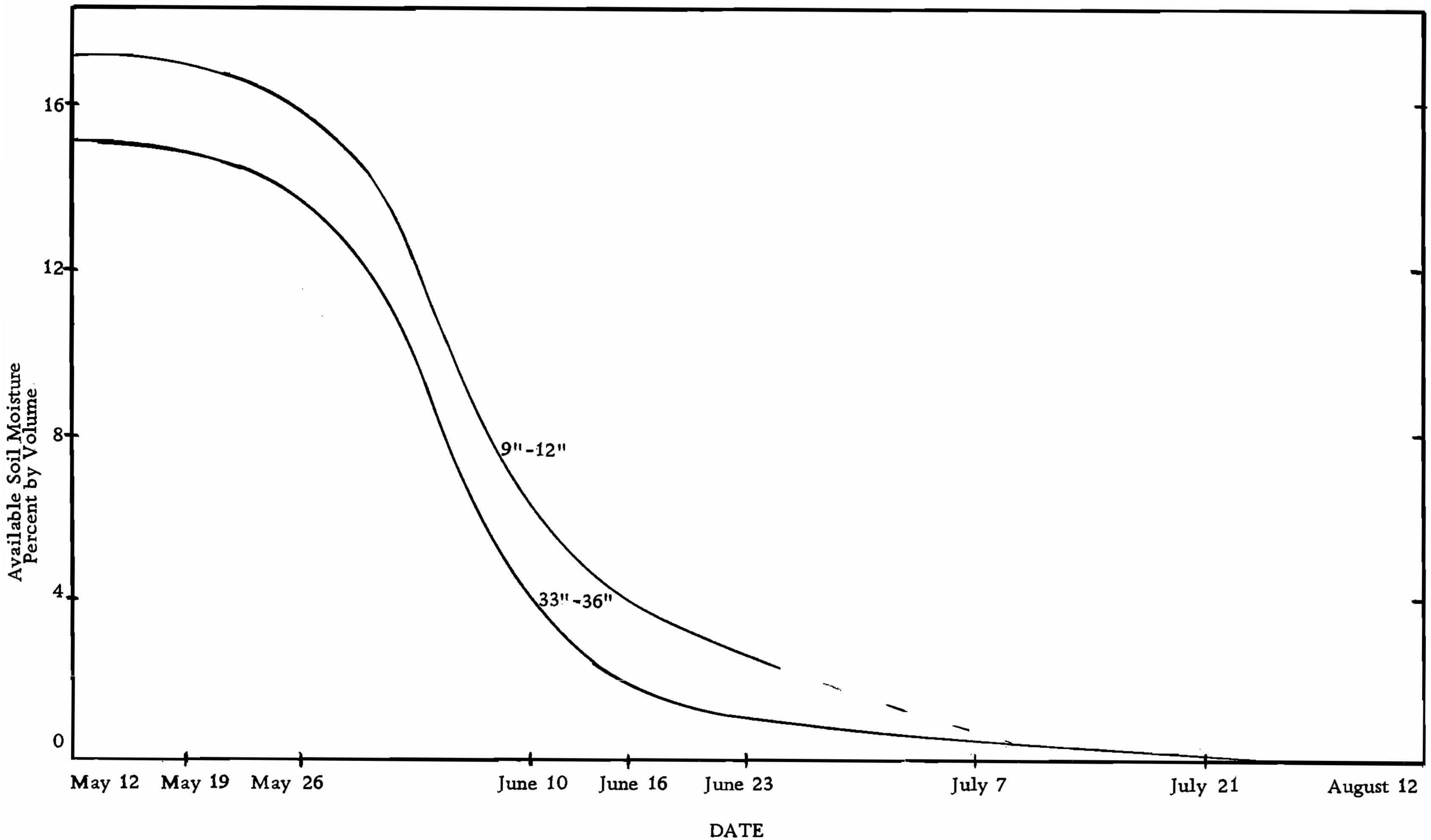

Figure 6. Available soil moisture depletion at the 9-12 and 33-36 inch depths in untreated vegetation. Average of four plots ranging from 808-1510 kg/Acre.

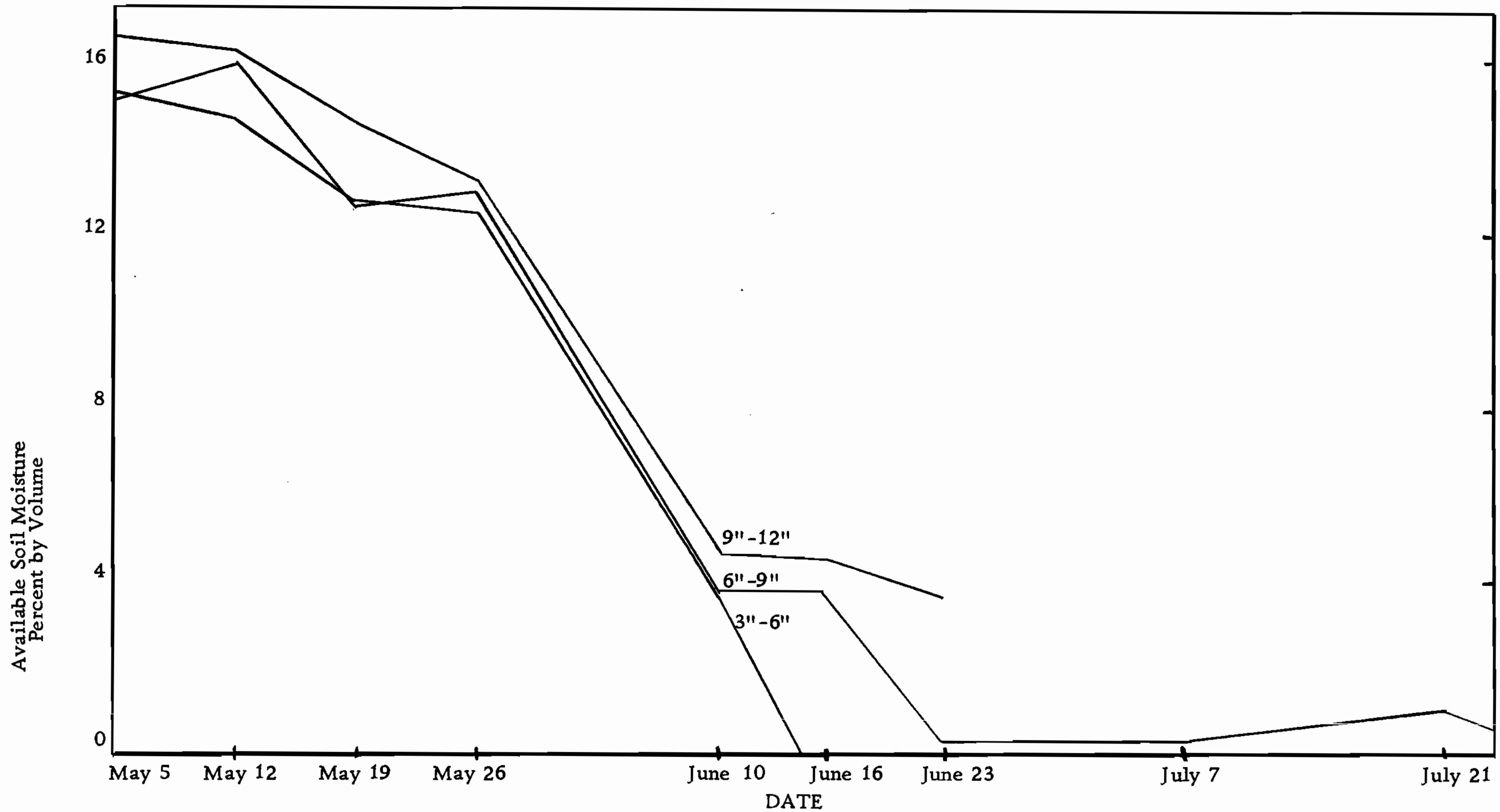

Figure 7. Predicted available moisture, percent by volume at three soil depths under the influence of 1000 Kg per acre of vegetation. Statistical predictions based on 1208 observations. 9"-12" data incomplete after June 23.

loss. Extension of the six-to-nine inch depth predictions illustrates that little further loss of moisture can be expected after June 23. The other zones were not analyzed statistically, but appeared consistent in the empirical plotting of field data. The static situation during the summer in which no further evaporation occurs is considered evidence for an equilibrium situation in which the moisture tension-forces balance the vapor pressure gradient. In view of the relatively great amount of moisture remaining in the nine-to-12 inch zone, it is speculated that the vapor pressure in this zone remains at close to saturation throughout the summer, but that there is considerable movement through the surface six inches as vapor or capillary translocation until the equilibrium point is reached below. The lack of evaporative moisture loss below 12 inches is consistent with the findings of Liacos (57). Rich, on the other hand, found in the southwest that the loss of moisture differed little between grass, brush, and bare soil (80). Presumably, his soils were sufficiently well aerated and supported light enough stands of vegetation that small vegetation effects would not be noted. Greater evaporative moisture losses in light-textured soils have been reported elsewhere (63).

Use of Moisture by Vegetation

It is of interest to note that all the functions of vegetation are linear in Equation 2 predicting the amount of moisture remaining at any time. The same regression equations were tested with the same variables plus the addition of the quadratic effect of vegetation, with the result that there was very little change in the shape of the curve, and the coefficient of determination was virtually unchanged.

The amount of available soil moisture did not express vegetation influence until after the cessation of effective rains. From May 19 to June 16 it will be noted that the vegetation effect increases (Figures 5 and 8). On June 16, the sites under heavy vegetation were virtually completely depleted of their available soil moisture. In view of the fact that these sites could no longer continue to lose moisture rapidly, through transpiration, it was to be expected that the vegetation effect would diminish after this point. This concept is illustrated to a slight degree in Figures 9, 10, and 11, in which the June 23 soil-moisture and vegetation relationship remains virtually unchanged after June 16.

Biological interpretation of the moisture equilibrium may give more insight as to environment during this period than statistical interpretation alone, since the range of available moisture subsequent to June 16 extended from readily-available moisture to the wilting point in any zone below six inches, depending upon the amount of vegetation which had acted upon the supply. Apparently, further loss is restricted by aestivation of perennials and mortality of annuals.

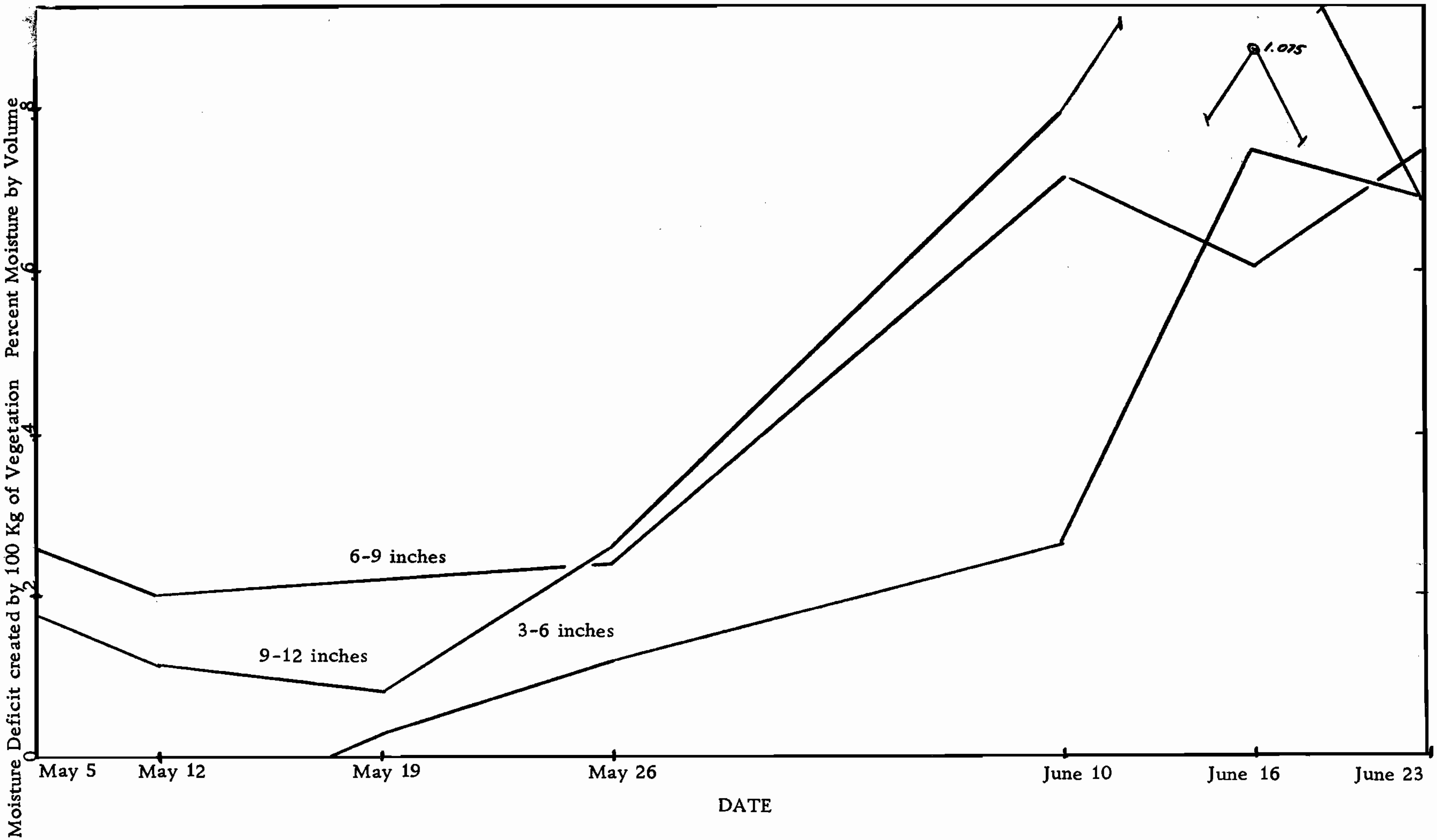

Figure 8. Relative effect of vegetation on moisture deficit by date and zone of sampling.

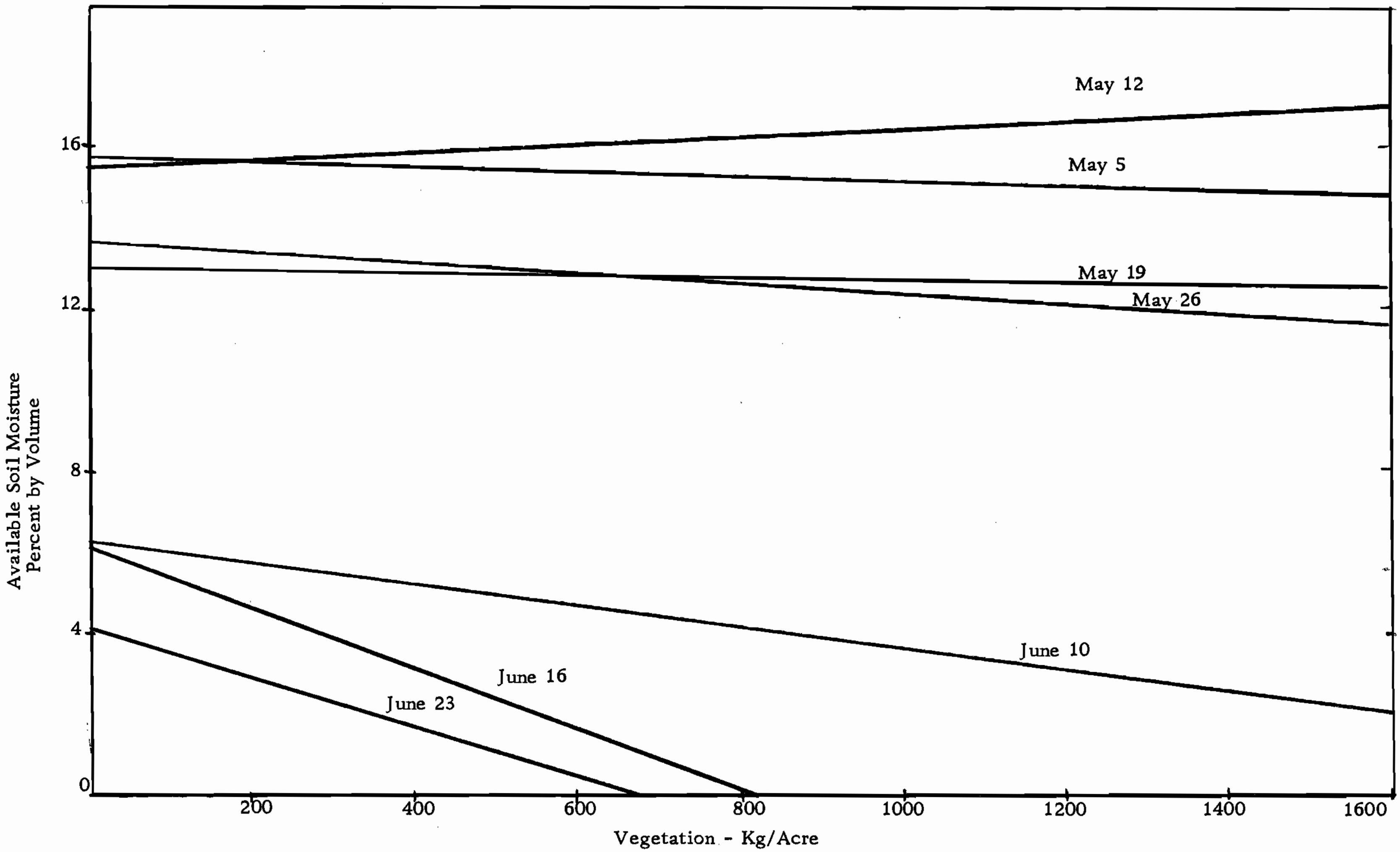

Figure 9. Available moisture in 3"-6" soil zone as the function of vegetation on well drained soil. Adjusted to 18" soil depth.

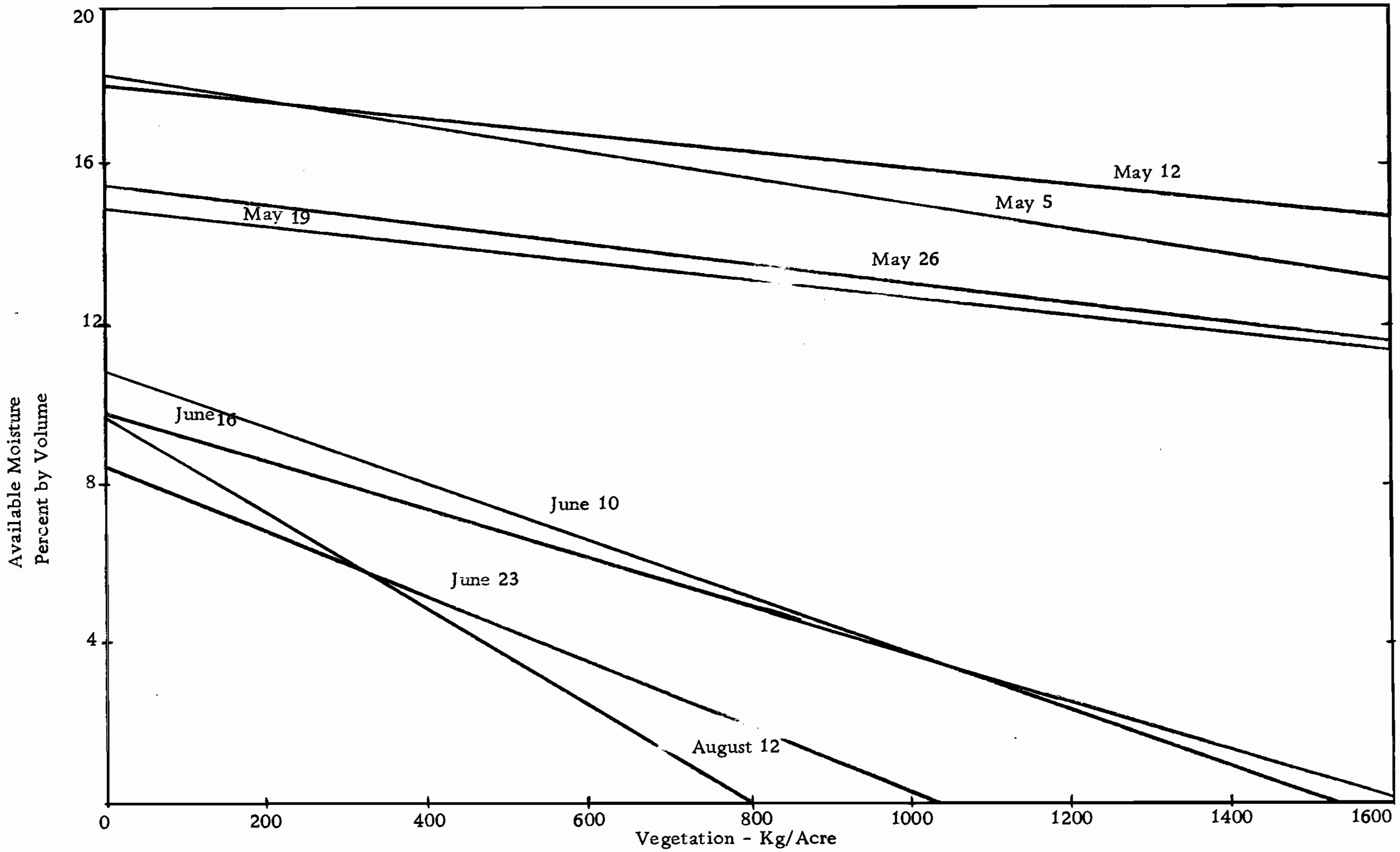

Figure 10. Available soil moisture in 6"-9" soil zone as the function of vegetation on well-drained soil. Adjusted to 18" soil depth.

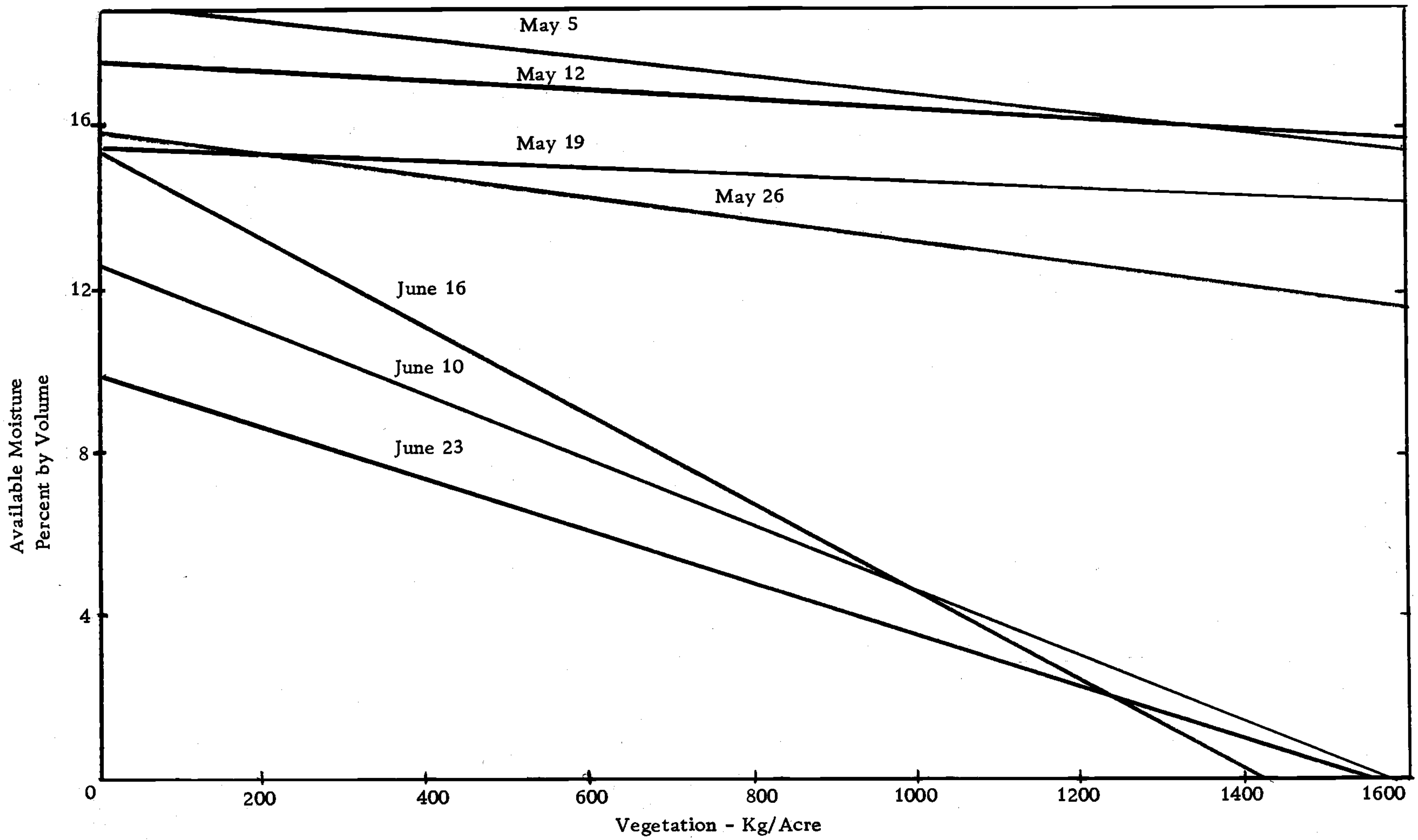

Figure 11. Predicted available moisture in 9"-12" soil zone as the function of vegetation on well-drained soil. Adjusted to 18" soil depth. Based on 311 observations.

The influence of vegetation on the moisture loss was necessarily qualified by several additional factors in Equations 3 and 4 to accommodate changes with time. It will also be noted that vegetation effect is further qualified by several interactions, and, with the confounding of vegetation composition with soil depth and drainage it is difficult to assign a precise quantitative value to each factor. The author suspects that the relationships could be derived from the field data used to verify these expressions, but time and computer funds limited efforts in this regard. It must be added further that the vegetation composition estimates used in these calculations were of the very crudest nature, separating all vegetation into two classes. Such an empirical separation would produce a vegetation composition influence which might be of doubtful ecological significance.

The use of moisture by vegetation was clearly influenced by the amount of moisture available, and this use was evidently curvilinear, although apparently not exponential. The relationships illustrated here are not strictly due to the ease with which moisture may be extracted by plants, since each of the observations pertaining to moisture loss was partly conditioned by the amount of moisture at the beginning of the sampling period, and hence is partly confounded with the sampling error. In view of the compensation of errors, however, this bias is not considered to be of major practical significance, yet the estimate must be interpreted with caution.

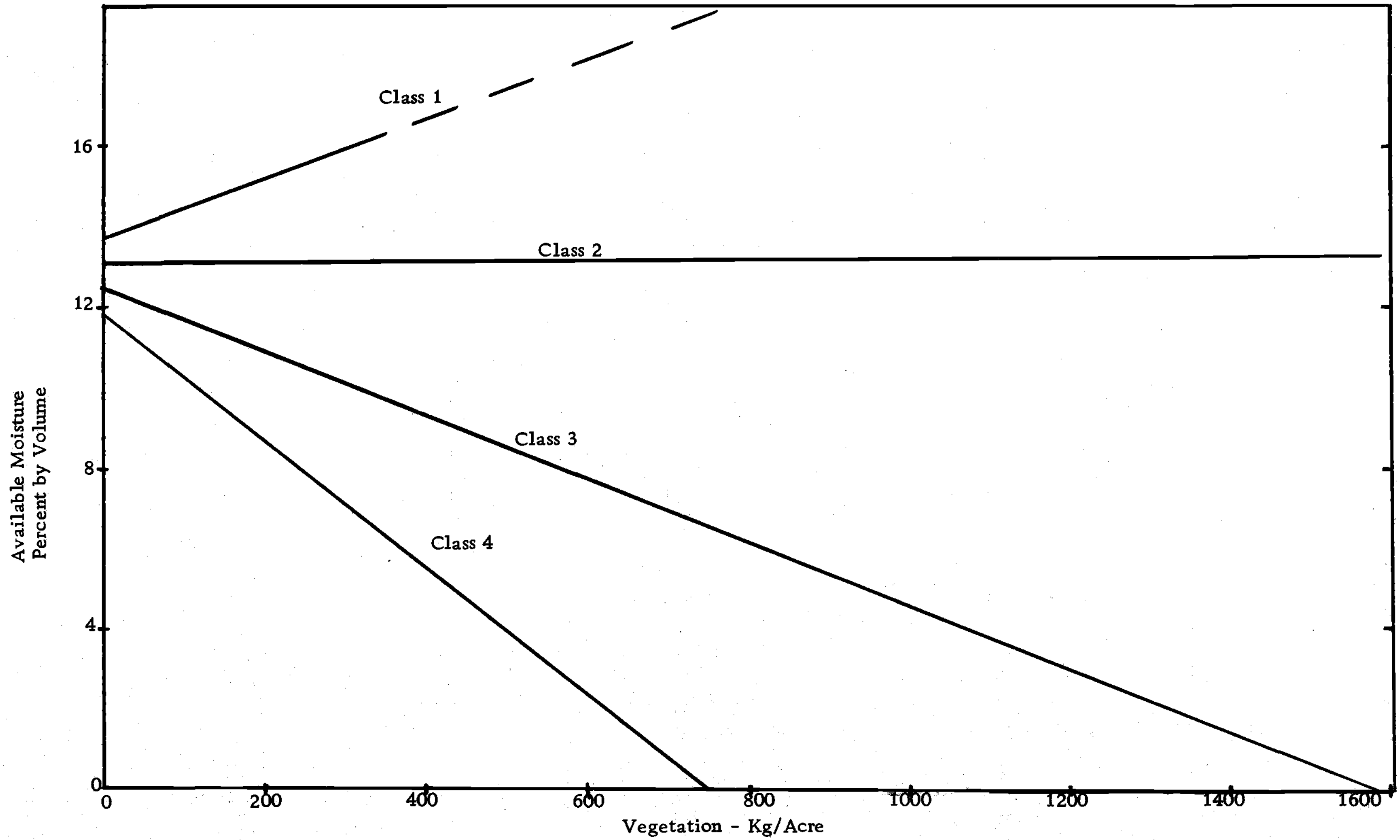

Figure 12. Predicted available moisture from 9"-12" as the function of vegetation and drainage. Adjusted to 18-inch soil depth. June 10 data. 156 observations.

The interaction of vegetation with drainage was used as an allowance for drainage problems, in which the vegetation influence could not be expected to manifest itself if the moisture supply were being replenished as fast as it had been removed. The expression of this interaction is made clear in Figure 12, in which it is illustrated that the moisture supply would be depleted in well-drained soils only in the nine-to-12 inch zone. The drainage effect is less pronounced closer to the surface. The increase in available moisture with increasing vegetation in Class 1 is considered to be a statistical artifact caused by a lack of observations in this class with high vegetation density.

The ratio of vegetation to soil depth was used to illustrate the influence of vegetation when considering the need to extract the entire moisture supply from a varying depth of soil. The effect of soil depth was much less than anticipated. Perhaps the reason is illustrated in Figure 6, page 57, which shows that the depletion rate in the 33 to 36 inch soil depth on fully vegetated plots proceeded at an identical rate to that from nine to 12 inches. The soils on which these observations were recorded ranged from seven to 15 inches in depth, and the observations all reflect the moisture depletion occurring in bedrock.

The curvilinear expression of vegetation influence varied with the approach used. In the prediction of the amount of moisture available for any given sampling period, the use of the curvilinear expression did little to improve the fit of the equation. Yet, in prediction of moisture loss as the function of vegetation, the quadratic effect was of greater importance. In view of the dependence of both equations on the same data, this difference is not fully understood, unless it is a statistical artifact which compensates for some other factor not considered in the equations. A slight negative quadratic effect might be expected to occur in the field, however, due to the limitations of fully-stocked stands of vegetation in utilizing the available solar energy at the same efficiency. Self-shading probably occurs, and full site utilization for some periods probably occurs with something less than the maximum density of stand. According to the concepts of Piemeissel and others (44; 79) better development of individual plants may occur in stands of lesser numbers of plants, although yield may not be considered.

The third-order interaction pertaining to vegetation x moisture availability x evaporation potential illustrates that the vegetation is dependent on the conditions influencing moisture vaporization in addition to requiring an abundant moisture supply for efficient utilization. This expression was consistently important in all preliminary equations relating the rate of moisture loss to different combinations of variables.

The use of the date in arriving at a moisture loss prediction equation substituted for a combination of radiation, evaporation, and precipitation, factors which are all interrelated, and have sigmoid changes with time, occurring at the same time. By the use of the linear, quadratic, and cubic functions of date, expressed as the number of days since the onset of the study, these variables were lumped into one expression which was very much easier to handle than the individual functions would have been. Moreover, the time of cessation of the rains, expressed as the number of days since rainfall $\geq$ 0.25 inches, was used in Equation 3 to account for the precise time of the onset of drying. The correlations between date and the changes in climatic variables are illustrated in Table 9, Appendix.

It was possible in Equation 2 to adjust drainage and soil depth to standard conditions to predict the influence of the vegetation under any fixed set of conditions (Figures 4, 9, 10, and 11, pages 55, 58, 59, 60). These data illustrate the consistent pattern of vegetation effect on the moisture supply, and further illustrate the usefulness of the model in estimating potential conservation of moisture with manipulation of the vegetative cover.

The period of maximum moisture loss occurred between May 26 and June 16, during which 85 percent of the moisture depletion from the top 36 inches of soil occurred, or 5.1 inches. This depletion was associated with a total of 13,279 gram calories per square centimeter of gross incoming radiation. Clouds prevailed over much of the sky during this period, but the cover was high and generally light. The average gross incoming radiation recorded was 632 langleys per day, or 82.6 percent of a possible 777 langleys per day based on clear skies with low humidity. Following the estimates by Lowry (60) relative to net radiation, interpolated for 15 percent south slopes, 648 langleys net radiation per daytime period would have occurred under clear conditions, with a loss of 108 langleys as nighttime reradiation. If it may be assumed that the 82.6 percent sunshine observed here would also apply to net radiation, net incoming energy amounted to 9,193 gram calories per square centimeter during the 21-day period.

According to Lange (52), the heat of vaporization of water is 584.9 calories per gram at 20 degrees Centigrade. The vaporization of 5.1 inches of moisture would account for 7,577 calories per square centimeter, or 82.4 percent of the available energy. This figure is in very close agreement with the estimates of Graham and King pertaining to evapotranspiration from a corn crop (32).

Inasmuch as devegetated plots lost four-tenths of an inch of water during the same period, it is conclued that transpiration accounted for at least 92 percent of the moisture depletion during this period. Since the evaporation rate from the soil surface must have been reduced by the presence of the vegetation cover, it would appear that almost the entire input of net radiation which is utilized in evapotranspiration must act through plant systems. The difference between actual moisture loss and potential incoming energy would then be the function of the efficiency of plants as energy transfer media, which must be very close to 80 percent under these conditions.

Response of Conifer Plantations to Physical Factors

The survival of all species of planted conifers except Monterrey pine was recorded during June, prior to the expectation of any mortality due to drought or heat. All species appeared to be surviving well, but many of the Douglas-fir in areas of high rates of herbicide application had evidently suffered badly from the effects of amitrole. In general, those areas which had received sufficient chemical to give control of 70 percent of the vegetation had received a damaging rate for the Douglas-fir. Those seedlings on the areas receiving less chemical were also exposed to increasing drought conditions. The pines, planted after the application of the herbicide, did not show any signs of damage.

Despite the amitrole damage, some of the Douglas-fir seedlings appeared to manifest substantial ability to recover. On those plots where susceptible vegetation occurred which was readily controlled by low rates of herbicide, the Douglas-fir developed chlorotic foliage symptomatic of amitrole damage, but without obvious reduction in vigor. Soon after the initiation of terminal buds, these seedlings were observed to be vigorously second-flushing, with a high percentage of the seedlings showing lammas growth. These observations were terminated quite suddenly with the onset of a very severe heat wave. Nine consecutive days of 90-degrees plus temperatures were recorded during July 22-30. At the end of this period, nearly all the seedlings were dead. At the end of the growing season, 40 seedlings out of the original 2,400 remained; many of these displayed some partial heat lesions.

The cause of mortality in the Douglas-fir was assumed to be heat girdling. Seedlings were examined closely while the damage was occurring, and the collapse of phloem tissue at the root collar was observed and photographed. Unfortunately, the entire series of photographs was destroyed, but Figure 13, illustrating a freshly-killed seedling, shows the live root tissue ending immediately at the ground line. The phloem tissue in the top was still fresh, indicating localization of damage at the root collar.

The pine species appeared to be less sensitive to heat, and to benefit from moisture conservation. One hundred percent of the ponderosa pine seedlings were alive after two growing seasons. Seventy percent of the lodgepole pines were found, and it is suspected that some living seedlings were not found. Some animal damage was sustained by the lodgepole pine, which may have also contributed to

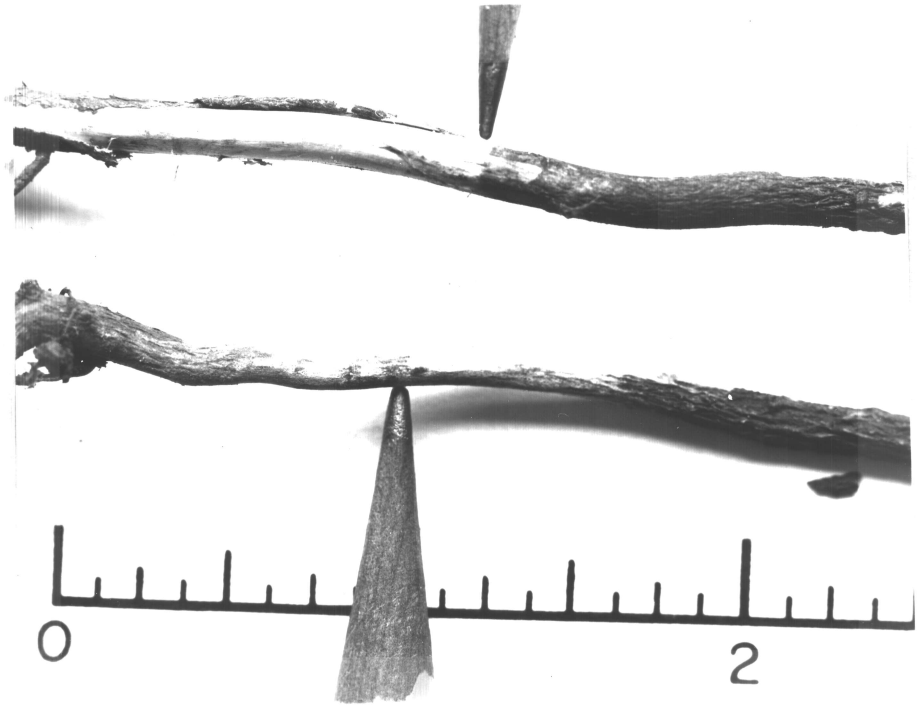

Figure 13. Photograph of heat-girdled seedling.

losses. The three Monterrey pines which were still alive one month after planting were all in good condition after two growing seasons, and were the largest seedling of any species.

Second-Year Verification of Concepts

In view of the seedling mortality which appeared independent of the drought, a series of plantations was established during the next growing season to further study the response of seedlings to a vegetation-free environment. Concurrent studies were made to evaluate several selective herbicides and a device for the protection of seedling root collars from heat damage.

Twenty one-quarter acre plots were treated with herbicides during December, 1962 and April, 1963. Rates of application of all chemicals were calculated to provide weed control at equal cost, such that moisture conservation per unit of cost could be evaluated. In each plot, 40 Douglas-fir 3-0 seedlings were planted, of which half were previously protected with a small band of asbestos paper around the root collar as described by Newton (70) (Figure 14).

Table 4 illustrates the success in habitat improvement conditioned by the use of atrazine[4/] and a mixture of amitrole and simazine. The survival recorded here is probably substantially less than

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[4/] 2-chloro-4-ethylamino-6-isopropylamino-s-triazine.

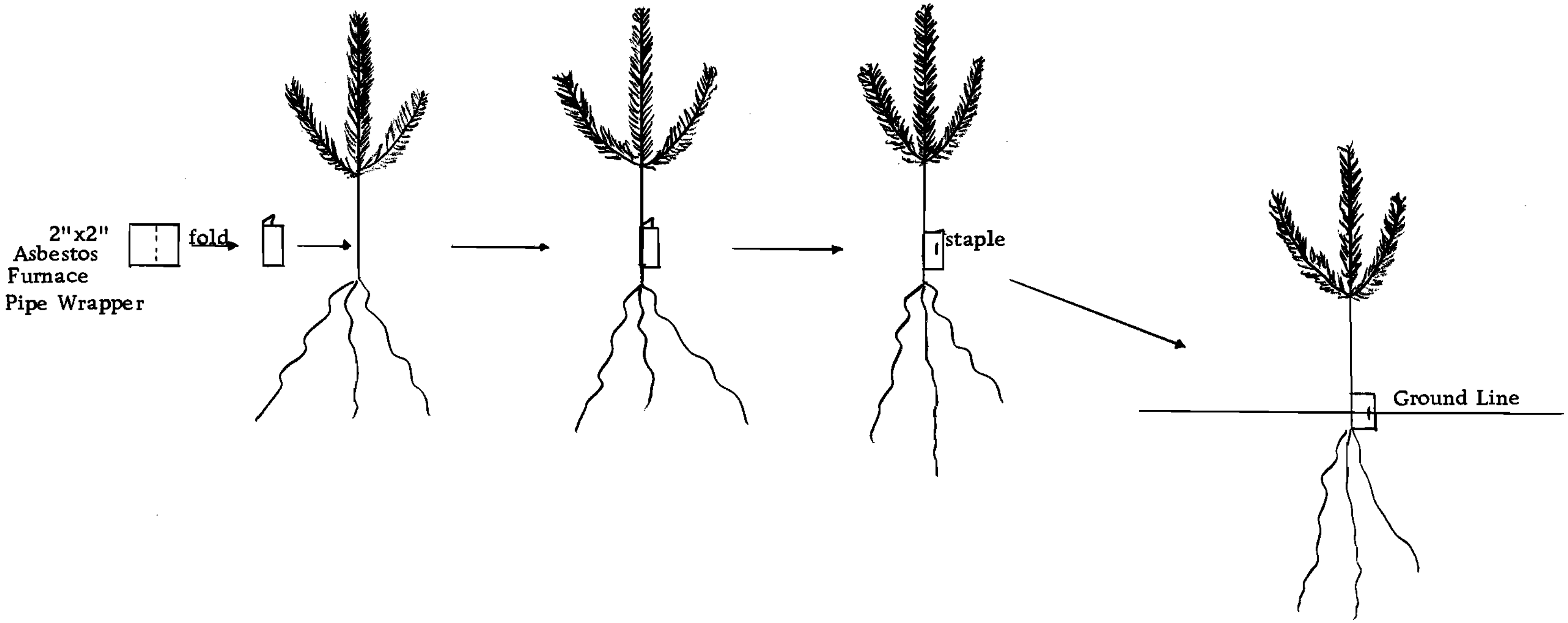

Figure 14. Asbestos protector for conifer seedlings. From Newton (70).

Table 4. First-year survival, in numbers of live seedlings, of Douglas-fir planted in plots treated with grass herbicides at two seasons. Seedlings planted before and after spraying on both dates. Half of seedlings protected with asbestos protectors.

Herbicide Treatment	Planted before spraying: Protected December	April	Planted before spraying: Unprotected December	April	Planted after spraying: Protected December	April	Planted after spraying: Unprotected December	April	Totals		
Isocil	4		3		5		7		19		
3 pounds		0		0		0		3		3	
per acre											22
Simazine	7		6		6		9		28		
5 pounds		6		5		10		4		25	
per acre											53
Atrazine	3		6		6		9		27		
5 pounds		6		15		14		11		51	
per acre											78
Amitrole-	8		9		10		13		40		
Simazine		9		8		16		13		46	
5 pounds											86
per acre	6		3		2		4		15		
None		0		3		4		8		15	
											30

Total survival:

Planted before versus after spraying:	113:156	Total trees planted:	800
Spring planted versus fall	140:129	Total survived	269
Protected versus unprotected	129:140	Percent survival - ave.	33.6
		Percent survival - best	80.0

might be expected under operational conditions due to skips in the spray patterns and spots of heavy vegetation in which much of the mortality occurred. As was expected, the use of amitrole on the foliage of the planted seedlings was detrimental, but atrazine produced no damage symptoms under any circumstances. Simazine by itself did not produce weed control consistent with the moisture conservation needs of the seedlings, and survival was not greatly improved. Isocil[5/] was evidently toxic to Douglas-fir, and mortality was greater than in the untreated plots. Differences between treatments were accentuated by evidence of interactions. Spring planting and spraying were apparently more favorable in the atrazine and amitrole-simazine plots, which were nearly devegetated. Fall spraying was less effective in controlling weeds, hence was associated with poorer survival. Seasonal influence was apparently reversed in plots treated with simazine, which produced better weed control with fall application, and in untreated plots. This is felt to be evidence that the season of planting diminishes in importance if moisture supplies are maintained. Temperature conditions during 1963 apparently did not reach damaging levels, hence the importance of the root collar protectors was not demonstrated. Statistical analyses were not complete at the date of the preparation of this thesis.

[5/] 3-isopropyl-5-bromo-6-methyluracil.

One of the salient features of this experiment was that the spring and summer of 1963 were considered as exceptionally favorable, yet the moisture economy of the plantation area of this study was virtually identical to that of the year before, and the untreated plantations were once more failures. In contrast to symptoms of moisture conditions in the control plots, the seedlings in vegetation-free environment once more illustrated the tendency to produce lammas shoots, and the foliage color and needle length suggested response to a soil release of nitrogen.

Pilot-size aerial applications of grass herbicide were undertaken by the Bureau of Land Management to verify these findings on a local basis in Salem, Roseburg, and Medford, Oregon. The herbicide, a mixture of amitrole and simazine, was applied at five pounds per acre, sufficient to provide 90 percent weed control or more, and plantations were set out immediately after application. In Medford, where ponderosa pine only was planted, plantation survival was nearly perfect. Vegetation control was sufficiently complete during early summer that cattle on open range avoided the 20-acre treatment area. Later in the summer, when surrounding range species had aestivated or wilted, recovery was beginning to manifest itself in the treated grass, and scattered lush bunches of grass appeared to attract cattle into the planted area. The cattle caused mortality of approximately 20 percent of the seedlings, largely through trampling. The check plantations were destroyed by road construction.

The Roseburg plantations were highly successful, with ponderosa pine having survival of 96 percent, Douglas-fir with asbestos collars 79 percent, and Douglas-fir without collars 84 percent. Salem survival figures were rendered useless by sheep trespass, with severe browsing damage as well as trampling. However, survival was known to be good, with the seedlings in apparently vigorous condition at the time of the sheep damage.

In view of the past history of at least three plantation failures on each of the sites selected for the pilot aerial treatments, the success of these applications was considered excellent. Further verification is necessary under conditions generally less favorable to seedlings.

DISCUSSION

Influence of Vegetation on Habitat

The overall relationship of water use to vegetation density is a factor of great importance in the establishment of conifer seedlings. The quantitative expression derived in this study between moisture loss and vegetation density gives a predictive index of moisture use that must be qualified by a number of considerations. The very fact that it was necessary to use so many variables in the statistical analysis is evidence of the complex nature of the environmental conditions being predicted, hence field use of the mathematical approach used in this study may be impractical. Perhaps it is most significant that any of the models herein presented will predict that a full stand of vegetation will deplete the moisture within a certain period after cessation of effective rains, depending upon growing conditions. Partial and late-developing stands, on the other hand, may deplete the entire available moisture supply, but they may do so at a time when seedling moisture requirements are no longer critical. Perhaps the greatest practical significance of this study is the point that the moisture will be rapidly depleted by a fully-stocked stand of living vegetation in a sunny climate. Chemical manipulation of this type of vegetation will prevent the loss of the moisture due to transpiration, making the moisture available for crop-plant use and lateral drainage. Variability of results with chemicals would tend to render of minor significance the precise estimation of the vegetation which would be acceptable for successful stocking with conifers, and which should be used as a basis for projecting herbicide use. In view of the small difference in cost between the lower rates of application which would produce acceptable control under optimal conditions, and heavier application rates which would produce acceptable control under more difficult conditions, higher rates would probably be justified simply in order to minimize the element of risk. On the other hand, the above simplification of the mathematical presentation is by no means meant to construe that the various factors in the prediction equations are of no importance.

The Influence of Moisture in the Environment of Douglas-fir Seedlings

It has been observed on a number of occasions that freshly planted seedlings burst buds at an earlier date than those of natural origin, perhaps by as much as two weeks. Root development activity of freshly-planted seedlings has varied substantially from the time the seedlings were lifted from the nursery to the time at which they were planted. In view of the work of Lavender and Stone (56; 97) one can expect the root activity of the seedlings to commence before initiation of bud-bursting, and to diminish towards mid-summer corresponding to the termination of terminal growth. If, as found by Zinke (113), the zone of available moisture were to recede at a predictable and steady rate, perhaps the rapid initiation of root activity would enable seedlings to evade drought conditions. It was apparent in this study, however, that the herbaceous vegetation depleted the moisture in the entire profile at a uniform rate, and it appears unlikely that drought evasion could be a successful mechanism for survival under the full influence of herbaceous vegetation. On the other hand, it was evident that some modification of the physiological activity resulted from the conservation of moisture by vegetation control. In the untreated natural vegetation, terminal growth was initiated early and ceased approximately at the time soil moisture became difficultly available, about June 16. Seedlings in the treated plots initiated lammas growth and continued to develop with great vigor after the time that the trees in the untreated plots had terminated elongation. Tessier and Walters (101) associated similar Douglas-fir response with availability of moisture. Wenger and Lavender have also reported similar moisture responses in hardwood and conifer seedlings (55; 109).

During the period of maximum heat in midsummer, seedlings in control plots were observed to turn yellow, with substantial mortality taking place. In the vegetation-controlled plots, however, the vigorously growing seedlings that continued terminal growth long after moisture stresses had induced dormancy on control plots, were decimated by heat injury. It is difficult to say if this heat injury was restricted to the seedlings in the devegetated plots or if it was also prevalent on the seedlings in the untreated plots. The late-summer lammas growth may have increased the sensitivity of growing tissues to heat damage.

It was noted during examination of some seedling roots, before the heat-induced mortality, that there was apparently considerable root activity on the seedlings that were continuing to elongate in mid-summer. Moreover, the top-development of the seedlings with the appearance of nitrogen-response leads to speculation here that physiological response of the seedlings to a change of environment, is, in fact, a multiple response. It is felt that the terminal growth response and general increase in physiological vigor may be initiated concurrently with the continued root development resulting from available moisture combined with the reduced physical resistance of the moist soil. The increased root proliferation is speculated to be a geometric response, in which increased vigor results from root development which in turn stimulates greater general vigor. The similarity to nitrogen-response may be more than coincidental in view of the herbicide action of reducing the density and activity of the existing vegetation. The equilibration of the nutrient elements in such a partially-occupied site would tend to favor the more vigorously developing vegetation, in this case the conifers.

There is a very real practical significance to this response. In many old-field plantations, second-year mortality constitutes a large portion of the total mortality. While today's weed-control practices may not produce good second-season control, increased vigor of both top and root-system, conditioned by favorable first year habitat, should produce a seedling that is far more capable of becoming well-established and attaining maximum juvenile growth rate than could be expected in seedlings that had had a difficult first growing season. The concept of planting-check, which has been discussed by other workers (101), is perhaps overcome by the improved environment. While inadequate time has elapsed for evaluation of long term effects of this treatment, there is substantial evidence from earlier work on this project, and from work by others who have assisted in screening and field-testing herbicides, that two to three years less time is required for Douglas-fir trees to reach breast height on devegetated sites. Moreover, the growth rate at the time the tree reaches breast height may be significantly greater on the early-developing seedlings than on those which develop slowly from the start. The greater growth rate of planted seedlings, combined with the improved survival on difficult sites, illustrates the possible economic significance of these results.

Influence of Vegetation Manipulation on Surface Temperatures

The heat-girdling encountered in these experiments illustrates some of the dangers which may arise from modification of the energy budget, yet it is possible that this degree of heat damage could have occurred under any comparable climatic circumstances. This problem may be approached from two points of view. It may be speculated that the soil surface temperature may be increased by devegetation to the extent that excessive heat would occur at the soil surface, causing heat girdling. From the other approach, it could be argued that in the presence of residual dead vegetation the lack of air circulation in dead vegetation would cause an accumulation of heat in the vicinity of the foliage, causing a markedly increased transpirational stress.[6/] The ultimate mechanism causing mortality was not clarified by the observations obtained in this study.

As a practical solution to the heat-damage problem, the asbestos root-collar protectors previously described have not had sufficient testing for field recommendation. Greenhouse tests with heat lamps in previous studies have illustrated that these collars give adequate protection of 170 degrees for two hours. All unbanded

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[6/] Robinson, Myles: personal communication.

seedlings died. The field testing of this procedure has thus far proved inconclusive. During the summer of 1963, heat conditions were not encountered which caused excessive mortality to seedlings in exposed soil. Negative evidence has been provided however, in that little mortality has taken place as a result of the root collars. If, indeed, protection by the asbestos collar prevents a substantial amount of heat damage, the redistribution of the energy budget in terms of soil surface heating becomes an academic question in terms of local significance. No attempt will be made to generalize regarding the application of herbicides to very large areas, where a major redistribution of heat might occur.

Justification of Herbicide Use

In recent years considerable alarm has been expressed by conservationists and others (22; 27) who decry the increasing environmental contamination with pesticides. The theory is advanced that the introduction of pesticides into the environment generally constitutes a deplorable imbalance of nature. The long-term implications of herbicide use under study here will be discussed accordingly.

The non-forested south slopes within the forested areas of western Oregon characteristically have long histories of non-forest cover. There is much unofficial speculation that areas of such stable vegetation cover could not be expected to support satisfactory forest growth or perhaps should be considered as natural clearings. Proponents of these theories generally speculate that if the forest sites were capable of producing forest growth, successional tendencies would manifest themselves, and conifers would reinvade the openings. While the history of these openings is sometimes related to general climatic changes as discussed by Hansen (35), there is evidence in support of more recent causes for non-forest conditions. It is speculated here that perhaps many of these openings would not have become openings in the first place had it not been for the introduction of numerous exotic weed species with growth habits peculiarly suited to the early utilization of moisture. Note will be made of the list of species earlier described (Table 1, p. 39) which illustrates the large percentage of the annual plants that are early-developing exotic species. Perhaps in the absence of these introduced species, abundant natural regeneration of conifers would have taken place following fires, the occurrence of which is revealed by bits of charcoal in the soil profile. It also became evident earlier in this work that many of the introduced weed species are highly sensitive to the s-triazine herbicides. Moreover, the herbicides of the s-triazine group are thought to have relatively small influence on microbial and animal populations.

As a corollary to the above discussion, it has been observed that animal habitat is distinctly modified by the changes in vegetation

(34), and it is suspected that substantial amounts of animal damage in conifer plantations might be avoided if some means were at hand for creating unattractive but not harmful forage conditions for browsing and grazing animals while improving conditions for seedling development (33). It was observed earlier that cattle damage began on one sprayed area as vegetation began to recover from the herbicide application, but that little activity was observed on the area while the forage was still better in surrounding areas. While it is not proposed that herbicides are the immediate solution to animal damage problems animals certainly are an important influence in the ecology of many areas of reforestation difficulty. Herbicides have been shown to be a powerful tool in habitat modification; perhaps the study of seedling habitat in the presence of herbicides should include the influence of the vegetation changes on animal movements. Moreover, the restoration of forest cover constitutes the ultimate return to native flora and fauna. If a single application of a pesticide which has no measurable adverse effect on animal populations and whose effect on the vegetation is temporary may result in successful reforestation of land which has been out of forest cover for a hundred or more years, it would appear that the use of such a pesticide may be justified.

Worldwide Implications of Vegetation Manipulation in Reforestation

Perhaps indicative of present day concern over dwindling arable land resources and the wasting of such resources as are currently available is Baker's newspaper article "Trees against the Desert" (6). Afforestation is proposed as a means of stabilizing the Sahara in the peripheral regions where destructive agricultural and grazing use policies are resulting in the encroachment of desert dunes on arable lands presently being over-exploited. Substantial newspaper and other lay speculation has been devoted to the merits of afforestation of such areas as the central Oregon desert, the Great Basin region, and areas of the great plains. Major efforts are being directed at the reforestation of area of the Middle East where trees have not grown for hundreds or thousands of years. It is not proposed in this thesis that the afforestation of such land is economically attractive or otherwise desirable, although there are many arguments in favor of such activity. The fact remains that afforestation of semi-arid and arid regions is an exceedingly expensive and difficult proposition.

In general, it can be said that moisture is the key to survival of planted and natural seedlings. In areas where it is obvious that vegetation is utilizing the site fully it may be concluded that the vegetation is removing moisture which might otherwise remain available within the root zones of seedlings. It is felt that the application of the concepts in this thesis might aid substantially in cost reduction and in improvement of chances for success. On the other hand, application of these concepts should not be blindly followed in regions where problems other than moisture may prevail to eliminate any possibility of success regardless of moisture supply. Conservation of moisture will not control depredations by animals, reduce the injury from heat, or cause planted trees to be immune to such physical factors as ice, sand, hail and other types of storms, severe winter dessication, hot dry winds which may make it impossible for trees to survive even in the presence of abundant moisture, and many other physical factors. The environment of a planted seedling is both large and small. It is evident that, in some ways, control of the local environment is possible. The only control we have over the macro-environment is in the adaptation of species with minimum sensitivity to harsh physical conditions.

Hydrologic Implications of Vegetation Reduction

Thornthwaite and Mather's "Water balance" (102) depicts the cumulative moisture deficit which occurs during any period when the precipitation fails to keep pace with the potential evaporation. The evidence in this study is that the actual moisture deficit does not necessarily correspond to the potential deficit and that the disparity is controllable. It has been shown that vegetation acts as a vehicle for the transmission of radiant energy. Different forms and amounts of vegetation may transmit energy with varying efficiency, which would result in different degrees of separation of radiant energy into latent heat of vaporization and sensible heat.

The vegetation under study in this thesis generally went dormant or died when the soil moisture content of the top 36 inches of the soil had reached the permanent wilting point. Subsequent loss of moisture was negligible. Some slight additional moisture may have been depleted from the lower depths but there may still be a major departure from the cumulative deficit of some 18 inches predicted by the Thornthwaite system for the current study. This point is consistent with the work done in several western states in which moisture use by grass is less than is lost by brush and forest types (11; 41; 80). In agreement with this principle, the author found in a study conducted concurrently with this project that the rate of soil moisture loss in the surface three feet of the soil was greater under grass cover than it was under a forest cover. However, the total soil moisture withdrawal by the woody plant cover, in this case Douglas-fir and Oregon white oak, was comparable to that of herbaceous vegetation. At the deeper depths, water consumption by the forest cover was undoubtedly greater than under the herbaceous vegetation simply due to the greater abundance of tree roots at the deeper levels. Moreover, while the herbaceous vegetation had largely aestivated in the late summer, the forest vegetation was still transpiring. In order of water-use then, it is apparent that the forest cover most closely approximates the Thornthwaite potential of moisture deficit. Herbaceous vegetation, undisturbed, appears to function more efficiently in soil moisture withdrawal during the period of ready availability.

The increase in the potential effectiveness of light rains, and the reduction of the amount of rain required to recharge the profile after devegetation is clearly demonstrated. In agreement with the findings of Boggess, it was found in this study that summer rains of up to one inch did not recharge fully-depleted moisture profiles and contributed little to the available moisture supply (14). Devegetated areas, in retaining all but one inch of the total storage capacity, would be expected to produce streamflow with substantially less rain. The practical significance of water retention for watershed management purposes is probably limited, however, due to problems of soil instability, chemical contamination of water supplies, and gross alteration of the energy budget under conditions of large-scale broadcast applications of herbicides. Moreover, the cost of moisture conservation per acre-foot would be far greater than is presently considered economically feasible.

Relationship of Climate to Effectiveness of Vegetation Manipulation

In the Pacific northwest, as in many parts of the world with a Mediterranean-type climate, the winter months are characterized by abundant precipitation, while the summer months normally have negligible rainfall. The onset of the summer drought period occurs after the last rain from which subsurface drainage occurs. Following the last effective rain, there may be additional rain before the rain ceases for the summer, yet drying proceeds rapidly when the depletion of moisture is such that the subsequent rains fail to recharge the profile. The longer the drying period after any rain, the heavier the precipitation required to recharge the profile. In western Oregon, the potential evaporation increases very rapidly during May and June, and where herbaceous vegetation is likely to transpire at between 80 to 85 percent of maximum evaporation potential, as is estimated from this study, soil moisture loss of 0.20 inch per day during mid-May can be expected. If a heavy rain occurs on the first of May, and is not followed by additional rainfall for eight days, the next rainfall must deposit 1.6 to 2.0 inches of rain to recharge the profile. According to Lowry (62) the likelihood of any such precipitation is very remote, and chances of such a period without appreciable precipitation are good. In the year 1962 the last effective rain occurred on May 17, which is roughly two weeks later than the average date of the cessation of effective rain (47, p. 11). There was, moreover, a relatively high incidence of cloud cover and low temperatures until the 17th of July.

In view of the soil moisture losses occurring under the above conditions in the untreated stands of vegetation, it may be assumed that moisture availability during an average season might become limiting as early as June 10. From the standpoint of moisture availability and high solar radiation intensity during the summer months, it is not surprising that high mortality should prevail generally in plantations of conifer seedlings on herb-covered areas in Mediterranean type climates. Despite the range in rainfall from 30 to more than 60 inches in the area of western Oregon on which non-forested south slopes occur, the period of extreme summer heat and radiation intensity occurs during a period of deficient rainfall. The resulting microclimatic condition is more nearly comparable to regions characteristic of semi-deserts. In support of this hypothesis, many of the semi-desert regions of eastern Oregon have lower soil moisture deficits during the period of seedling establishment in May and June than generally occur in the central Willamette Valley (47).

In view of the severity of the conditions encountered in the general area in which the study was conducted, it is proposed that the results of this study may be applied under a wide variety of conditions with some chance for habitat improvement.

SUMMARY AND CONCLUSIONS

Large areas of potentially productive forest land remain non-stocked after long exposure to abundant forest seed supplies, and after many failures in reforestation efforts. Grasses and other herbs are often associated with planting failure on these sites, and recognition of this has spawned the practices of scalping and cultivating. The recent development of selective herbicides for grass and forb control in the presence of crop species has created an opportunity for the quantitative study of the influence of herbaceous vegetation on the habitat of planted seedlings.

Herbicides were aerially applied to some grassy sites which had failed to restock after several planting efforts. Moisture depletion was studied as the function of the degree of vegetation control, soil depth, soil drainage, and meteorological data. It was found that the use of moisture by the vegetation accounted for 92 percent, or more, of the total moisture depletion during the period of most rapid drying. In the absence of all vegetation, 84 percent of the moisture in the surface 36 inches of soil at the end of the effective spring rains still remained at the onset of fall rains. Nearly all the moisture loss due to evaporation came from the surface nine inches of soil. Between nine and 12 inches, the moisture remained at the readily-available range of tension throughout the summer.

Seedling response to the improved moisture conditions involved much-improved survival and greatly improved vigor of the individual seedlings. Lammas growth occurred on many seedlings, and symptoms similar to nitrogen response appeared. Root development occurred during midsummer, when seedlings in droughty soils were dormant or dying. Evidence in older plantations indicates that the rapid establishment of the seedlings results in greater subsequent growth equivalent to the reduction of two to three years in the time required to reach breast height.

Mathematical models were developed for the prediction of soil moisture depletion rate and residual moisture content. The models were too complex for field use, but served to illustrate the importance of vegetation as a habitat factor both independently and in interaction with climatic and edaphic factors. Moreover, the relationships characterized by the above equations provide a quantitative estimate of the dynamics of drought which reveal the futility of depending on drought evasion as a means of providing seedling survival. It was shown that the severity of drought conditions under the local Mediterranean climate are comparable to those of far more arid regions, but that the drought conditions could be ameliorated by reduction of vegetation density on a roughly linear scale.

The onset of drying conditions under the influence of herbaceous vegetation was shown to occur early in May, becoming critical in mid-June, although it has been commonly supposed that seedlings are not exposed to severe moisture stress until midsummer or later. By mid-June, moisture conditions were critical at depths to 36 inches, despite the so-called favorable conditions of 1962.

Favorable moisture conditions created by the reduction of vegetation had no clear bearing on seedling mortality due to heat. Ring-girdling killed nearly all the seedlings used in the 1962 test plantations. The use of an asbestos root collar protector that was successful in the laboratory may help to solve the heat problem.

The heat diversion due to vegetation control may not have the predicted result of soil surface heating during the midsummer period. By the time heat-girdling becomes a problem, moisture is no longer available for transpiration on untreated sites, hence the heat exchange near the ground may not differ greatly. Furthermore, the reduction of organic matter and dead vegetation resulting from vegetation control increases the foliage ventilation, hence avoids the high foliage temperatures with resulting moisture stress gradients within the seedlings.

It is considered unlikely that the use of herbicides for moisture conservation for watershed management will become practical at present water values. In reforestation the economic picture already demands attention. The cost of each established seedling in plantations not using herbicides is far greater than the cost where mortality risk is reduced, hence the use of herbicides is clearly justifiable on grassy sites.

The general applicability of these results, in grassy areas where restocking with forest species is desired, is dependent upon the moisture-holding properties of the soil and other factors of the environment. Moisture conservation by vegetation control may be accomplished only to the extent that vegetation is removing moisture. Physical site problems other than water deficiencies may be related to vegetation conditions, as may animal movements. The vegetation may be only the first of several problems which must be overcome for successful reforestation. On the other hand, it is felt that where moisture removal by herbaceous vegetation is a primary source of seedling mortality, careful analysis of the herbaceous vegetation conditions followed by appropriate control measures will cause an improvement of moisture conditions to the general benefit of conifer plantations.

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APPENDIX

Table 5. Moisture deficit during the period of study. Based on local estimates of precipitation and potential evaporation. All quantities in inches of water.

Date	Evaporation per period	Cumulative Evaporation	Precipitation	Cumulative precipitation	Cumulative (precip-evap)
May 12	0.68	0.68	1.03	1.03	+ 0.35
May 19	0.78	1.46	0.53	1.56	+ 0.10
May 26	0.48	1.94	0.06	1.62	- 0.32
June 10	2.53	4.47	0.33	1.95	- 2.52
June 16	1.36	5.83	0.00	1.95	- 3.88
June 23	1.86	7.69	0.00	1.95	- 5.74
July 8	2.91	19.60	0.00	1.95	- 8.65
July 22	3.51	14.11	0.00	1.95	-12.16
Aug. 10	5.27	19.38	1.35	3.30	-16.08

Table 6. Soil and vegetation data by plot.

Plot Number	Inches Soil depth	Drainage	Bulk densities 3"-6"	6"-9"	9"-12"	Kg/A Total Vegetation	Percent Annual
1001	36	1	1.2	1.2	1.2	388	75
1002	36	2	1.2	1.2	1.2	658	31
1011	24	1	1.2	1.2	1.2	331	12
1012	36	2	1.2	1.2	1.2	581	40
1021	36	1	1.2	1.2	1.2	567	12
1022	36	2	1.2	1.2	1.2	625	22
1101	13	1	1.2	1.2	1.4	351	24
1102	7	4	1.1	1.4	1.6	390	84
1111	12	3	1.1	1.2	1.4	424	79
1112	9	4	1.0	1.3	1.6	49	60
1121	12	2	1.2	1.2	1.4	183	47
1122	14	1	1.3	1.2	1.1	176	24
1201	18	1	1.2	1.2	1.2	179	19
1202	24	1	1.4	1.3	1.3	204	18
1211	28	1	1.2	1.2	1.2	249	16
1212	36	1	1.2	1.2	1.2	177	24
1221	18	2	1.2	1.3	1.3	267	13
1222	20	1	1.4	1.3	1.2	94	36
1301	24	2	1.2	1.2	1.2	89	33
1302	24	3	1.2	1.2	1.2	50	30
1311	36	2	1.2	1.2	1.2	66	0
1312	24	2	1.2	1.2	1.2	79	21
1321	30	1	1.2	1.2	1.2	43	20
1322	24	1	1.2	1.2	1.2	47	12
1901	15	3	1.1	1.2	1.3	1255	91
1902	15	3	1.1	1.2	1.3	1510	97
2001	18	2	1.3	1.2	1.2	109	63
2002	12	3	1.3	1.2	1.2	496	67
2011	24	2	1.3	1.2	1.2	205	6
2012	14	3	1.3	1.2	1.2	287	64
2021	18	2	1.3	1.2	1.2	159	78
2022	18	3	1.3	1.2	1.2	155	79
2101	12	2	1.2	1.2	1.4	184	24
2102	12	4	1.2	1.2	1.4	524	84
2111	10	2	1.2	1.4	1.7	194	33
2112	12	3	1.3	1.2	1.4	500	90
2121	12	2	1.1	1.2	1.4	291	77
2122	9	3	1.2	1.4	1.6	226	82
2201	16	3	1.2	1.2	1.2	176	19
2202	36	3	1.3	1.3	1.3	68	24
2211	18	3	1.2	1.2	1.2	337	8
2212	24	3	1.3	1.3	1.3	84	69
2221	24	3	1.2	1.2	1.2	256	53
2222	18	3	1.3	1.3	1.3	104	0
2301	20	3	1.3	1.2	1.2	62	38
2302	18	2	1.2	1.2	1.2	38	44
2311	20	2	1.3	1.2	1.2	61	12
2312	20	2	1.2	1.2	1.2	96	27
2321	18	3	1.3	1.2	1.2	82	2
2322	22	3	1.2	1.2	1.2	39	0
2901	8	3	1.2	1.4	1.7	808	100
2902	7	3	1.2	1.4	1.7	866	100

Table 7. Correlation matrix showing relationships between 14 input variables of Equation 3 (p. 50), of which eight were used in the predictions. Variables listed at bottom of table.

Variable:	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(Y)
(1)	1.00000	.85025	-.29728	.93597	.37530	.88165	-.29142	.75670	.89526	.94633	.63243	.32421	-.29748	-.28294	.15555
(2)		1.00000	.09183	.73312	.19085	.89684	-.00038	.71860	.76704	.76085	.56096	.15801	.00643	-.00780	.27336
(3)			1.00000	-.35726	-.58938	-.09722	.80820	.00086	-.18787	-.34277	.00070	-.41757	.84213	.76729	.13894
(4)				1.00000	.35404	.77427	-.22946	.71095	.83259	.87915	.59823	.30869	-.25490	-.20081	.18956
(5)					1.00000	.44503	-.60514	-.16399	.13860	.52390	-.20887	.65903	-.61637	-.59214	.31091
(6)						1.00000	-.19571	.57988	.70566	.91998	.42898	.30746	-.19201	-.19835	.27475
(7)							1.00000	.00202	-.18241	-.36131	.00164	-.42400	.99691	.99653	.19113
(8)								1.00000	.81668	.60241	.92010	-.01294	.00201	.00199	.07885
(9)									1.00000	.76180	.77869	.20527	-.18637	-.17683	.07801
(10)										1.00000	.47707	.39945	-.36612	-.35345	.18610
(11)											1.00000	.06376	.00164	.00161	.04866
(12)												1.00000	-.42994	-.41487	.23995
(13)													1.00000	.98697	.18621
(14)														1.00000	.19595
Y															1.00000

Supplement to Table 7.

Variable		Variable	
(1)	Vegetation x moisture available	(9)	$(\text{Vegetation})^2$ x moisture available
(2)	Vegetation x moisture available x potential evaporation	(10)	Vegetation x $(\text{moisture available})^2$
(3)	Potential evaporation	(11)	Vegetation x percent annuals
(4)	Vegetation x moisture available x stage of growth of annuals	(12)	Moisture available x drainage
(5)	Moisture available, percent by volume above permanent wilting percentage	(13)	$(\text{Date})^3$
(6)	Vegetation x $(\text{moisture available})^2$ x potential evaporation	(14)	Date
(7)	$(\text{Date})^2$	(15)	Y = Moisture loss per day. percent by volume
(8)	Vegetation		

Table 8. Simple correlations between some independent variables and (1) the moisture loss per day, (2) moisture residual available. Nine to 12 inch data. Three hundred eleven observations.

Variable	Moisture loss/day	Available moisture
$(\text{Date})^3$	.50289	-.34153
(Vegetation/soil depth) x evaporation x drainage	.48677	-.10718
$(\text{Days since precip})^2$	.37252	-.29619
Vegetation x $(\text{date})^2$	.34802	-.17910
Veg. x (days since precip)	.34610	-.27130
Veg. x percent annuals	.29094	+.06161
Vegetation	.16868	.03837
Veg. x H_2O avail x evap	.15288	.36744
Available moisture	-.10676	1.00000
Veg. x available H_2O	.03813	.49293

Multiple coefficient of determination: $R^2 = .47$

Table 9. Climatic data for the study area, 1962, and stages of development of annual and perennial vegetation, by sampling period. Meteorological data from U. S. Weather Bureau, (103).

Date	Radiation Langleys/day Gross	Evaporation Open pan Inches day	Precipitation total/period Inches	Ave. Cloud Cover	Mean Max Temperature °F	Stage of growth[1/]	
						Annuals	Perennials
May 5							
	490.4	0.097	1.13	8.8	61.6	2	1
May 12							
	563.8	0.112	0.53	8.9	61.6	3	2
May 19							
	437.0	0.064	0.03	9.0	61.9	4	2
May 26							
	612.0	0.090	0.33	6.8	66.9	4	2
June 10							
	683.3	0.226	0.00	3.9	71.3	4	3
June 16							
	697.1	0.265	0.00	2.7	81.8	1	3
June 23							

1/ Stages of growth indicate the following degrees of development, averages:

1 Post-emergence to four-inch height; later used to indicate aestivation
2 Four-inch to boot stage
3 Boot stage to initiation of head development
4 Mature head