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Abstract

A portable hand-move sprinkler irrigation system was designed to provide water distribution and operating characteristics suitable for continuous variable irrigation-fertilizer cowpea (*Vigna unguiculata* [L.] Walp.) production studies. Both the single and interactive effects of irrigation water, phosphate fertilizer and irrigation scheduling techniques on cowpea dry matter production were investigated in a field-conducted randomised complete block experiment.

The relative merits of irrigating frequently but with smaller amounts of water than the design water application depth as compared to stage-of-growth and normal interval irrigation were studied with five levels of fertilizer P and three water levels. Soil water depletion by crop was measured by gravimetric methods and water use as well as water use efficiency were subsequently evaluated. Plant growth rate indices monitored were: plant height, number of trifoliates and number of nodes on a weekly basis for seven weeks following emergence.

Statistical analyses of yield and P uptake indicated positive response of the crop to added fertilizer and irrigation water, most noticeably under the high-frequency schedules. Water use efficiency was observed to be highest under the most frequently-irrigated plot (S3) but this happened to be obtained at the expense of depressed yields. It was therefore concluded that irrigating twice within the designed interval was optimum for both yield and water use efficiency considerations.
The line-source irrigation system and experimental design used in this project were found to be satisfactory for field study of the interactive effects of these test factors on the crop. One major difficulty encountered with running the experiment was the operation of the system under calm wind conditions to ensure high uniformity of water distribution. Special care was needed also, to achieve sediment exclusion from the lateral that was frequently uncoupled and moved from plot to plot, but these were the special features of the irrigation system that made working with it interesting.
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I. INTRODUCTION

1.1 Background and Statement of the Problem

Irrigation is widely recognized as one of the oldest known agricultural technologies, but improvement in irrigation methods and practices are still being made. The demand for even greater improvements in the future can be seen in the light of ever-increasing competition for limited water supplies both in arid regions and in humid regions, where water is supplied on farms to offset more or less temporary droughts.

Most concern in irrigation water management is with determining when to irrigate to prevent drought-induced yield reductions. The traditional methods of water application by furrow, basin and solid-set sprinkler systems impose, almost inevitably, an irrigation cycle consisting of a brief period of water infiltration into the soil followed by a relatively much extended period of water extraction by the crops. These systems have fixed costs for each application, and understandably, the economic constraint encourages the minimization of irrigation frequency and a maximization of both the quantity of water stored in the root zone and the proportion of this water used by the crop before the next irrigation (Rawlins and Raats, 1975).

The introduction of sophisticated pressurized irrigation systems (such as solid-set trickle systems and centre-pivot sprinklers) that distribute water to the field in small quantities as often as desired with no additional cost reversed the economic picture and changed the irrigation cycle from a soil moisture extraction-dominated process to one that is
predominantly infiltration. This brought into play a set of laws governing water flow within the soil which frequently did not apply previously. Consequently, management criteria had to be updated. Yet it is cautioned that there is by this method, the modification of the aerial and soil environments to which the various crops respond differently depending on the geography of the area, climate, crop variety, endemic diseases and pests.

Since the development of high-frequency systems does not necessarily suggest the replacement of surface and solid-set sprinkler systems, the challenge to improve crop productivity with these latter inherently long-interval (low-frequency) systems emerges. Their energy demand and water consumption rate continue to face competition not only from modern systems but also from other users of these two (water and energy) extremely important resources. This calls for a need to address carefully, current farm water management practices with a view to improving water cost and energy savings alongside increased water use efficiency and better fertilizer management.

The most critical decision for an irrigator is determining when to irrigate and how much water to apply. In humid areas like the coastal area of British Columbia where rainfall occurs during the growing season, special irrigation management procedures need to be applied to make effective use of the sporadic rainfall.

Irrigation scheduling objectives vary: when water supplies are readily available and irrigation costs are low, the objective of scheduling for maximizing yield per unit area is
obvious and may be economically justified; however, as irrigation water supplies become more limited or as water costs increase in an area, the management objective may shift to optimizing production per unit of applied water. In addition, there are those methods whose objectives are maximizing net profit— in a broad sense, and minimizing energy requirements. These objectives set forth the concepts of "critical growth stage irrigation" proposed by Musick and Grimes (1961); "evapotranspiration(ET) deficit irrigation" developed by Woodruff et al (1972) and Miller (1976); and "stress day index method" introduced by Hiler and Clark (1971); amongst others, as the major irrigation scheduling techniques. They were developed on the basis of defined criteria.

The criteria for deciding when a crop should be irrigated are: (i) the depletion of water in the effective rooting zone to some predetermined level [effective rooting depth is defined (BCMAF, 1983) as that depth in the soil above which the roots obtain 90% or more of their water between irrigations], or (ii) the decrease of water potential at some given soil depth to a predetermined level. The value one chooses for either of these criteria to indicate that irrigation is needed depends on soil properties, crop rooting characteristics and stage of plant growth (Cary, 1981). Essentially, the scheduling procedures highlighted in the preceding paragraph and their various technical ramifications may be said to differ from each other in the following ways:

(a) filling the maximum expected root zone to field
capacity on an interval basis throughout the crop's lifespan,
(b) filling the effective rooting zone to field capacity only at some 'critical' stage of growth of the crop,
(c) sequencing of the ET deficits within the growth period such that the crop may not be adversely affected, and
(d) applying water frequently but in amounts insufficient to refill the soil profile (high-frequency deficit irrigation). This approach advocates applying water at a rate to meet the daily evapotranspiration demand of the crop thereby keeping the root zone at constantly high matric potential but not necessarily at or above field capacity.

This study incorporated, almost explicitly, the first, second and fourth of these basic principles of irrigation scheduling.

At soil wetness levels that are conducive to high rates of seasonal evapotranspiration and hence yield, optimum yield may not be achieved. Factors such as root zone aeration deficiency, plant lodging, nutrient availability and the potential for higher disease incidence may contribute towards the failure of the water management process that would otherwise achieve optimum yield. Thus, as Jensen (1975) observed, despite their availability, irrigation operators have not been greatly receptive to any one particular scheduling method because of reasons that include (i) the cost of irrigation water is often low relative to costs of practices that would improve water
management, (ii) yield reductions caused by delayed irrigations, improper fertilization and excessive irrigations are not easily recognized or quantified and (iii) irrigation management decisions are generally made by busy people with limited technical background and training in the management of a complex crop-soil-climate system. Typically, the irrigator would adopt that scheduling procedure that, when integrated with fertilizer management on the farm, and weed and pest control, produces improved net income from the farm. Furthermore, a method will be preferred which, when applied to a particular crop under a known soil nutrient status (native or applied) will give a strong predictive capability with respect to yield. Such a method could only be found through adopting the new technique, testing it accurately, reliably and consistently in combination with other farm management practices, and finally, evaluating and interpreting the results so as to arrive at the best combination of practices.

Soil nutrient status can markedly influence water use by crop (Black, 1966). In turn, total nutrient uptake by the crop at harvest is a function of both the time of onset of drought stress where soil water is limited and, the strategy for irrigation where water supply is not limited (Begg and Turner, 1976). In particular, these authors state that nitrogen and phosphorus influence water use in different ways: higher concentration of each leads to increased leaf area and prolonged development or to increased root proliferation, but both can have detrimental effects on yield when soil moisture is limited.
Nutrient levels in the field are usually highest near the surface and this portion of the soil profile is the first to dry out in a drying cycle. Available moisture plays a special role in nutrient uptake not only through the amount alone but also according to its distribution during the cropping season.

Although many studies on the effect of high-frequency irrigation on irrigation efficiency and crop water use efficiency have been conducted, most are laboratory or greenhouse based and have placed emphases on corn and wheat. Even with these limited studies, conflicting results have been reported with regard to the relative water use efficiency (units of crop production per unit of water) of irrigating frequently but lightly as compared to low frequency (long interval) deficit irrigation. Keller (1965) reported that efficiency was directly related to the depth of water stored per irrigation, but Musick and Dusek (1971 and 1980) working on corn and sorghum in the Southern High Plains of the United States, obtained a water use efficiency increase. Deboer et al (1977) found that for corn, water use efficiencies were not affected by application depth. In spite of the conflicting findings, Hobbs and Krogman (1978) are quite optimistic that the prospects for high-frequency, light irrigation scheduling technique are bright and that advantages such as effective use of summer precipitation, controlling drainage and maintaining nutrient supplies abound. Their work was on spring wheat in outdoor lysimeters as well as in the greenhouse at Lethbridge Research station, Canada.
1.2 **Study Objectives**

This study was concerned fundamentally with two resources: soil water and soil nutrient. It was a field experiment designed to test the performance of cowpea (black-eyed pea, *Vigna unguiculata* [L.] Walp.). In the tropics (particularly West Africa where cowpea is the most important legume) cowpea grown for its grains is often intercropped with other "more important" crops under rain-fed conditions. It is rarely cultivated as a sole crop, neither is it irrigated appreciably. Under these practices, it becomes difficult to know how much water and nutrients the crop requires at its various stages of growth when grown alone. The proposed study is aimed at gaining an insight into the growth and yield response of this crop when monocropped and supplied with supplementary irrigation that is scheduled in various ways and fertilized with phosphorus fertilizer in a humid climate.

The objectives of this study were:

1. To investigate cowpea growth rate and dry matter yield response to irrigation water and phosphorus fertilizer under the climatic conditions of the coastal area of British Columbia,

2. To evaluate water use efficiency of this crop under different irrigation scheduling techniques with a view to identifying which method saves water and makes the most optimum use of the unpredictable rains,

3. To make (based on 1 and 2) preliminary recommendations of
fertilizer P and irrigation water levels as well as an optimal water management procedure for the cultivation of the crop for forage in the environment in question, and

4. To develop a tool (some response function) for predicting the performance of cowpea under a given set of agronomic management specifications of the response surface (soil).

Upon first consideration, one becomes curious at an attempt to irrigate black-eyed pea, a legume that is largely drought-resistant and normally cultivated under rain-fed conditions. In a summary of the variation in drought tolerance among crop species, Levitt (1972) and Ludlow (1976), found that the degree of drought tolerance was associated more with the environment to which the plants had adapted than to taxonomic grouping. The results of this study will throw more light on the validity of this statement in this experimental situation. Moreover, irrigation in humid areas has often been economical even though annual rainfall exceeds evapotranspiration. Lambert et al (1981) point out three factors necessitating irrigation in humid regions: (a) the annual distribution of rainfall does not coincide with the evapotranspiration distribution, (b) the water holding capacity of soil generally is not sufficient to provide adequate water for crops during the deficit rainfall periods and (c) restricted rooting due to mechanical impedance for example, limits soil water availability to plants.
II. LITERATURE REVIEW

2.1 Evapotranspiration, Crop Growth and Yield

The rate of entry of water into the soil and its retention, movement and availability to plant roots are all physical phenomena and constitute the complex soil-plant-water relationship. This continuous system may be divided into four sequential processes: the supply of water to the root surface, the entry of water into the root, the passage of water in the plant's conducting elements and the movement of water vapour through and out of the leaves. The complete path of water may be analysed by evaluating the potential difference between soil and atmosphere in contact with root and leaf respectively (Pierre et al., 1965; Kozlowski, 1968; and Hsiao, 1973), and the rate of water movement is everywhere proportional to the potential energy gradient and inversely proportional to the resistance to flow in the pathways of water and/or vapour flow (Michael, 1978). The principal driving force for transpiration is thus, the difference between the vapour pressure at evaporating leaf surfaces and the bulk air.

Although the total potential (partial specific free energy of water relative to that of pure free liquid water at the same temperature and height and at atmospheric pressure, ISSS, 1974) in dry air is typically equivalent to -1000 bars or less, most plant processes would have been severely inhibited by the time the leaf water potential drops to -10 bars. Therefore, to maintain the water potential of the leaf above this critical level as water moves from the soil into the plant through the
transpiration stream to the atmosphere, the flow resistance
impeding water loss from the leaf must be at least 100 times
that in the pathway supplying water to it (Rawlins and Raats,
1975).

Soil water potential affects photosynthetic rate and
transpiration insofar as it controls stomatal opening or closure
which allows or inhibits respectively, carbon dioxide
assimilation from, and water vapour escape into the atmosphere.
Most physiological processes are affected by the time the plant
reaches permanent wilting point at which stage the soil water
potential in the range of water availability to plant is very
high, that is, small negative value (Gardner, 1960).

When leaf water potential drops into a critical range,
stomatal openings begin to close, preventing excessive loss of
water even at the expense of decreased carbon dioxide
assimilation. It is generally known and accepted (Slatyer,
1969; Hsiao, 1973; and Begg and Turner, 1976) that (i) cell
expansion and division processes require high turgor pressure
(that potential component of leaf water potential due to turgor
pressure acting outward on cell walls - a term analogous to
hydrostatic pressure in soils) levels and (ii) plant growth (the
conversion of assimilates to living tissue) ceases at leaf water
potential levels much above those which cause stomatal closure
and a decrease in transpiration rate. In effect, in most crops,
growth proceeds completely unimpaired if the evapotranspiration
rate is not limiting and yield is maximal only when water
potential remains high throughout the life of the crop. Often,
however, crop production constraints do not permit this. For most crops, keeping plant water potential high by ensuring continuously ample supply from the soil results in maximum production per unit of area but a simultaneous maximization of production per unit water consumed is not guaranteed. Maximizing water use efficiency (Wue) as pointed out by Veits (1962) may not be desirable since crops grown on dryland (no irrigation) frequently use water more efficiently than 'well-watered' crops, but at much lower levels of production. Hillel and Guron (1973) state that it appears more promising to increase Wue by increasing crop yields than by decreasing ET, since plants growing in the field are subject to an externally imposed evaporative demand. This statement is valid for well-watered crop regimes but Howell and Hiler (1975) argue that it does not fully explore the possible implications of limited irrigation in regions of short and/or costly water supplies. They agree that limited irrigation will presumably decrease crop yields but this yield decrease may not be directly proportional to the water deficit imposed on the crop.

Besides, maintaining high leaf water potential may entail ensuring an excessively wet soil which can impair gaseous exchange and restrict root development. Restricted oxygen diffusion into poorly drained and excessively wet soils limits root respiration necessary for growth on the one hand (Stegman et al., 1980), and regardless of how wet the soil is kept, crop plants are still subject to water stress during periods of high transpiration as a consequence of increased water potential drop.
across resistances within them on the other (Rawlins and Raats, 1975).

Thus, it is obvious that maintaining a constantly high soil moisture content is not always desirable for optimum physiological processes but from the standpoint of dry matter production, either per unit of water used or per unit of land occupied, there seems to be no advantage in permitting crops to undergo water stress. Avoiding water stress is the delicate subject of irrigation timing. Fortunately, results from experiments on the aftereffects of water stress on plant growth suggest (Hsiao, 1973) that periods of decreased leaf water potential during which plant growth slows or stops do not decrease net growth if they are not too long. Hsiao observed that during each period of depressed growth, assimilates can be stored for several hours before non-stomatal effects cause photosynthesis to decrease from the potential rate, and can then be used in accelerated growth when stress is relieved. Hence, repeated brief stresses, such as in mid-afternoon maximum evapotranspiration periods, may only slightly affect yield potential and are preferable to less frequent stress that lasts for days such as is at times inevitable in rain-fed agriculture and which may also occur in surface or long interval irrigation scheduling methods. The latter statement is fundamental in irrigation water management and forms the basis for this study: an investigation of dry matter production under variable irrigation frequencies (that is, programming of one or more periods of water stress of different durations in the crop's
growth span). Literature on the subject of relationship between crop yield and ET (or consumptive use of water) reveals that yield relationships to water can range from linear to curvilinear (both concave and convex) response functions. The variations are influenced (Stegman et al, 1980) by the type of water parameter that is chosen, its measurement or estimation accuracy and the varied influences associated with site and production conditions. The further interaction of this response function with soil fertility is reserved for review in section 2.3.

2.2 Irrigation Scheduling

An optimal irrigation regime would be one which emanates from a good program developed to estimate soil moisture depletion, the number of days before the next irrigation, and the amount of water that should be applied at each irrigation. This program constitutes an irrigation scheduling procedure - the application of the right amount of water at the right time, many alternatives of which exist. Irrigation scheduling can be accomplished using direct reading methods such as tensiometers and soil moisture blocks as indicators of soil moisture content. Estimated rates of consumptive use coupled with gravimetric determinations of existing soil moisture provide an excellent basis for predicting irrigations (Jensen, 1970) and constitute perhaps the oldest known method of scheduling irrigation.

Efficient irrigation implies complete control of the available soil moisture reservoir. Such control requires adequate knowledge of the soil moisture content at all times,
and the application of just enough water to refill this reservoir to the desired level, plus the leaching requirement for salt control where necessary.

From literature there appears to be two major theories regarding plant response to water supply and different soil moisture levels that are helpful to the irrigator: one theory, put forward by Veihmeyer and Hendrickson (1950 and 1955) maintains that the utilization of soil moisture by plants is uniformly effective throughout the whole range between permanent wilting point (PWP) and field capacity (FC) called the available water storage capacity (AWSC); the opposing theory, advocates of which are Furr and Taylor (1939), Hagan et al., (1959) and others, claims that plants do respond differentially to variations in soil moisture content within the availability range, and that depletion of soil moisture, even above PWP may appreciably reduce growth rates and final yields. Little controversy exists over these opposing views as the latter theory is of much wider acceptability and application in irrigation design and scheduling. The reason is clear: if the Veihmeyer-Hendrickson theory is justified, that plants indeed utilize soil moisture uniformly well in the whole range between PWP and FC, then there is no need to irrigate as long as the soil moisture content has not reached PWP and it follows that the optimal irrigation regime is one in which water is applied whenever this point is reached.

However, several points have been put forward (Haise and Hagan, 1967; Jensen, 1968; Denmead and Shaw, 1962; Stewart
et al., 1975; and English and Nuss, 1982) against allowing moisture depletion to approach closely the permanent wilting percentage because, this may cause failure of the crop to obtain enough water from soil due in part to (a) position of the permanent wilting percentage on the energy-soil moisture (soil moisture characteristic or retention) curve in the region where a slight decrease in moisture content results in a great increase in resistance to removal of the water, (b) supply of water may fail because of the slowness of movement of water into the mass of soil dried by roots, (c) failure of roots to elongate rapidly enough into regions where there is still water above the wilting point, and (d) depending on availability and cost of water and the market value of the crop being cultivated, only a defined fraction of the available water storage capacity of the soil is allowed to be depleted by crop before water application is necessary if stress-induced economic yield depression is to be avoided. This percentage of AWSC or availability coefficient (as defined in B.C. Irrigation Design Manual, 1983) multiplied by the AWSC gives an estimate of the maximum soil water deficit. In effect, the availability coefficient is changed depending on the market value of the crop grown on any particular soil. This concept was implicitly utilized in three of the irrigation scheduling techniques adopted in this investigation.

The experiment was based on an irrigation scheduling procedure by which there was a fixed and equal length of time interval between irrigations for any given scheduling technique.
The concept of "irrigation interval" is a typically low-frequency method (common with gravity systems) requiring completely filling the effective rooting depth of a given crop to high matric potential and often to field capacity and then allowing gradual extraction until a stipulated water level above permanent wilting is reached when irrigation is applied again. This application method may cause almost inevitably, deep percolation and possibly, surface runoff (Hobbs and Krogman, 1978).

According to Hobbs and Krogman (1978), deep percolation can be minimized or even eliminated by applying less water than is required to replenish the soil profile, but applying it frequently enough that moisture stress does not occur. This supports the earlier suggestion by Phene (1974) that in soils with distinctively low storage capacities, high-frequency irrigation systems make it possible to keep the soil matric potentials high and at the same time leave sufficient capacity to store intermittent rain that often occurs in humid regions during the cropping season. Earlier, Rawlins (1973) had recorded that as long as sufficient water is applied to meet the transpiration (or evapotranspiration) demands of the crop, adding extra water should not increase soil water content significantly; it would simply allow more to escape out the bottom of the root zone. This means that low soil water content can be eliminated as a factor affecting plant growth without wasting water to deep percolation. This latter researcher concluded that the only reason for applying water in excess of
Evapotranspiration under high-frequency irrigation management is to provide leaching to control salinity and, instead of irrigating on the basis of soil water potential or soil water content, the irrigator need only adjust the rate of water application to control the flux of water out at the bottom of the root zone. The water holding capacity of the soil, therefore, becomes unimportant.

It is well known that with good design and water management, sprinkling inherently eliminates runoff and deep percolation but Hobbs and Krogman (1978) further add that application of small amount of water more frequently increases evaporative losses from nozzle sprays and wet soil surfaces but admittedly, deep percolation and runoff would be avoided.

Using sprinklers, irrigation frequency can be highly manipulated. Various scheduling alternatives exist with this technology unlike with surface irrigation which is faced with the fundamental constraints of flow over the soil surface to distribute water from a turnout to the field requiring a minimum depth of water simply to achieve coverage, and a fixed cost associated with each application of water.

Rawlins and Raats (1975) pointed out certain economic benefits to be gained by high frequency irrigation with pressurized systems. They observed that the capital costs of such systems depend largely upon pipe size (within the limit of the pumping pressure), which in turn depends upon water delivery rate. Delivery rate, and therefore capital costs, can be minimized by designing the system for continuous operation.
They added furthermore, that frequent irrigations may optimize the root environment while reducing water use so that maximum yields could be realized with a minimum of water. These conclusions were predicted on several implicit assumptions: that the crop is to be fully irrigated, the pipe cost is the dominant component of system cost, and that labour, pumping cost and maintenance costs will not increase significantly with high-frequency irrigation.

With high frequency deficit irrigation, water will be applied frequently but in amounts too low to prevent the decline of soil moisture and crops will experience moderate stress more or less continuously. In the case of low-frequency deficit irrigation (long interval method) soil moisture will fluctuate within a wider range. A heavy irrigation will be followed by a long period of extraction during which the stress experienced by the crop will range from none at all to severe. A subsequent full irrigation will then refill the profile and the pattern repeats itself.

Whether yields will differ significantly or not under these two watering regimes is an essential question. Research on this question is inconclusive. Miller (1976) reported relatively good yields of sugar beets, wheat and beans in a high-frequency deficit irrigation. According to Miller, the high irrigation frequencies appeared to mitigate the effects of water deficits. Results of Hobbs and Krogman (1978) on wheat in Canada supported Miller's findings. However, other workers have arrived at opposite conclusions in similar studies. Federes and Faci
(1980) found that yields produced under deficit high-frequency irrigation were the same as, or lower than, yields produced under normal frequencies with the same levels of deficit. The lower yields reported under the high-frequency regime were attributed to the lower application efficiency associated with that technique. For the moment, therefore, the effect of irrigation frequency on crop yields under deficit high-frequency irrigation can at the best be regarded as uncertain. This research will certainly be a useful contribution in this direction.

2.3 Water Supply and Nutrient Availability to Crops

Today's emphasis on efficient crop production has stimulated greater concern for the methods used to investigate crop responses to various growth factors in the field. There are several factors but soil water and soil fertility have received considerable attention. Box and Hunter (1958) observed that the production approach to describing crop responses is used for two reasons namely: (i) to find the combinations of variables that give the best yield and (ii) to determine the characteristics of the response surface (soil or broadly speaking, land) in the neighbourhood of the optimum combination of growth factors. The response surface can then be used to determine whether management can be modified if conditions change.

The interactions between water supply and soil fertility with respect to their effect on crop yield is complex. In a critical review of this subject, Black (1966) indicated that
crop yield may evidently be increased, unaffected, or decreased by a given change in fertility level, depending on the magnitude of the change, the initial soil fertility level, and the water supply. Furthermore, Veits (1962), Black (1966), Hsiao (1973), and Begg and Turner (1976) have given good analyses and summaries of most of the information available on the effects of fertilizers on yield and associated evapotranspiration as affected by canopy density under conditions with either adequate or deficient soil water.

Black (1966) in his contribution, holds the view that where there is a deficiency of water for evaporation from bare soil containing available water at some depth below the surface, the high conductivity of plants for water substitutes in part for the loss of conductivity for water that has occurred in the surface portion of the soil. Under this condition, an increase in density of vegetative canopy from zero up to the maximum the soil will support, then causes an increase in evapotranspiration; the control is in the soil. Under moist conditions, the control is in the atmosphere. However, under intermediate conditions, the control may be partly in the atmosphere, partly in the soil and partly in the plants.

The term 'density of vegetative canopy' as defined by Black (1966), is the marketable yield in forages and is used often because of association of transpiration with expanse of transpiring surface. Differences in soil fertility affect evapotranspiration primarily by changing the expanse of transpiring surface and only in a minor way by changing the
character of the surface. Black further suggests that an increase in crop yield produced by increasing soil fertility does not produce a corresponding increase in evapotranspiration (ET); on the contrary, wide differences in yield induced by differences in soil fertility may result in only relatively small differences in ET. This is to say, in essence, that the magnitude of the increase in yield that can be obtained by increasing the soil fertility under a given water regime may be said to depend on the initial fertility level and the capability of the crop to produce additional dry matter under the prevailing circumstances.

An increase in production of dry matter by crops without an appreciable increase in use of water under conditions of a deficiency of water for evapotranspiration is said to be achieved in many ways including: (a) capability of plants at a higher soil fertility level to carry on photosynthesis at greater rate than those at a comparatively lower fertility level despite somewhat greater deficiency of water (Veits, 1966; Begg and Turner, 1976), (ii) differences in rate of use of water at different times. Two variations of the latter mechanism of additional dry matter accumulation could occur: first, Black (1966) observed in an experiment in which water was used more rapidly from fertilized than from unfertilized soil while the water supply was ample and more slowly after the available water was largely depleted and secondly, according to Sneva et al (1958), fertilized wheatgrass under desert conditions in Oregon made more rapid growth early in the season, exhausted more
rapidly the water supply in soil, and matured at an earlier date than did the unfertilized grass.

Although nutrient and water absorption are independent processes in the plant root (Veits, 1972), the necessity for available water in both the plant and soil for growth and nutrient transport makes them intimately related especially as the quantity of water in the soil affects not only the amount (concentration times volume) of nutrient in the soil solution, but also, the rate of movement to the root by diffusion and flow in the water (mass flow) as water is absorbed by the root (Unger et al., 1981). Veits (1972) states that under a field situation, soil water content near field capacity allows for the best combination of sufficient air space for oxygen diffusion, the greatest amount of nutrient in solution form, the greatest cross-sectional area for diffusion of ions and mass flow of water and favourable conditions for root extension.

This last statement, assuming it is true for all experimental situations, poses clearly, two practical challenges:

- a plant growing in the field is usually subject to fluctuations in water availability that may range from soil saturation to drought. The investigator would therefore be confronted with the problem of maintaining constant soil water at a suction of 1/3 bar (which is the matric potential at FC) approximately. This requirement could be met by drainage provisions and
irrigation scheduling precisions — the latter being part of this study.

- a situation analogous to the relationship between the potential or free energy of water in a soil (availability) and the amount present (supply), is the amount of nutrient present or added in the solid phase (quantity factor) in a given circumstance to guarantee continued replenishment of the absorbable nutrient form in soil solution (intensity factor) to ensure optimal absorption by a growing crop in view of the point above.

The ability of the soil system to replenish the soil solution is measured by the capacity factor defined (Sumner and Boswell, 1981) as the ratio of the change in the quantity factor to unit change in intensity factor. But according to Larsen (1967), having a particular nutrient in the liquid phase is only one facet of the solution to the crop management problem; it then has to be supplied at a rate (diffusion factor) sufficient to satisfy the needs of the plant for high yield. The size and morphology of a root system have a tremendous effect on the extraction. Thus, Sumner and Boswell (1981) remark that diagnoses of a nutrient problem and its correction and, scheduling irrigation to maintain timely and adequate consumptive water use of crops can only be considered in the context of the whole soil-plant-atmosphere continuum. In other words, for a particular environment, recommendations of water requirement of a stated crop would be dictated by the level of fertilization to which economic yield response will be obtained.
Fertilizer is usually applied either over the entire soil surface by broadcasting (and at times ploughed in); in a localised area below the surface close to seed or plant, usually termed 'banding' or row placement; or by 'fertigation', a recent innovation used to describe the introduction and application of soluble fertilizer material to the land through irrigation water, typically in sprinkler and trickle systems.

These patterns of fertilizer application, coupled with the accumulation of organic matter and the cycling of nutrients from the subsoil to the surface by plants and earth-dwelling fauna tend to favour (Veits, 1972) concentrations of extractable and exchangeable nutrients in the surface soil, held there by adsorption on clays and organic matter. Unfortunately enough, water availability fluctuates most in the surface soil that usually contains highest concentrations of the soil and fertilizer nutrients.

The preponderance of evidence obtainable in the works of Veits (1966), Begg and Turner (1976) and Sumner and Boswell (1981) indicates that drought or water deficit decreases nutrient availability to plants as measured by total nutrient uptake and sometimes in reduced concentration. Sumner and Boswell state in principle, that as crop depletes water in the surface layer of soil so that nutrient-laden mass flow of water is unable to meet its demand, its growth rate will decrease or in the alternative, the crop would have to speed up its rate of root extension into new, undepleted soil areas in order to increase the rates of water and nutrient supplies to sustain
growth.

With specific reference to phosphate, the test nutrient in this study, most researchers including Larsen (1967), Williams (1971), and Hagin and Turner (1982) hold the common view that phosphate uptake by crop is influenced very much by root proliferation since the utilizable phosphate ion ($H_2PO_4^{-}$ ionic species) is limited in movement. Therefore, moisture content of soils, influencing both root development and phosphate diffusion, interact strongly with phosphorus uptake by plants — cultivated and eutrophic ones all alike.

In dry conditions or not well-irrigated fields, the absorption of phosphorus by crops is reduced, presumably, by longer diffusion paths which may be compensated for by an increase in phosphate concentration (Olsen et al., 1961). It was shown for soybean that phosphorus uptake was impaired by high moisture stress, largely through its influence on phosphate diffusion in the soil (Marais and Wiersma, 1976).

According to Black (1966), in humid and irrigated regions, when the plough layer quickly goes dry, the subsoil is usually moist to depths beyond the maximum extension of crop roots. An increase in soil fertility under these conditions may increase the use of subsoil water, provided that deep penetration of roots is not inhibited by unfavourable physical and chemical properties of the soil. That is to say, that, by increasing the fertilizer even in the face of deficient water supply in the upper layers of a soil profile, a crop will be able to develop deeper and denser root system to explore deeper layers of the
soil profile for moisture. But to this recommendation, Veits (1972) cautions that this could be another kind of "drought" affecting root activity in which the plant is getting its water from one part of the soil deficient in nutrients while the soil's main supply of nutrients is locked up in dry soil lacking active roots. He adds however, that wheat and some species of wheatgrass (and perhaps some many other crop species) growing in wet soil have sufficient capability to absorb sufficient P and store it for use during periods when P availability in surface soil is low, but this depends on the concentration of P in the soil solution and the duration and frequency of the wet or dry periods.

2.4 State of Knowledge in Irrigated Cowpea Research

Cowpeas (Vigna unguiculata [L.] Walp.) are grown for dry bean production, mature green pods, leaves and hay. Efficient irrigation practices are needed for both shoot biomass production and dry beans.

For soybeans, Constable and Hearn (1980) proposed that fewer irrigations could be applied during the vegetative phase than is the present commercial practice in Australia, and the water saved could be used to grow a larger area of crop. Similar studies have been undertaken for cowpea in several ecological zones. Turk et al (1980) and Shouse et al (1981) demonstrated that for cowpeas in a rain-free environment, water use may be reduced by withholding irrigation during the vegetative stage without affecting seed yield. But, added Turk and his group, the influence of vegetative stage drought on seed
yield may depend upon subsequent environmental conditions during flowering and pod filling. This is partly in agreement with one of the observations of Summerfield et al. (1976) that moisture stress can reduce productivity considerably during the period from emergence to first flower, but with determinate cultivars, this may not significantly affect yields when stress occurs thereafter. In a recent experiment, Ziska and Hall (1983), working on cowpea at Riverside, California, found that vegetative stage drought caused significant reductions in seed yield when the crop was irrigated at intervals of 15 days. They felt that this irrigation treatment probably did not permit sufficient recovery of growth after resumption of normal irrigation following the vegetative stage drought. The harvested crop did in fact record lower shoot biomass production than the ones that were well-watered. In the same experiment, vegetative stage drought did not influence biomass production under low or high nitrogen fertilization.

The application of fertilizer P to cowpea has been widely reported to improve nodulation, increase vegetative growth rate and hence dry matter production, and raise grain yield (Tewari, 1965; Rhoades, 1980; and Kang and Nangju, 1983). On the other hand, cowpea subjected to water stress during the active vegetative stage experienced reduced seasonal nitrogen fixation; however, the reduction in nitrogen supply to the plants was small, and did not reduce seed yield (Tewari, 1965).

Clearly, from the onset, the investigator must be aware of whether the crop is to be irrigated for hay or its beans because
of several unequivocal findings in different environments.

These major highlights would serve as a useful guide though such findings in themselves are not universally expected:

i. Major increases in water use efficiency may be achieved by withholding irrigation from plant emergence to the first appearance of macroscopic floral buds, providing a 'reasonable' supply of water is present in the soil profile and no precipitation occurs (Ziska and Hall, 1983). In many circumstances however (Allen and Lambert, 1971), economic analysis indicates that planned water deficits will only be profitable if yields are maintained close to maximum levels because the savings from reductions in applied water may be small compared to the value of the crop.

ii. Excessive moisture, abundant soil nitrogen and high phosphorus availability combine to favour luxuriant foliage production. This is very desirable in hay production or fresh forage. Where cowpea is cultivated for commercial seed production, excessive leaf and stem production is considered superfluous and has no real advantage for pod production and ultimate seed yield (Kang and Nangju, 1983).

iii. Vegetative stage water stress has been observed by Zisk and Hall (1983) to result in increased damage
due to lesser corn stalk borer (or Elasmopalpus lignosellus) and charcoal rot (Macrophomina phaseoli). Frequent irrigation at any stage of crop growth increases chances of attack by fungi, virus and nematodes (Summerfield, 1974 and Sinha, 1977).

It appears that the factors responsible for the broad adaptation of cowpeas are poorly understood and Sinha (1977) did agree that cowpea can yield satisfactorily under a greater diversity of climatic, soil and cultural conditions than most other leguminous crops. The interactive effects of irrigation versus phosphorus fertilizer and irrigation versus nitrogen fertilizer were studied respectively by Malik (1974) in India and Ziska and Hall (1983) in California, United States and these effects could be used to develop cowpea production functions. But these crop production functions are of limited value because they are site specific, integrating a range of relatively unquantified environmental effects. Therefore, for cowpea, experimental studies relating irrigation, fertilizer application, crop yield development and phosphorus uptake are needed for water and soil fertility management, especially in areas where production functions for the crop are not available at present. This field study, conducted to obtain information about cowpea performance in a humid environment is therefore, not unreasonable.
III. MATERIALS AND METHODS

A. EXPERIMENTAL METHODS

3.1 Irrigation System Design

The field experiment was conducted using a hand-move sprinkler lateral designed specifically for this study. The irrigation design procedure is essentially as described elsewhere (BCMAF, 1983).

Meteorological data from the weather recording station located on the University of British Columbia campus were obtained for 20 years and only those of the relevant months were utilized (Appendix A). Crop potential evapotranspiration was computed from Class 'A' pan evaporation records and coefficients according to the method of Doorenbos and Pruitt (1977). Crop coefficients for the irrigation months were evaluated using part of Appendix A in conjunction with tables given in Doorenbos and Kassam (1979). Soil texture from three representative profile sites of the experimental area was found to be sandy loam, 30cm thick, overlying loamy sand at least 60cm thick (Table I).
### Table I - Soil Report of the Experimental Area

<table>
<thead>
<tr>
<th>SAMPLING SITES OR PITS*</th>
<th>CROP AND ROOT DEPTH</th>
<th>SOIL PROFILE</th>
<th>MAX.</th>
<th>ABLE RATE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>DEPTH (cm)</td>
<td>TEXTURE</td>
<td>AWSC (mm)</td>
</tr>
<tr>
<td>A</td>
<td>Cowpea (Vigna unguiculata)</td>
<td>0 - 30</td>
<td>SANDY</td>
<td>38.1</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>30 - 60</td>
<td>LOAM (1.5 in)</td>
<td>30.5</td>
</tr>
<tr>
<td>C</td>
<td>60 cm</td>
<td>60 - 90</td>
<td>SAND</td>
<td></td>
</tr>
</tbody>
</table>

* Soil samples were taken from three depths (0-30, 30-60, and 60-90 cm) from pits A, B and C.

3.1.1 **Maximum Crop ET Estimation By Pan Evaporation**

From Doorenbos and Pruitt (1977), the following equations were extracted:

\[ ET_o = K_p \times ET_p \] [3.1]

and

\[ ET(max) = K \times ET_o \] [3.2]

where:

ET(max) = reference crop maximum evapotranspiration, mm/day
$K = \text{crop coefficient}$

$ET_0 = \text{reference evaporation}$

$ET_p = \text{Class 'A' pan evaporation rate, mm/day}$

$K_p = \text{pan coefficient.}$

Based on cowpea's lifespan of 90-100 days when it is to be harvested for forage, the tabulation in Table II was obtained using Doorenbos and Pruitt (1977) and Doorenbos and Kassam (1979). Average (over 20 years) relative humidity between May and August, inclusive, of 70-80% and wind speed of 112-144 km/day (very strong) were estimated from the quoted reference and used in subsequent computations.

Table II - Computed Evapotranspiration Information

<table>
<thead>
<tr>
<th>MONTH</th>
<th>PAN COEFFICIENT ($K_p$)</th>
<th>CROP COEFFICIENT ($K$)</th>
<th>REFERENCE EVAPORATION ($ET_0$), mm/day</th>
<th>MEAN ET (max), mm/day</th>
<th>PEAK ET, mm/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>0.8</td>
<td>0.75</td>
<td>3.6</td>
<td>2.5</td>
<td>3.3</td>
</tr>
<tr>
<td>June</td>
<td>0.8</td>
<td>0.75</td>
<td>3.5</td>
<td>2.5</td>
<td>3.3</td>
</tr>
<tr>
<td>July</td>
<td>0.8</td>
<td>1.05</td>
<td>3.9</td>
<td>4.1</td>
<td>4.6</td>
</tr>
<tr>
<td>Aug.</td>
<td>0.8</td>
<td>0.95</td>
<td>3.3</td>
<td>3.0</td>
<td>4.1</td>
</tr>
<tr>
<td>Sept.</td>
<td>0.7</td>
<td>0.90</td>
<td>3.3</td>
<td>3.0</td>
<td>3.6</td>
</tr>
</tbody>
</table>
3.1.2 Irrigation System Design Computations

Cowpea has an effective rooting depth of 60.5 cm (2 ft). For the soil at the site of the experiment, the available water storage capacity, AWSC = 68.58 mm (Table I). In this design, an availability coefficient of 50% was assumed. Availability coefficient (AV. C) represents that portion of the total AWSC that can be depleted before irrigation is necessary. Then, the following calculations were performed:

(a) Maximum soil water deficit, MSWD, is
\[ \text{AWSC} \times \text{Av. C} = 68.58 \times 50\% = 34.28 \text{ mm} \ (1.35 \text{ in}). \]

(b) Gross Water Requirement, GWR = MSWD/Application Efficiency = 34.28/0.80 = 42.85 mm (1.7 in). Here, an application efficiency of 80% was assumed based on wind speed and average temperature during the irrigation season (BCMAF, 1983).

(c) Irrigation application rate, A.R = GWR/Time set = 42.85 mm/6 hrs = 7.14 mm/hr (0.28 in/hr). A time set of 6 hours was chosen because it was intended to operate the irrigation system during the calm hours of the morning and if need be, evening; a longer period of time set would entail enchroaching into the afternoon hours which were quite windy, and this was not desirable. Sprinkling rate of 7.1 mm/hr (0.28 in/hr) is less than the maximum intake rate of the soil (Table I). Therefore, this A.R is acceptable.

(d) Irrigation interval, I.I = MSWD/Peak ET.
From Table II, the intervals are as follows:

May 10 days
June 10 "
3.1.3 Sprinkler Selection and Configuration

The selection method was a compromise between the design information and the wetted diameter at optimum operating pressure (206.9 KPa). A Rainbird Turf Sprinkler, model 2800A Standard spray nozzle was selected with the following configuration:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application rate</td>
<td>6.1 mm/hr (24 in/hr)</td>
</tr>
<tr>
<td>Nozzle</td>
<td>2800A-F [Full]</td>
</tr>
<tr>
<td>Operating pressure</td>
<td>206.9 KPa (30 psi)</td>
</tr>
<tr>
<td>Wetted diameter</td>
<td>7.3 m (24 ft)</td>
</tr>
<tr>
<td>Flow rate/nozzle</td>
<td>0.16 l/s (2.5 U.S gpm)</td>
</tr>
<tr>
<td>Coefficient of Uniformity</td>
<td>84%</td>
</tr>
<tr>
<td>Wind range</td>
<td>3.2 - 6.5 km/hr (2 - 5 mph)</td>
</tr>
</tbody>
</table>

3.1.4 Lateral Design

- 4 sprinklers, each sprinkling 0.14 l/s (2.23 gpm) at 206.9 KPa (30 psi) were used. Total flow into the single lateral was 0.56 l/s (8.92 gpm). This flow rate could be delivered by 25.4mm internal diameter pipe without flow velocity exceeding 1.5 m/s (5 ft/s).
- a 38.1mm diameter (internal) PVC pipe was chosen for ease of handling in the field.
Figure 1 - Line-Source Sprinkler System

**UNLESS STATED, ALL DIMENSIONS ARE IN m**
• sprinkler spacing was 3.66m - an overlap of 50% along the lateral, since the identical sprinklers had a nozzle throw of 3.66m when operating at 206.9 KPa.

• Figure 1 shows the lateral and other accessories.

3.1.5 Mainline Design

76 mm diameter aluminium pipes already being used on the University of British Columbia Research farm were used. Irrigation water outlet was located about 3 m from the experimental area. Water was delivered at a maximum pressure of 482.7 KPa from the underground network of mainline hydrant covering the whole University farm.

3.2 Experimental Design and System Layout

3.2.1 Irrigation System Characteristics

The single lateral line with suitably spaced sprinklers was designed to provide a wetting pattern with features similar to the 'continuous variable design' first described by Fox (1973) and further developed for irrigation research by Hundtoft and Wu (1974) and Hanks et al (1976).

The sprinkler nozzle size chosen had a wetted diameter of 7.3 m. This was the width of an experimental plot. Figure 2 shows a schematic layout of the line-source sprinkler plot design. The line of sprinklers was through the centre of the plot and across the row direction. The wetted length of each plot was 14.5m (48ft). However, only 10.9m (36ft) of length was used as 3.6m (12ft) was left out at each end of the lateral from
the first and last sprinklers, to account for border effects and lack of sprinkler overlap at these ends.

The portable irrigation system produces a water application pattern which is uniform along the length of the plot and continuously, but uniformly variable across the plot. This is made possible by using sprinklers of same configuration. Furthermore, individual sprinklers inherently produce triangular-shaped profile when operated in low winds at the design pressure.

These are the characteristics that make the irrigation system suitable for the conduct of a compact experiment in the field.

3.2.2 Experimental Design and Field Layout

From Fig. 2, an experimental plot was, in effect, 7.3 m (24 ft) wide by 10.9 m (36 ft) long (15 ridges or rows). The width of the plot was governed by the wetted diameter of the sprinklers but the length could be increased by designing for more than the 4 sprinklers used in this study. Within each plot, there were two replications or blocks— one on either side of the sprinkler line. There were 5 plots comprising the control or non-irrigated plot and different irrigation scheduling procedures in the remaining 4. The experimental design was a randomized complete block and the field layout is given in Figure 3.

This field experiment was conducted during the Summer of 1983 on the University of British Columbia Plant Science Field, South Campus Road along South-West Marine Drive, Vancouver,
British Columbia.

The soil type is Bose sandy loam. The site was last planted to corn and fertilized (name and dose of fertilizer not documented) four years before the start of this experiment. It was, however, habitual to harrow the whole area several times during Spring and Summer even when nothing was being grown.

3.3 Application of Treatments

The growth and yield response of a test crop to three irrigation water levels (hereafter denoted W1, W2 and W3) under five phosphorus fertilizer levels (P1, P2, P3, P4 and P5) when subjected to five irrigation scheduling techniques (S1, S2, S3, S4 and S5) were to be investigated. Thus, there were 75 treatment combinations each replicated twice and, it follows that the experiment consisted of 75 experimental units each appearing in two blocks.

Cowpea (Vigna unguiculata [L.] Walp.) was selected for the study. Dry matter production on the basis of metric tons per hectare (t/ha) of areal dry matter produced was used as the yield indicator. The plants were harvested when the more advanced individuals reached the late boot stage immediately preceding the appearance of their inflorescences.

3.3.1 Crop Establishment and Maintenance

White variety of blackeyed pea seeds were planted. The seeds were moistened with clean water and, Nitragin inoculant (cultures of nitrogen-fixing bacteria, Rhizobium spp, in a peat-base medium from the Nitragin Company, Clearwater, Florida
33516, USA) was added and carefully shaken until seeds were thoroughly coated with the inoculant. [Preliminary soil analysis of samples from the site showed evidently high organic matter content and total nitrogen but this seed treatment was a further insurance against nitrogen-induced problems].

Seeds were planted on June 20th, 1983. Within-row spacing was 30cm (1ft) while the rows were 60cm (2ft) apart. Depth of seed placement was 1.27-2.54cm on the row, and two seeds were placed per hole requiring no thinning. Before planting, germination test was ran and about 95% viability was obtained. Seeds germinated five to seven days after planting. There were 12 stands per experimental unit, 180 stands per replicate, 360 stands per plot and a total of 1800 stands in the entire experimental area. A stand had 2 plants or one (in the latter case, when the second failed to emerge or died off even after replanting).

Fertilizer was applied two days after 90 percent emergence was recorded.

Weed control was manual and performed three times - on July 20th, July 31st and August 25th, 1983. No pest or disease symptom was observed hence no control in that direction was undertaken.
Figure 2 - Schematic of a Test Plot

3.66 m nozzle throw at 206.9 KPa

Direction of increase in soil moisture levels

W1  W2  W3  W3  W2  W1

IRRIGATION LINE SOURCE

MAIN SHUT-OFF VALVE

MAIN LINE HYDRANT

FARM IRRIGATION WATER OUTLET SOURCE
Figure 3 - Experimental Design and System Layout in the Field

MAIN LINE

FLEXIBLE HOSE

0.60m foot path round each plot

IRRIGATION WATER SOURCE

ROW DIRECTION

Slope = 3 - 5%

38.41 m

7.31 m

12.19 m

10.97 m

38.41 m

7.31 m

12.19 m

10.97 m
3.3.2 Irrigation Water Treatments

Water treatments were imposed by placing the single line-source sprinkler system designed, in the middle of each plot. This system (Hanks et al., 1976), applied water uniformly down the lateral line in the experimental area and continuously, but in uniformly decreasing amounts with distance from the line when operated in early mornings or late evenings under calm winds. This water application pattern provided high flexibility in the number of irrigation water levels to select within practical limits.

Figure 4 shows an outlay of the lateral and the soil sampling legend for gravimetric soil moisture determinations before and after irrigation and after a rainfall event. The three irrigation water levels, W1(31.2mm), W2(106.8mm) and W3(169.8mm) were essentially, soil sampling sites located about 1 m (3.5ft), 2 m (6.5ft) and 3 m (10ft) respectively away from either side of the lateral. Because of uniform water distribution along the plot at a distance perfectly parallel to the lateral, and assuming sprinkler operation during low wind speed, sampling along the line W1 or W2 was assumed to give an estimate of the same depth of irrigation water.

A major limitation of the continuously variable design using sprinklers was also exhibited here: the water levels could not be randomized. The statistical liability of this design characteristic will be discussed later.

Since reasonable uniformity along the line could be achieved only under calm wind conditions (Hanks et al., 1976),
sprinkling in this experiment was done in the early hours of the morning except for Plot 2 (or S2) in which time set was 6 hours and coupled with the fact that irrigation was applied in intervals (intermittently) to keep runoff at zero, irrigating this plot often stretched to afternoon and at times wind speed was so high that it had to be continued in the evening.

One row of plants each (across field machinery rows) on either side of the sprinkler lateral position was left out entirely from experimental measurements because:

(i) of exceptional influence over them as compared to the rest, of starting and stopping sprinkler operation, and
(ii) constant movement of lateral (from experience) damaged or disturbed these two rows uniquely.

The areas used for plant harvests as well as plant and soil water determinations are illustrated in Figure 4. Crop water use was determined by hydrologic balance at each soil sampling site. Applied water was measured with catch cans and is reported in Appendix B. Precipitation record was obtained from the University of British Columbia weather station. Soil moisture depletion by crop between irrigations was measured by gravimetric difference between pre- and post-irrigation samplings.
Seasonal and shorter time periods of water use were determined using the equation:

\[ 
ET = IRR + P + D + \Delta S - Q \]  
where:

ET = water use (eg seasonal, monthly), mm
IRR= irrigation water applied
P = precipitation
D = drainage
\Delta S = change in stored soil moisture for the period considered
Q = surface runoff.

In the application of this moisture balance equation, the following assumptions were made:

1. All precipitation excluded runoff — i.e., all rainfall water passed through the root zone
2. Drainage, which assumes a positive value when there is contribution from groundwater and a negative value when there is deep percolation from IRR or P, was taken as zero under either circumstance. But in irrigating the root zone to field capacity, deep percolation was unavoidable.

Water use and hence water use efficiency under the different irrigation scheduling methods were determined by balancing these hydrologic inputs.
Figure 4 - Experimental Units and Soil Sampling Sites

LEGEND:

P Arbitrarily randomized fertilizer P levels.
X—X Field machinery row orientation
W3—W3 All soil samples taken along this line after an irrigation were assumed to have received the same amount of water.
WO—WO Disturbed rows, not sampled for analysis

An experimental unit with 12 plant stands, 2 plants/hole
3.3.3 Phosphorus Fertilizer Treatments

Five levels (0, 50, 60, 70 and 80 kg/ha) P$_2$O$_5$ of single superphosphate (18% active ingredient) were applied. This was equivalent to applying 0, 6.2, 7.4, 8.6 and 9.8 g/plant stand respectively (Table III).

Fertilizer was applied on June 25th, 1983. Going by the standard practice of row fertilizer application, a hole about 5cm deep was dug round and 2.54cm away from the crop stand, manually. The appropriate amount of fertilizer was applied in the ring and covered back with top soil.

The P fertilizer treatments, henceforth referred to as P1, P2, P3, P4 and P5, in that order, were randomized along the plot and in effect, were at right angles to the water variable. Figure 4 shows an arbitrary randomization in one replicate of a plot. Each level of fertilizer was applied on three rows — the latter ran across the length of the plot. Further information on the fertilizer treatments is as given in Table III.
Table III - Fertilizer data

<table>
<thead>
<tr>
<th>FERTILIZER LEVEL</th>
<th>FERT. RATE kg/ha a.i.*</th>
<th>ACTUAL Wt of 18% FERT. (kg/ha)</th>
<th>FERT. Wt PER SUBPLOT (g)</th>
<th>Wt of FERT per stand (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>P2</td>
<td>50</td>
<td>277.8</td>
<td>222.2</td>
<td>6.2</td>
</tr>
<tr>
<td>P3</td>
<td>60</td>
<td>333.3</td>
<td>266.7</td>
<td>7.4</td>
</tr>
<tr>
<td>P4</td>
<td>70</td>
<td>388.9</td>
<td>311.1</td>
<td>8.6</td>
</tr>
<tr>
<td>P5</td>
<td>80</td>
<td>444.4</td>
<td>355.6</td>
<td>9.8</td>
</tr>
</tbody>
</table>

Total amount used = 11.6 kg
* a.i. = active ingredient

3.3.4 Irrigation Scheduling Techniques

In Section 3.1, climatic, soil, and crop data were used to estimate evapotranspiration (ET) and the latter was in turn utilized in subsection 3.1.2 to derive irrigation intervals. The relationship between the actual ET experienced by the crop and the maximum possible ET varies with climatic conditions, crop development and soil moisture. Actual evapotranspiration will proceed at approximately the maximum rate until perhaps half of the available soil moisture has been depleted (Jensen et al., 1970; Stegman et al., 1981 and English and Nuss, 1982). Beyond that point, actual ET will fall progressively farther...
behind the maximum rate. The key assumption used in specifying the irrigation schedules in this study was that the ratio of actual evapotranspiration (ET) to maximum possible evapotranspiration (ET*) will equal 1.0 until 50% (availability coefficient) of the maximum available soil moisture has been depleted after which it would decline linearly from 1.0 to 0 as available moisture approaches exhaustion.

On the basis of this simplified but widely used soil moisture depletion model, a relationship between time set, minimum irrigation interval, ET and Av.C was established. ET* was assumed constant for a period of several days so that the elapsed time or irrigation interval until 50% depletion ($T_{50}$) occurs will be

$$T_{50} = M_0/(2ET^*)$$  \[3.4\]

where $M_0$ denotes the initial soil moisture.

Using a selected time set of 6 hrs., and assuming irrigation schedules in which any ET deficits were uniformly distributed throughout each month, in conjunction with the specification that AWSC in the root zone would not be depleted by more than 50% between irrigations during a period of maximum evapotranspiration demand, the design for full irrigation produced these irrigation intervals in the cropping months: June = 10 days, July = 8 days, August = 8 days and September = 10 days. The following irrigation schedules and their specifications were derived from the full irrigation system:
This was the control. It was allotted Plot I (Figure 3). This plot was irrigated to field capacity before planting to ensure germination and good seedling establishment. It received no further irrigation water but no attempt was made to control the rainfall that fell on it, just as any other plot.

Allotted Plot II, this was the irrigation schedule specified for the full irrigation system. The configuration of the full irrigation system was based on standard design procedures as described in Section 3.1 of this chapter, and the key assumptions and relationships discussed above. In summary, it is helpful to mention again that time set per irrigation was 6 hours, to wet 60cm (or 2ft) of soil to FC with 42.85mm (1.7in) of irrigation water, sprinkling at a rate of 7.1mm/hr (0.28in/hr). The minimum interval between irrigations (whenever there was no rainfall inbetween) was 10 days in June, 8 days in July, and 8 days in August. Early in September, the Fall rains had stabilized, the soil was quite moist and therefore, no further water was applied. In fact, no plot was irrigated in September.

This is the first of two high-frequency deficit irrigations. On the basis of intervals enumerated in S2, if no rainfall event occurred within
any particular interval (or between any two successive irrigations), the same amount of water would have been applied as in S2 but in three separate and smaller amounts (14.3mm each). However, when there was enough rainfall, say, soon after applying the first one third of 42.85mm, to carry the crop to the next interval, 2/3 of 42.85mm of water and 4 man-hours would have been saved in comparison to S2 in which the whole of that 42.85mm of water was applied requiring 6 man-hours per irrigation. This irrigation schedule was ran on Plot III. Technically, only 16.5% = 1/3 of 50% AWSC depletion was allowed under this procedure.

[S4]. Plot IV, also called 'Stage-of-Growth' scheduling method, was irrigated based on the lifespan of the crop and in particular, the type of plant product to be harvested. The test crop, Cowpea, was harvested for its dry matter yield and accordingly, the time from planting to harvest (90 days), was broken into three vegetative stages, strictly on the basis of age:

1st stage = emergence to 30 days;
2nd stage = 31-60 days;
3rd stage = 61-90 days.

The plot was irrigated to field capacity by appropriate lateral overlapping on the 4th July and on 5th August. The third irrigation was scheduled for
September but for the reason stated under S2, this was not implemented.

[S5]. This was the 2nd high-frequency irrigation schedule. It was conducted on Plot V and was irrigated at half the calculated interval in S2 for each month and only one half of the gross water required was applied at each time set i.e., 3 hours. In essence, the crop was allowed to deplete only 1/2 of S2 irrigation depth or 25% of AWSC or 1/2 of 50% AWSC before the next irrigation became necessary.

All plots were irrigated before planting. Therefore, irrigation water treatments and scheduling procedures started after seedling emergence.

B. ANALYTICAL PROCEDURES

3.4 The Soil

3.4.1 Soil Analyses

Soil samples were taken from three representative pits at the site immediately before the experiment began and immediately after the crop was harvested. Samples were collected from three depths (Table I). The following analyses were performed:

i. Soil pH (soil in calcium chloride solution)

ii. Available K, Mg and Ca by Morgan's extraction method

iii. Available P by Bray-1 method

iv. Organic matter content by Walkley-Black method
v. Available nitrate-N
vi. Sulphate-S
vii. Soil texture.

These are standard laboratory soil tests and references to the procedures adopted could be made to Black et al. (1965) and Lavkulich (1983).

3.4.2 Soil Moisture Determinations During Experiment

Soil sampling for gravimetric moisture content determinations was undertaken for each sampling site for two profile layers — the top 0-30cm and 30-60cm by augering on the following bases:

- before every irrigation
- 4-5 hours after irrigating Plots III and V
- 2-3 days after irrigating Plots II and IV
- 2-3 days after every heavy rainfall.

Note:

Plots II and IV were irrigated to field capacity, therefore, it was necessary to allow moisture distribution in the profile for a period of 2-3 days.
3.5 The Crop

3.5.1 Crop Growth Indicators

The plant performance at different stages of growth was assessed using three growth indicators. The following measurements were taken on a weekly basis for seven weeks beginning one week after seedling emergence:

1. Plant height
2. Number of nodes per plant
3. Number of trifoliates per plant.

These growth indices were chosen out of many others recommended for cowpea because, they were relatively easy to measure, requiring little equipment. Furthermore, Sinha (1977) explained that the realisation of a high leaf surface area (related to trifoliate counts per plant) as a dry matter "source" to be mobilised to sites of accumulation or "sink" as the crop matures is vital; and according to Kassam (1976), seed yield in cowpea is largely dependent on the total number of nodes produced before the onset of flowering and the number of pods subsequently produced and retained at these nodes. Thus, an explanation for the ultimate yield obtained from a combination of treatments originates from a data source of these physiological performances of the crop at the various stages of its growth cycle.

These growth indicators were measured on three healthy-looking plants representative of an experimental unit. Only the mean of the recorded values was reported in each case.
3.5.2 Crop Yield

The crop was harvested for dry matter production on September 20th, 1983. Only the above-ground plant part was taken. However, some plants were uprooted at random from each plot to give a general idea about the actual rooting depth achieved by the crop and the extent of nodulation when cowpea was inoculated with non-specific bacteria in a field where the crop had never been cultivated before. The areal parts harvested were weighed fresh in the field before drying for dry matter measurement.

3.5.3 Nutrient Uptake

The crop was harvested at the boot stage at which time, some stands had already developed flower buds. Most workers on cowpea — the most authoritative being Shanthakumari and Sinha (1972 and 1973), agree that photosynthesis in cowpea leaves ceases immediately prior to flowering. Grain filling is by transfer of assimilates from these leaves, especially terminal ones, and from nodules as well as from the still photosynthesizing fruit wall. Hence, collection of terminal leaves immediately prior to flowering gives a good index of uptake of applied nutrient. Nine terminal leaves per experimental unit (3 leaves from each plant collected in subsection 2.5.2 above) were preserved for foliar (chemical) analyses.

The method of preparation and total analyses of the leaf samples for N, P, K, Ca and Mg was by the Parkinson and Allen Digestion for foliage (Lavkulich, 1983).
3.5.4 Statistical Comparison of Results

A statistical analysis was performed to determine the main effects and interactions of irrigation amount of water, phosphorus fertilizer and irrigation schedules on dry matter produced by the crop. The results of this analysis are presented in the form of 'Analysis of Variance' (ANOVA) table in chapter IV. Significance levels of 5 and 1% were used to determine yield differences between any two treatment means.

Phosphate uptake data was also subjected to a similar statistical analysis.
IV. RESULTS AND DISCUSSION

4.1 Soil Properties

Results of analyses of soil samples taken from the experimental site prior to planting are shown in Table IV. The soil is slightly acidic down to the 90cm profile depth analysed. The area is well-drained, on a slope of 3-5%. Other pertinent soil properties are as given in the same table.

It was necessary to determine the moisture retention properties of the soil. Figure 5 is a presentation of the soil moisture characteristic curve of the plow layer (approximately 30cm of top soil, Curve A). The plot of the moisture retention characteristic of the subsoil (Curve B) was found to follow this one very closely and is also shown on the same figure.

Table IV - Soil Analyses Results Based on Morgan Soil Testing System

<table>
<thead>
<tr>
<th>SAMPLE DEPTH (cm)</th>
<th>ORG. MATTER PH (%)</th>
<th>AVAILABLE NUTRIENTS IN SOIL</th>
<th>Nitrate-N ppm</th>
<th>P ppm</th>
<th>K ppm</th>
<th>Sulfate-S ppm</th>
<th>TEXTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30</td>
<td>5.9</td>
<td>1.35</td>
<td>75</td>
<td>12</td>
<td>14</td>
<td>nd</td>
<td>SL</td>
</tr>
<tr>
<td>30-60</td>
<td>5.5</td>
<td>0.88</td>
<td>16</td>
<td>12</td>
<td>12</td>
<td>nd</td>
<td>LS</td>
</tr>
<tr>
<td>60-90</td>
<td>5.3</td>
<td>0.75</td>
<td>25</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>SL</td>
</tr>
</tbody>
</table>

nd = not detected in soil sample; SL = sandy loam; pH = soil in 0.01N Calcium chloride (1:1); LS = loamy sand

Results represent the average values for 3 profiles.
It can be seen in curve A of Figure 5 that the field capacity (suction of about 30 KPa or 0.3 bar) of the top layer of soil is 30.7% while the permanent wilting point (suction of 1500 KPa or 15 bars) is 12.1%. One obvious limitation of this curve (derived from results of a laboratory moisture retention test) is the fact that whereas field situation during irrigation is a series of wetting and drying cycles, the laboratory test was a straight-forward drying exercise. Subsequent conversions of the curve to yield available water depletion thus, overlook hysteresis effect and at best, then, are approximations which must be contained with as they always have been in irrigation practice. The dry bulk density of the soil was found to be 1.01 g/cc.

Soil test values for available P at the end of the experimental run are shown in Table V. The availability trend reflects the rate of phosphorus fertilizer applied. It may be noted that the fertilizer was band-applied and subsequent sampling was from these highly concentrated sites – a sort of quasi-pot experiment. Figure 6 is a further illustration of the same data. Analysis for K, Ca, Mg and organic matter content are also reported (Table VI).
Figure 5 - Moisture Retention Curves of Experimental Soil

Legend

△ CURVE A
× CURVE B

FIELD CAPACITY (FC)

SUBSOIL CURVE B

TOP SOIL CURVE A

PERMANENT WILTING POINT (PWP)
Table V - Mean Extractable (Available) P in soil in ppm

<table>
<thead>
<tr>
<th>FERTILIZER</th>
<th>TREATMENTS</th>
<th>P</th>
<th>L</th>
<th>O</th>
<th>T</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S1</td>
<td>S2</td>
<td>S3</td>
<td>S4</td>
<td>S5</td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>64</td>
<td>98</td>
<td>36</td>
<td>72</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>122</td>
<td>132</td>
<td>134</td>
<td>174</td>
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</tr>
<tr>
<td>P3</td>
<td>124</td>
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<td>177</td>
<td>120</td>
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<td></td>
</tr>
<tr>
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<td>160</td>
<td>232</td>
<td>228</td>
<td>186</td>
<td>206</td>
<td></td>
</tr>
<tr>
<td>P5</td>
<td>186</td>
<td>186</td>
<td>204</td>
<td>166</td>
<td>238</td>
<td></td>
</tr>
</tbody>
</table>

4.2 Crop Development

Weekly measurements of rate of stem elongation, trifoliate counts and number of nodes per plant as from seven days after emergence were carried out. For all plots, the number of trifoliate leaves was 3-5 after the fourth week from seedling emergence and number of nodes was 5-7 per plant. However, on unfertilized plots, plants were a lighter green than fertilized plots. Cold soil temperatures and/or nitrogen deficiency were suspected. That there was no nitrogen deficiency became evident by the disappearance of this symptom after five weeks, at which time, day temperatures were a stable 15 deg. Celsius or over and the plants had also established themselves. Plants growing under the wettest treatment combination (S3W3) were most stunted.
throughout these 7 weeks compared to the control and less frequently irrigated plots.

The maximum root depth observed in profile pits was some 30cm, about 90 days after planting. Non-irrigated (control) plants exhibited the greatest root elongation, perhaps, because of the attempt by the plants under this treatment to explore the deeper profile layer for moisture, in view of the occasionally moisture-deficient top soil of this plot. A maximum root depth of 60cm was expected from this crop but it was obvious that mechanical impedance was not a restricting factor to vertical root development on this site. The combination of irrigation and band application of phosphorus fertilizer might have contributed to the shallow rooting as it was not necessary for the crop to extend its roots below 30cm of soil depth in this group of plots.

4.3 Crop Yield Response

Dry matter yields in relation to the different combinations of seasonal irrigation water, phosphorus fertilizer and irrigation scheduling techniques are as in Table VII. Table VIII contains the result of the analysis of variance (ANOVA) performed for the yield.

The statistical test revealed that block effect was not significant. This, in statistical terms, may be due to two reasons (Steel and Torrie, 1983): (a) the experiment was not successful in reducing error variance by the grouping of
Figure 6 - Extractable P in Soil

EXTRACTABLE P IN SOIL (ppm)

APPLIED PHOSPHATE (kg/ha)

Legend

△ SCHEDULE 1
× SCHEDULE 2
□ SCHEDULE 3
× SCHEDULE 4
× SCHEDULE 5
Table VI - Results of Soil Chemical Analyses.
(at end of experimental run)

<table>
<thead>
<tr>
<th>PLOT</th>
<th>TEST</th>
<th>FERTILIZER LEVELS</th>
<th>PHOSPHORUS</th>
<th>POTASSIUM</th>
<th>MAGNESIUM</th>
<th>CALCIUM</th>
<th>ORG. MATTER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>P1 P2 P3 P4 P5</td>
<td>52.0 76.0 128.0 116.0 96.0 152.0 108.0 212.0 212.0 160.0</td>
<td>0.17 0.20 0.16 0.22 0.16 0.19 0.34 0.12 0.56 0.19</td>
<td>1.41 1.46 1.77 1.46 1.41 1.46 1.56 1.16 1.56 1.46</td>
<td>16.64 17.24 19.66 16.94 16.64 19.06 17.85 14.82 18.76 18.45</td>
<td>2.5 2.4 2.1 2.6 2.1 2.8 1.9 2.3 2.7 2.6</td>
</tr>
<tr>
<td>P</td>
<td>160.0 36.0 160.0 104.0 152.0 150.0 268.0 196.0 156.0 176.0</td>
<td>0.23 0.22 0.20 0.20 0.22 0.19 0.17 0.20 0.14 0.14</td>
<td>1.61 1.36 1.51 1.41 1.26 1.71 1.51 1.41 1.11 1.26</td>
<td>17.55 16.64 17.24 18.45 16.64 18.45 19.06 16.64 14.22 17.24</td>
<td>2.4 2.4 1.9 1.9 2.5 2.5 2.7 2.5 2.1 2.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>1.36 1.51 1.16 1.71 1.36 1.36 1.36 1.36 1.01 1.56</td>
<td>15.73 17.55 15.73 16.03 16.64 14.52 16.03 16.94 12.10 18.45</td>
<td>2.0 1.9 2.1 2.4 1.9 2.1 2.2 2.2 1.8 2.2</td>
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Table VI continued

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<th>80.0</th>
<th>204.0</th>
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<table>
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<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

NB:

* P in ppm
* Ca, K and Mg in meq/100g soil
* Organic matter, O.M, in %
* A and B are replicates (blocks)
Table VII - Mean Dry Matter yield (metric tons/ha)

<table>
<thead>
<tr>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>W3</td>
<td>W2</td>
<td>W1</td>
<td>W3</td>
<td>W2</td>
<td>W1</td>
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<tr>
<td>11.8</td>
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<td>14.2</td>
<td>14.2</td>
<td>18.1</td>
<td>16.2</td>
<td>11.3</td>
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<td>15.2</td>
<td>19.6</td>
<td>17.1</td>
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<td>16.2</td>
<td>15.6</td>
<td>19.8</td>
<td>18.0</td>
<td>12.6</td>
</tr>
</tbody>
</table>

SUM  68.3  69.4  68.6  89.6  77.2  55.3  65.4  73.7  94.0  68.7  65.8  64.2  109.3  106.1  90.0
SUM  206.4  223.4  233.1  198.7  300.5
MEAN  68.8  74.5  77.7  68.2  100.2

S = IRRIGATION SCHEDULE
W = IRRIGATION WATER
P = PHOSPHORUS FERTILIZER TREATMENT
<table>
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<th>SOURCE OF VARIATION</th>
<th>DEGREE OF FREEDOM</th>
<th>SUM OF SQUARES</th>
<th>VARIANCE</th>
<th>F</th>
<th>% CONTRIBUTION</th>
</tr>
</thead>
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<td>81.4</td>
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<td>30163.3</td>
<td>312.59 **</td>
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<td>1742.8</td>
<td>18.06 **</td>
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<td>22782.7</td>
<td>236.09 **</td>
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</tr>
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<td>6507.3</td>
<td>67.40 **</td>
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<td>112.7</td>
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<td>(s-1)(p-1) = 16</td>
<td>11712.6</td>
<td>732.0</td>
<td>7.59 **</td>
<td>4.0</td>
</tr>
<tr>
<td>SWP</td>
<td>(s-1)(w-1)(p-1) = 32</td>
<td>8248.5</td>
<td>257.8</td>
<td>2.67 **</td>
<td>2.8</td>
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<tr>
<td>ERROR</td>
<td>(swp-1)(r-1) = 74</td>
<td>7139.0</td>
<td>96.5</td>
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<tr>
<td>TOTAL</td>
<td>(spwr-1) = 149</td>
<td>295410.9</td>
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</tbody>
</table>

Analysis of variance on raw data of yield from 2 replicates
n.s = not significant at 5% level
** = significant at 1% level
individual units into blocks, and (b) the units were essentially homogeneous to begin with. Considering the smallness in size of the experimental area (39 m by 14.6 m) and the data on pH, available K, Mg & Ca and soil organic matter content (Tables V and VI), one would be inclined to accept the latter reason as the major factor responsible for the statistical insignificance of the block treatments. Thus, the configurations of the surfaces do not differ, indicating that they are members of the same population of surfaces and differences in results would be attributed to the treatments.

4.3.1 Effect of Irrigation on Yields

In a factorial experiment of this nature, simple effects of individual treatments are never conclusive especially when there is either a first order interaction between any two factors considered or, as in this case, where all the three factors indicate that their influence on yield is dependent on each other. This latter case indicates that there is a statistically significant second order interaction \((W \times P \times S)\).

There was a positive response to irrigation water \((W)\) and this was statistically significant at 1% level. But, as mentioned in the preceding paragraph, this is not conclusive since it can be seen (Table VIII) that the contribution by sum of squares, SS, due to this effect in the factorial arrangement was a mere 1.2%. When compared to schedule and phosphorus with respectively 40.8% and 30.8% contributions, the physical interpretation of the effect of irrigation on yield becomes
clear: that it was highly influenced by other factors and hence might or might not be an important factor if it were tested separately in another experimental set-up. In other words, limiting the discussion to the result of this study alone, it is evident that amount of irrigation water affected cowpea yield, but because of its interactive effects with P and S detected by the experimental design, the possibility that W could as well have been an unimportant factor in cowpea production if tested separately and alone cannot be ruled out at this site.

In general, dry matter yield differences between W1 and W3 treatments were evident while the yields of W2 plants were not significantly different (0.05 level) from either those of W1 or W3. It should be mentioned here that S and W treatments were so intimately connected (not in statistical sense) in this experimental design that they have to be discussed alongside each other and not in isolation. As shown in Table VIII, the SxW interaction was significant at 1% level. The contribution by sum of squares, of this interactive effect ranked third (17.6 %) and demonstrated that it did substantially influence the differences in yields. Furthermore, it is statistically evident that these two variables did not act independently in their effects. The high contribution by sum of square(SS), of S treatment (40.8) was probably responsible for this result; it will be argued later in the text that S, the irrigation scheduling procedure tended to exert a greater impact on dry matter yield of cowpea than did the irrigation amount of water, W.
Since no attempt was made to control the amount of rainfall that fell on the different plots during the irrigation season, the cowpea crop was subjected to different water stress and nonstress periods depending on the irrigation schedule. The ANOVA (Table VIII) indicated significance at 0.01 level for S treatment. From a knowledge of the permanent wilting point (Figure 5), and by comparison with the gravimetric determinations (Appendix E) throughout the cropping period, it was evident that S1 (the control) and S4 (the Stage-of-Growth) plots were under moisture stress several times especially between June 26th and July 10th (4.9 mm rainfall total) and throughout August (46.8 mm rainfall).

Despite the apparent water deficits that prevailed in plots S1 and S4 early after germination and in August, S1 still produced high yields and perhaps, if it were possible to allow the crop to flower and fruit (night soil temperatures of below 8 deg. C in September preclude the success of this contemplation), ultimate grain yield might not have differed significantly from those of the other schedules. Growth rate of plant was slower and, number of trifoliates and nodes was relatively lower in S1 and S4 when compared to S2, S3 and S5. It appears the former group followed the concept of "crop conditioning" to water stress in view of the high dry matter yields obtained from them ultimately. These yields were however, lower for all fertilizer levels by comparison with yields from S2, S3 and S5 plants. Hsiao (1973), suggested that some reduction in leaf area from stresses in the early vegetative period of a crop will often
minimally affect yield of a reproductive organ because (i) reduced leaf area can allow greater canopy light penetration to maintain assimilative capacity, and (ii), assimilates accumulated during the day may exceed requirements for growth at night because of other growth-limiting factors (such as temperature and nutrient deficiencies). That optimally-irrigated (S2) and frequently-irrigated (S3 and S5) plants excelled in yield ultimately is in agreement with the conclusion of Stegman et al. (1981), that maximum yields are usually associated with maximum seasonal photosynthesis which requires optimal leaf area development and the maintenance of a healthy and photosynthetically active plant during the vegetative, reproductive and natural maturation stages.

Furthermore, Table VII illustrates that while maintaining the normal irrigation interval (S2) would produce reasonable yield, improving on this yield could be achieved by reducing the allowable water depletion by the technique of irrigating more frequently but with half the design consumptive use at each irrigation and twice within the design interval (S5). But there is a limit to the frequency of irrigation as far as this crop is concerned on this ecological site. Increasing the frequency from 50% allowable water depletion in S2 to 25% maximum soil water deficit in S5 increased yield in the order W3 > W2 > W1 but on further increase of this irrigation frequency to 3 times within the interval (S3), the identical yield trends recorded in S2 and S5 were reversed to W1 > W2 > W3, probably because of waterlogging and the chain of other soil complications set forth
once the soil was so treated. In fact, not only was the yield lower in this plot relative to plots 2 and 5, but it almost came down to the same order of magnitude recorded in the control plot (S1) and, the stage-of-growth scheduling procedure (S4) which was also clearly inadequately irrigated. Also, the quality of foliage was quite poor, which is a debit on its acceptability as good forage. The control plants produced the most succulent-looking foliage followed by the S2 plants.

These results demonstrated that on physiological grounds, the use of total water quantity that passed through the root zone (IRR + R + D) can have but limited usefulness since (1) the total water quantity in this case might fail to consider water distribution over the irrigation season as an important variable in its own right and (2) total irrigation water applied cannot be directly correlated with plant water use. Indeed, Clements (1964), using tissue moisture as a guide for irrigation during vegetative phase of sugar cane development, demonstrated that once tissue moisture level dropped significantly as a consequence of irrigation water being applied too late, and after the moisture stress has already triggered a drought reaction in the plant, slower growth and carbohydrate accumulation will result and, complete recovery from this setback in growth is difficult. The effect of water stress will be further discussed under its interaction with fertilizer treatments, but possible reasons for the failure of S1 and S4 plants to yield optimally have been offered by the points borrowed from Clements and stated above.
However, a significant point to reiterate at this juncture is that irrigation amount of water or total evapotranspiration was not as important in influencing cowpea yield as the time distribution of the applied water or the scheduling procedure under which the crop was grown.
**Table IX - S x P Interaction on Cowpea Yield, t/ha**

<table>
<thead>
<tr>
<th>FERTILIZER</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
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<td>16.2</td>
<td>17.8</td>
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**Table X - P x W Interaction on Cowpea Yield, t/ha**

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Figure 7 – Interaction of S and P Treatments on Yield

Legend

- △ SCHEDULE 1
- × SCHEDULE 2
- □ SCHEDULE 3
- ✶ SCHEDULE 4
- ✷ SCHEDULE 5
**Figure 8 - Examination of S x P Interaction on Yield:**
(Mann-Whitney non-parametric comparison)

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* X = 5% significance level

**e.g.:** An X corresponding to say, the intersection point between treatment combinations S3P1 (ROW) and S4P3 (COLUMN) means that there is a significant difference at 5% level between these two yields; (X).
Figure 9 - Interaction of W and P Treatments on Yield

Legend
△ WATER LEVEL 1
× WATER LEVEL 2
□ WATER LEVEL 3
4.3.2 Effect of Phosphorus Fertilizer on Yield

Forage yield increased with increasing level of phosphate fertilizer applied and these increases were found to be statistically significant at 1% level. This result is in agreement with that of Malik (1974) who obtained increases in cowpea forage yield up to an optimum dose of 88 kg/ha \(\text{P}_2\text{O}_5\).

In this experiment, maximum yield was obtained under irrigation schedules S2, S4 and S5 with 70 kg/ha \(\text{P}_2\text{O}_5\) at water level W3 and at W1 in S3 with the same dose of fertilizer. In the control, S1, yield response to fertilizer P was maximum at W2 at P5 fertilizer level and, perhaps, with further increase in phosphate dose, the crop would still improve in forage production. But for reasons to be given later and especially in the discussion on interactions that will follow shortly, it is reasonable to say that increasing the phosphorus fertilizer level beyond 80 kg/ha \(\text{P}_2\text{O}_5\) is unjustifiable. The substantial response of cowpea to P application is in agreement with the works of Tewari (1965) in Nigeria, Malik (1974) in India, Kang and Nangju (1983) in Nigeria and Rhoades (1980) in U.S.A. Effect of P on nodulation was not part of this study but it is worthy of mention here that although all seeds were innoculated with non-specific Rhizobium prior to planting, fertilized plants produced more thriving nodules than unfertilized ones. Of greater importance is the phosphorus kinetics that could have exerted tremendous influence on the yield response to fertilization.

A careful study of Table VII further reveals that while
consistent yield increases with phosphorus fertilizer were recorded under irrigation schedules S2, S3 and S5, corresponding results in S1 and S4 were irregular and in general, of lower magnitudes. This relatively poor response of crop to applied fertilizer P in S1 and S4 may be due to the irregular water supply which is a subject of discussion in the next section. It could be noted however, that the findings in this study have pointed out the fact that when water supply is deficient or irregular or both, crop utilization of applied fertilizer nutrient would be difficult to predict. Often, the response could be low.

4.3.3 Effects of Factor Interactions on Cowpea Yield

There was a highly significant interaction between irrigation schedule (S) and phosphorus fertilizer (P). In effect, these factors were dependent on one another in influencing cowpea dry matter production, and it follows that the simple effects of any single factor differ and the magnitude of any simple effect depends upon the level of the other factor of the interaction term. The means of S x P yields (over all W) are presented in Table IX, and Figure 7 is a graphical illustration of the same data.

Referring to Table IX or Fig. 7, it will be observed that for all irrigation schedules except S5, yield obtained was of the same order of magnitude (approximately 11.5 t/ha) at P1. Beyond 0 kg/ha P$_2$O$_5$, all schedules showed sharp response to P applied up to and including P3 and then diminishing returns set
in and so, depending on the economics of fertilizer use, P3 might be considered an optimum fertilizer level for S1 – S4. However, with S5, maximum yield was obtained with P4 and although yield decreased slightly when the fertilizer level was increased by 10 kg, this yield was still higher than those obtained under any of the other schedules irrespective of the fertilizer treatment level.

It is important to explore this result further. Forage production in S1 under zero irrigation, was still increasing at P5 (Figure 7), and perhaps would continue to respond given more phosphate. But given the present 15% level of crop recovery of applied phosphorus (Larsen, 1967; and Hagin and Tucker, 1982) it is obvious that a lot of residues are left in soil after harvest. For all fertilizer levels, S2, S3 and S5 produced higher yields than no irrigation or stage irrigation. This is an indication that to improve fertilizer use, irrigation is essential. S3 and S5 gave higher yield than S2, further indicating that frequency of irrigation which is essentially maintaining a high available soil moisture, could improve yield at all fertilizer levels. However, apparent waterlogging and other injurious soil reactions which occurred in S3 led to reduced yields, thereby demonstrating that there are limits to how frequently this crop can be irrigated without negative effects.

Phosphorus has long been claimed (Black, 1966) as a possible limiting nutrient for deep root development because of its immobility in soil and its low level of availability in many
subsoils. P uptake by crop is strongly affected by soil moisture level, particularly near the permanent wilting percentage (Pierre et al., 1965). The results described above follow this fact. Plants in the non-irrigated plot (S1) and the inadequately irrigated plot (S4) were subjected to stress at several times which no doubt affected their phosphorus nutrient utilization when compared to the rest of the plots. Since the plow layer was subject to periodic drying in S1 and S4, the presence of available P in the subsoil might have improved root growth in the lower horizons during periods of depressed uptake (because of moisture deficit) in the surface soil. There was evidence of deeper plant root penetration in S1 although not substantial. There is reason to believe that this pronounced root elongation was more attributed to moisture deficiency in the upper layer forcing roots to extend and explore deeper layers as a result of which response to P levels was exhibited to greater strengths than it would otherwise have been. But since the applied fertilizer nutrient was locked in the surface layer, it is not surprising therefore, why the overall effort was not sufficient to accomplish the yield optimum generated in other plots at similar fertilizer levels. This is the phenomenon explained by Veits (1972) as another form of 'drought'.

Within any plot as well as between plots, there was a significant difference in yield between S1P1 and S1P5 or S5P5. The Mann-Whitney U-Test for non-parametric comparisons of treatment means was adopted in studying S x P interaction and
the results are shown in Figure 8.

*W x P* interaction was not significant and has a similar meaning to the *S x P* interaction. That *P x W* interaction was not significant means, statistically speaking, that these factors acted independent of each other in influencing cowpea performance; the simple effects of any of them were the same for all levels of the other within chance variation, as measured by experimental error; and simple effects were equal to the corresponding main effects and in effect, a main effect in this factorial experiment was estimated as accurately as if the entire experiment had been devoted to that factor.

Data on *W x P* interactive effects on crop yield are presented in Table X. Unlike in *S x P* interaction, yield was of the same order of magnitude at any given fertilizer level under all amounts of irrigation water (Figure 9). There was an obvious increase in yield (dry matter accumulation) with increase in fertilizer *P* applied up to *P4*, when any one irrigation water level is considered. But these were not statistically significant. In practice, it is left to the farmer to choose what level to apply or what economic yield is acceptable. The closeness of the curves in Fig. 9, their similar direction of orientation as *P* levels increase, and the criss-crossing of *W2* and *W3* are clear manifestations of the insignificant differences (at 0.05 level).

A further scrutiny of Table X reveals that yields were higher under *W3* than *W1* at any given *P* level. A possible explanation is that water availability maintained high intensity
of P in soil solution as well as ensured a consistent P uptake (diffusion factor) culminating in higher yield under W3 relative to the other two levels. Also, the observed increase in yield, albeit not significant statistically, with increase in P in soil at say, a single irrigation water treatment level, W1, is quite in order. This result only shows that stress due to water deficiency as modified by soil fertility, favors plants grown under more fertilizer quantity than the required optimum; more quantity than the stated recommendation for a defined area, dictates the nutrient replenishment rate from the store house in the solid phase into the soil solution. Additional factors such as more extensive root development under higher nutrient availability and hence utilization when rain water was sporadically available must have contributed towards increased yields with increased fertilizer applied at any given level of irrigation amount of water.

In field crop experiments aimed at deriving recommendations for fertilizer and irrigation water requirement, the validity of the experimental design is always crucial (Steel and Torrie, 1983). Pioneers of the 'Continuous Variable Design' (Fox, 1973 and Bauder et al, 1975) were cautious of the statistical limitations of this design as a basis for reliable agronomic recommendations. This was because of firstly, the fact that the individual irrigation treatments are always surrounded by the adjacent treatments and cannot therefore be considered randomized, and secondly, the design as given by Fox (1973) has small individual plot sizes (Figure 2) which are feared to lead
to more variability. Fortunately, subsequent investigators (Hanks et al, 1976) concluded that when properly used, the design can be a very effective research tool and lack of randomizations of the irrigation water levels and replications may not always be a serious limitation considering the substantial opportunities the design offers for small system and experimental design studies. The results of this study are no doubt, handy for recommendations except that such recommendations would be within the limitations of the crop and environment for which the experiment was conducted.

4.4 Effect of Irrigation on Fertilizer Utilization

Digested cowpea foliage was prepared for determinations of total N and P on an autoanalyser. Appendix C is a portion of the printout from the analyser while the necessary computations of elemental concentrations in leaf as extracted into solution were done with an Apple II computer using the appropriate programme available in the University of British Columbia Soil Science Laboratory. The results of the computations as produced by the computer are presented in Appendix D. The results were rearranged (Table XI) to conform with the experimental design and in line with Table VII, for ease of interpretation.

Table XII is the analysis of variance table obtained upon statistical evaluation of P-uptake. Phosphorus uptake followed a trend similar to the dry matter yield except that nonsignificance was obtained for the S x W x P interactive effect on P uptake. The data of Table XIa offers an indication
of improved P nutrient uptake with irrigation as well as with heavier rates of fertilizer. In general, the results of this study suggest that heavier rates of fertilizer nutrient were required to satisfy the needs of the larger crops produced by irrigation and that nutrient deficiencies did not occur as a result of moisture stress. The favorable performance of crop stands that received zero irrigation (S1) and "minimum" irrigation (S4) adds weight to this argument because these plants apparently were able to absorb sufficient nutrient to capitalize on the occasional precipitation. However, Figures 10 and 11 which are graphical plots of Tables XIII and XIV respectively, clearly leave one with the impression that under zero irrigation or a minimal one in which the crop is forced to depend on unpredictable rains during summer, phosphate uptake could be as variable in the field as yield itself — a pattern few farmers would tolerate.

Nitrogen uptake levels in samples from the various treatment combinations were so close (3 - 5% N in solid, Tables XII and XIII) that the insignificant differences are obvious under all schedules and at all fertilizer levels receiving the different amounts of water. Again, variations exist in plots 1 and 4. These results of N uptake could be: (a) a proof that N was not deficient in soil and so did not affect P uptake and (b) due to the fact that all plants were capable of fixing N given the appropriate bacterial inoculation.

Upon digestion, the plant extract was diluted and analyses for elemental K, Ca and Mg were done by directly reading on an
Atomic Absorption Spectrophotometer and data in Table XIb are a presentation of the result. The concentrations of these elements in leaf were within such a close range that it was not necessary to subject the data to statistical analysis. Besides, there is no literature to suggest that uptake of P by cowpea is correlated to any of these elements.

The increased uptake of P by plants receiving successively higher phosphate applications apart from being significantly different (0.01 level), is a finding that is consistent with the dry matter yield results and agrees with works of Malik (1974), Ziska and Hall (1983) and Kang and Nangju (1983). The observation that the relative uptake of nitrogen was not related to phosphorus application was unusual as it is known (Black, 1966; Veits, 1972; and Sumner and Boswell, 1981) that phosphorus and nitrogen are complementary. However, there is no information to confirm that this N-P relationship is true for cowpea.
Table XIa - Plant Analyses Results.
Total N & P read on Auto Analyser from original digest without dilution.

TOTAL P (ppm in solution)

<table>
<thead>
<tr>
<th>FERT.</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEVELS</td>
<td>W3</td>
<td>W2</td>
<td>W1</td>
<td>W3</td>
<td>W2</td>
</tr>
<tr>
<td>P1</td>
<td>64.29</td>
<td>56.20</td>
<td>58.24</td>
<td>65.04</td>
<td>51.97</td>
</tr>
<tr>
<td>P2</td>
<td>42.50</td>
<td>78.75</td>
<td>47.32</td>
<td>68.65</td>
<td>61.52</td>
</tr>
<tr>
<td>P3</td>
<td>69.59</td>
<td>73.80</td>
<td>72.50</td>
<td>72.24</td>
<td>53.56</td>
</tr>
<tr>
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<td>97.60</td>
<td>78.46</td>
<td>73.04</td>
<td>67.45</td>
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<tr>
<td>P5</td>
<td>40.52</td>
<td>72.36</td>
<td>69.75</td>
<td>79.18</td>
<td>59.66</td>
</tr>
</tbody>
</table>

TOTAL N (% in plant solid)

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>4.32</td>
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<td>4.22</td>
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</tr>
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<td>P2</td>
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<td>4.84</td>
<td>4.56</td>
<td>4.24</td>
</tr>
<tr>
<td>P4</td>
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<td>3.81</td>
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<td>4.79</td>
</tr>
<tr>
<td>P5</td>
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<td>4.48</td>
<td>3.43</td>
<td>4.14</td>
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Table XIIb - Plant Analyses Results contd.

Total K, Mg and Ca in % plant of foliage.

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<th>FERT.</th>
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<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
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<td>LEVEL</td>
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<td>W1</td>
<td>W3</td>
<td>W2</td>
</tr>
<tr>
<td>K</td>
<td>2.85</td>
<td>1.92</td>
<td>2.47</td>
<td>2.63</td>
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<td>Mg</td>
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</tr>
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</tr>
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<td>2.99</td>
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<tr>
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<td>0.83</td>
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<td>0.65</td>
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<td>Ca</td>
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<td>0.85</td>
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<td>0.88</td>
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<tr>
<td>K</td>
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<tr>
<td>Mg</td>
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<td>0.58</td>
<td>0.68</td>
<td>0.88</td>
<td>0.53</td>
</tr>
<tr>
<td>Ca</td>
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<td>0.50</td>
<td>1.10</td>
<td>1.08</td>
<td>0.58</td>
</tr>
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</table>
Table XII - Analysis of Variance for P-Uptake

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>d.f</th>
<th>SUM OF SQUARES</th>
<th>MEAN SQUARES</th>
<th>F - TEST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td></td>
<td>(36431.65)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>2</td>
<td>458.77</td>
<td>229.39</td>
<td>10.92 **</td>
</tr>
<tr>
<td>W</td>
<td>4</td>
<td>9369.81</td>
<td>2342.45</td>
<td>111.55 **</td>
</tr>
<tr>
<td>P</td>
<td>4</td>
<td>9853.81</td>
<td>2463.45</td>
<td>117.31 **</td>
</tr>
<tr>
<td>S x P</td>
<td>8</td>
<td>630.05</td>
<td>78.76</td>
<td>3.75 **</td>
</tr>
<tr>
<td>S x W</td>
<td>8</td>
<td>1746.35</td>
<td>218.36</td>
<td>10.40</td>
</tr>
<tr>
<td>P x W</td>
<td>16</td>
<td>13696.04</td>
<td>856.00</td>
<td>40.76 **</td>
</tr>
<tr>
<td>S x W x P</td>
<td>32</td>
<td>676.32</td>
<td>21.14</td>
<td>1.01 ns</td>
</tr>
<tr>
<td>Block</td>
<td>1</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00 ns</td>
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<tr>
<td>Error</td>
<td>74</td>
<td>1546.98</td>
<td>20.91</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>149</td>
<td>37978.63</td>
<td></td>
<td></td>
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</tbody>
</table>

All values are uncoded

** = significant at 0.01 level

ns = not significant at 0.05 level

F = Treatment Mean square/Error Mean square.
Table XIII - S x P Interaction on P-Uptake, ppm

<table>
<thead>
<tr>
<th>FERTILIZER</th>
<th>IRRIGATION SCHEDULES</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>S1</td>
</tr>
<tr>
<td>P1</td>
<td>64.29</td>
</tr>
<tr>
<td>P2</td>
<td>42.50</td>
</tr>
<tr>
<td>P3</td>
<td>69.59</td>
</tr>
<tr>
<td>P4</td>
<td>80.05</td>
</tr>
<tr>
<td>P5</td>
<td>40.52</td>
</tr>
</tbody>
</table>

Table XIV - P x W Interaction on P-uptake, ppm

<table>
<thead>
<tr>
<th>FERTILIZER</th>
<th>IRRIGATION</th>
<th>WATER LEVELS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W1</td>
<td>W2</td>
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<td>P1</td>
<td>57.68</td>
<td>60.22</td>
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<td>P2</td>
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<td>P3</td>
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<td>P4</td>
<td>70.11</td>
<td>69.71</td>
</tr>
<tr>
<td>P5</td>
<td>62.71</td>
<td>58.68</td>
</tr>
</tbody>
</table>
Figure 10 - Interaction of S and P Treatments on P-Uptake

Legend

- △ SCHEDULE 1
- × SCHEDULE 2
- □ SCHEDULE 3
- ○ SCHEDULE 4
- ⬠ SCHEDULE 5
Figure 11 - Interaction of W and P treatments on P-uptake
4.5 Water Use Efficiency

Crop water use efficiency (WUE) may be defined as the amount of dry matter produced per unit volume of water taken up by the crop from the soil. This term is essentially the reciprocal of transpiration referred to (Briggs and Shantz, 1913) as the mass of water transpired per unit mass of dry matter produced. In this work, water use efficiency (ton/ha/mm) is expressed as:

\[ \text{WUE} = \frac{Y}{\text{ET}} \]  

where:

- WUE is as defined above,
- \(Y\) = dry matter yield, ton/ha,
- \(\text{ET}\) = seasonal water use, mm.

Seasonal ET was estimated from equation [3.3]. In principle, \(\Delta S\) in the latter equation could be computed from historic data before irrigating. In practice however, these computations were performed at the end of the irrigation period to facilitate estimation of WUE under the different irrigation regimes and schedules. Results of such computations are presented in Table XV.

It can be seen in equation 4.1 that WUE may be increased by (a) increasing yield and maintaining equal water use or (b) maintaining equal yield and decreasing water use. Maximizing water use efficiency per se is not the objective in this study but an "optimum" WUE – maximum yield relationship, subject to
local constraints of water availability, is a desirable tool for water planners in assessing future water requirements of the crop in question.

From Table XV, it is apparent that while the control plot (S1) gave the highest water use efficiency, its yield was much lower than those of S2, S3 and S5 at W1-W3 water levels though the latter were obtained at relatively low WUE's. Highest irrigation water use efficiencies associated with individual irrigation treatments occurred either when irrigation water was applied during dry periods when little or no rainfall occurred or when longer irrigation intervals were used during periods when appreciable rainfall occurred and generally involved treatments that incurred some moisture stress (as indicated by gravimetric sampling of soil) and slight to moderate yield reductions. Maintaining adequately watered treatments for high yields, as expected (Musick and Dusek, 1971; and Stewart et al, 1980), lowered irrigation water efficiency associated with some individual irrigations like S2W2, S2W3, and S5W1 to S5W3. Maximizing irrigation WUE in combination with seasonal rainfall permitted applying fewer irrigations as was demonstrated by the results of S3W1 and S5W1 in Table XV; if this crop were grown for grains, this practice would have tended to favor early irrigation cutoff date when significant rainfall that occurred as September began, would have been sufficient for grain filling.
Table XV - Yield, Evapotranspiration and Water Use Efficiency Results.

<table>
<thead>
<tr>
<th>SCHEDULE</th>
<th>IRRIGATION INTERVALS</th>
<th>No. of RAINFALL DEPTH (mm)</th>
<th>SEASONAL IRRIG. (P), mm</th>
<th>SEASONAL ET, mm</th>
<th>YIELD (Y), t/ha</th>
<th>WATER USE EFFICIENCY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>J - J - A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>138.8</td>
<td>13.76</td>
<td>99.1</td>
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<tr>
<td>W1</td>
<td>31.2</td>
<td></td>
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</tr>
<tr>
<td>W2</td>
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<td>6</td>
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<tr>
<td>W3</td>
<td>169.8</td>
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<td>W1</td>
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<td>326.0</td>
<td>11.26</td>
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<td>18.00</td>
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<td>818.0</td>
<td>21.92</td>
<td>26.8</td>
</tr>
</tbody>
</table>

Note: Water Use Efficiency is defined as kg/ha/mm as given on page 90.
Figure 12 - Cowpea Dry Matter Yield as Related to Seasonal ET

Y = 13.06 + 0.012ET
Correlation coefficient = 0.92

Y = 9.19 + 0.0077ET
Correlation coeff. = 0.99 at 0.01 level.
The high yield response (and high WUE) obtained from scheduled irrigation combinations S3W1 and S5W1 are indicative of the fact that it is not necessary to largely rewet the soil profile to obtain efficient use of irrigation water and that seasonal irrigation water requirements may be reduced somewhat by using smaller irrigations and relying to some extent, on expected seasonal rainfall as suggested by Rawlins and Raats (1975), and Hobbs and Krogman (1978). It is important to add here that under surface irrigation conditions, a farmer may not be able to substantially reduce the size of irrigations and still obtain reasonably good water distribution over the field but use of sprinklers makes this practice feasible.

Low water use efficiency values in S2 were due principally to the occurrences of heavy rains on two occasions a day after full irrigation in each case. On the other hand, irrigating when the soil was moderately wet from recent rainfall or the previous irrigation could be responsible for the low values in S3, particularly in W3 treatment.

4.6 Crop Production Functions

The economic evaluation of the potential use and development of water resources requires, inter alia, estimates of the marginal value product of water. These marginal values are often needed to assess the benefits (or otherwise) from potential projects to supply irrigation water and in determining the optimum allocation of existing water supplies and competing uses. Estimates of the marginal product of water imply some
knowledge of the production function of water. The existence of such knowledge is of two obvious advantages:

(i) its importance in the study of irrigation policy, and
(ii) the systematic handling of climate as a major component of error in crop production functions and as a source of production instability in agriculture.

Although simple models have been developed which allow prediction of ultimate yield as related to soil water conditions, the functions are in reality complex and interrelated to many other factors of which soil fertility and climate are very important. Many of these production functions are statistical in nature and thus, often site-oriented (Hanks and Hill, 1980). In this study, physically-oriented, widely applicable and simple models developed to predict yield as related to water use and fertilizer utilization, first as single, independent factors and secondly, as dependent variables were adopted and fitted to the experimental data.

4.6.1 Yield-Water Model

When regression equations were developed relating crop yield to crop evapotranspiration, different relations for different locations were found which indicate that there are site differences with respect to soil and climate (Hanks and Hill, 1980). Thus, the equations could not be used to predict results at different sites. Moreover, even at the same location, the same equation does not hold true from one year to another.
For irrigation management purposes, relations that can be transferred (that are constant) from site to site are needed to predict future situations. One of the most simple models is that of Stewart (Stewart et al., 1977):

\[
\frac{Y}{Y_m} = 1 - \beta_o \frac{ET}{ET_p} = 1 - \beta_o (1 - \frac{ET}{ET_m})
\]

[4.2]

in which

\(Y\) = actual dry matter yield

\(Y_m\) = maximum (potential) yield when \(ET = ET_m\); \(ET\) is actual seasonal evapotranspiration and \(ET_m\) is maximum seasonal ET.

\(ET_p\) = evapotranspiration deficit = \(1 - \frac{ET}{ET_m}\), and

\(\beta_o\) = slope of relative yield \(\frac{Y}{Y_m}\) vs \(ET\).

Significant qualities of this model (Stewart et al., 1977) are:

(a) \(ET\) can be measured or estimated (In this study, water balance equation [3.3] was used as a basis for estimate of ET, Table XV).

(b) \(ET_m\) was determined by the equation where growth was considered not to be limited by water

(c) Model can be applied directly if total dry matter is desired product and timing of irrigation is not of practical importance [Timing here refers to cultivation for grain so that irrigation timing as related to growth stage, influences ultimate yield so much so that the simple relation accounting only for seasonal ET may not hold well as a predictive tool].
Hanks (1980) suggests that by equation [4.2], the ratio \( \frac{ET}{ET_m} \), where \( \frac{Y}{Y_m} \) is zero, can be shown to approximate the portion of ET that is due to evaporation (E) directly from the soil; and the portion of ET that is transpiration (T) is approximated by the fraction \( \left( 1 - \frac{1}{\beta_0} \right) \). Thus, \( \beta_0 \) is always \( \geq 1.0 \). In effect, \( \beta_0 = 1 \) points to the fact that no evaporation occurred from the soil surface while a \( \beta_0 \) of 1.5 would mean that one-third of the ET was E and two-thirds T, which is a true interpretation of the mathematical relationship between the factors in the equation.

Figure 12 illustrates dry matter vs ET. Because only four points per data set could be plotted, model validation in the form of equation 4.2 would have further entailed reducing this to three which might in turn reduce the predictive power and the reliability of any graph obtained from 3 points. Rather than do that, the model was reported in Fig. 12 as data that reflect primarily the maximum yield potential and the rate of yield increase per unit water use that is attainable for a given set of production inputs (such as non-limiting nutrient level under a given irrigation schedule). According to Stewart et al. (1980), a plot of the ratio of ET/ET_m achieves a greater generalization of yield function. However, since this experiment is considered site-specific, no serious accuracy was lost by the direct linear regression.

Regression analysis could be performed for S3 as well, but because of the negative response to ET under this schedule, S2 and S5 are preferred for predictive purposes. Under S2, the
measured ET of 326 and 779 mm gave predicted yields of 11.6 and 15.2 tons/ha respectively, using the regression line in Fig. 12. Measured yields for this plot were 11.3 and 15.4 tons/ha respectively. Similar comparisons could be made using the S5 curve.

4.6.2 Yield-Fertilizer Functional Relationship

One yield equation that has been frequently used to quantitatively relate crop yield response to soil nutrient or applied fertilizer is the Mitscherlich equation (ASA, 1975 and Hagin and Tucker, 1982). The Mitscherlich formulation is an exponential yield-nutrient response function developed originally for a single growth-limiting nutrient, such as P.

Mitscherlich stated in his law of effects of growth factors that (Hagin and Tucker, 1982) the increase in yield (y) resulting from increase in supply of a plant nutrient (x) is proportional to the decrement from the maximum yield (A) that can be produced when the supply of the nutrient is increased indefinitely (x \( \to \infty \)). Where all other growth condition variables can be taken as constant, or nonlimiting, the following functional relationship holds:

\[
\frac{dy}{dx} = K(A-y) \tag{4.3}
\]

where:

A is defined as above,

K is a proportionality constant,
y is the yield response, and
x is the soil-P supply.

By integration of the above equation and insertion of proportionality factor, c \( [c = \ln K = 0.434K] \), the logarithmic form is

\[
\log(A-y) = \log A - cx \tag{4.4}
\]

By this equation, as x is successively increased, y becomes asymptotic to A. It has to be emphasized here that the equation assumes that when only one nutrient factor, x, is limiting, and the remaining growth factors are constant, the differential increase, dy, of yield, y, with respect to the differential increase, dx, of the limiting nutrient factor, x, is proportional to the maximum yield A (attainable when x is present in excess and yet not harmful amount) minus the actual yield.

In practice, the nutrient is coming from two sources: the fertilizer, x and the available nutrient present in the soil before fertilization, b (Hagin and Tucker, 1982). Incorporating this development into Eq. \([4.4]\) modifies it to:

\[
\log(A-y) = \log A - c(x + b) \tag{4.5}
\]

A subsequent approximation differentiated the proportionality factor, c into the portion \( (c_1) \) originating from the soil and the one coming from the fertilizer (c) so that the equation took the form:
\[
\log(A-y) = \log A - (cx + c,b) \quad [4.6].
\]

The Mitscherlich function or some modification thereof, is used for estimating fertilizer requirements throughout the world. It has been found (ASA, 1975; and Hagin and Tucker, 1982) to describe well the relation between applied nutrient and yield in the practical range of soil conditions and rates of application. To further justify the choice of this model, it could be added that phosphorus (the test nutrient in this study), as well as potassium uptake patterns by crops are said to follow the Mitscherlich concept due principally to their relative immobility in soil; the same is not true for nitrogen.

Model Validation.

The model in the form presented in Equation [4.5] will suffice for this paper:

\[
\log(A-y) = \log A - c(x + b) \quad [4.5].
\]

While Hagin and Tucker (1982) recommended that \( b \) in the above equation be that value obtained from soil analysis, Analogides and Rendig (1972) preferred the standard set by Mitscherlich — that \( b \) be calculated. To be of practical significance, results from both methods should agree closely otherwise it would be difficult to accept the accuracy of the model as sufficient for predictive purposes.

To fit the data to the model in this analysis, \( c \) and \( b \) were calculated and the latter was found to agree reasonably with
soil test values (Equation [4.9] or Figure 14). The expressions used for the computations are:

\[ c = \frac{1}{x} \log\left(\frac{A-y_0}{A-y}\right) \]  

[4.7]

\[ b = \frac{\log A - \log(A-y_0)}{c} \]  

[4.8]

where \( y_0 \) is the yield obtained with P1 fertilizer level.

The following points should be kept in mind in the model fitting and are helpful in understanding the results presented herein:

(i) \( b \), the amount of x or phosphorus originally present in the soil was assumed to be uniformly available in all plots. Accordingly, average P from soil test value (Table V) was used.

(ii) \( A \), the maximal potential yield was assigned the yield obtained when phosphate was adequate (irrigation schedule and irrigation water depth held constant while it was assumed that other growth processes remained unchanged and nitrogen was adequate for attaining the yield \( A \)).

(iii) It was considered that predictions from S2, S3 and S5 would give more reliable yields since the extractable P levels in S1 and S4 (Table V) were not comparable to those of the former plots. Furthermore, the Mitscherlich equation stipulates that the model be adopted only when all other factors are adequate except the limiting one on test. To do justice to this concept, S1 and S4 could not be regarded as
adequately irrigated. Thus, data presented in Table XVI are averages for S2, S3 and S5 which satisfy the conditions stated in application of the model.

The relationship between P added to the soil and Bray-1 extractant (0.03N NH₄F in 0.25N HCl) - soluble P was linear for the test soil (Figure 13). The linear regression was highly significant, indicating that in this sandy loam, the fraction of soil P extracted by Ammonium flouride is directly proportional to the added. With this confidence established, the soil test value in ppm was used directly in model validation. In Table XVI, P added (Column 4) refers to that amount of P in soil additional to the availability before the different levels of fertilizer P were applied, or (x-b) ppm. b is P available in the soil prior to application of P-fertilizer treatments.

Table XVI - Comparison of Actual and Calculated Yields of Cowpea

<table>
<thead>
<tr>
<th>FERTILIZER TREATMENT LEVEL</th>
<th>SOIL TEST MEASURED YIELD (t/ha)</th>
<th>ADDED P (x-b) ppm</th>
<th>CALCULATED YIELD (t/ha)</th>
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<tbody>
<tr>
<td>P1</td>
<td>58=b</td>
<td>11.5</td>
<td>0</td>
</tr>
<tr>
<td>P2</td>
<td>140</td>
<td>15.3</td>
<td>82</td>
</tr>
<tr>
<td>P3</td>
<td>169</td>
<td>18.2</td>
<td>111</td>
</tr>
<tr>
<td>P4</td>
<td>222</td>
<td>19.3</td>
<td>164</td>
</tr>
<tr>
<td>P5</td>
<td>239</td>
<td>18.9</td>
<td>181</td>
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</tbody>
</table>
Figure 13 - Applied P as Related to Bray-1 Extractable P

Regression line: $Y = 48.6 + 2.25X$

Correlation coefficient, $r = 0.97$ at 0.01 level.
Figure 14 - Mitscherlich Equation and Yield Curves

\[
\text{log}(19.3 - y) = \text{log} 19.3 - 0.0066(X + 58.6) 
\]

- ○ ACTUAL YIELD CURVE
- --- CALCULATED CURVE
The equation describing the yield curve of Figure 14 is:

\[ \log(19.3 - y) = \log 19.3 - 0.0066(x + 58.6) \]  \[4.9\].

It is interesting to note that calculated b (58.6 ppm) agreed sufficiently with average soil test value of 58.0 ppm shown in Table XVI. The "maximum yield", \( A = 19.3 \) t/ha, was estimated by extrapolation of the yield curve to its asymptote in accordance with Equation [4.4] and by adoption of the method of Analogides and Rendig (1972).

The theoretical yield values calculated by means of Equation [4.9] are reported in Table XVI also. Except for P2, predicted yields from the Mitscherlich equation described well, the relation between applied P and yield in the practical range of the experimental results discussed herein. Figure 14 further clarifies this result. Of course, the equation failed to detect the yield depression caused by fertilizer level-P5 and reported in column 3. This is not unusual as Mitscherlich did admit (Hagin and Tucker, 1982) that the equation does not fit data obtained at both extreme ends of the yield curve. In general also (ASA, 1975) an exponential function, such as the one in question, never reaches an absolute maximum nor can it predict toxicity level of an applied nutrient. It must be conceded here then, that the range and levels of fertilizer trial in this experiment were not wide (0 - 80 kg/ha P\(_2\)O\(_5\)) and many (5 levels) enough to capture sufficiently accurately, the sensitivity zone - the level of P that is toxic to the crop or a point at which
yield significantly begins to decrease as a result of excess nutrient, for both the experimental and calculated yield-added nutrient curves.

The Mitscherlich equation has of recent been radically expanded to incorporate not only two or more nutrients at a time but several other crop production variables. It could be applied in this situation too, to relate the simultaneous effects of P and irrigation water on yield but, partly because of the reason stated in the preceding paragraph and partly because there were only three water treatment levels (W1, W2 and W3), the reliability of any functional relationship derived therefrom for predictive purposes would be very doubtful and worth little more than a mathematical exercise. The American Society of Agronomy (ASA, 1975) states: "--- any given factor that decreases the growth rate (of a crop) over the growth period must be reflected in the same way as any other factor that reduces the rate in the same amount. Therefore, if a rate reduction occurs, whether caused by variations in levels of an essential nutrient, weeds, sunlight, moisture or soil compaction, the relationship between causative agents and growth should remain unchanged and subject to the same mathematical treatments."

Thus, the Stewart model for relating irrigation water to yield (Eq. 4.2) and the Mitscherlich function describing the relationship between P added and cowpea dry matter yield (Eq. 4.5) would be accepted as adequate for the purposes of prediction, and, because of the limitations of the experiment
being reported. In a subsequent analysis of these growth factors with the aim of arriving at their recommended levels for this crop and the site where the experiment was conducted, purely qualitative statements would be made but the quantitative treatments of the models in this section must be frequently borne in mind. While the information obtained from this experiment and subsequent model validations can be used to predict the separate effects of irrigation and phosphorus treatments on cowpea crop yield and phosphorus content, the effects of the combined influences of the two effects are less easily predicted, particularly in view of the highly significant interactions between factors as presented in the analysis of variance tables.

With this treatment, the fourth objective of this thesis has been addressed to the extent that the experimental data could allow.
5.1 Summary

An irrigation-fertilizer experiment was conducted with cowpea (Vigna unguiculata [L.] Walp.) on the University of British Columbia research farm. Water was applied from a line-source sprinkler lateral designed with iterative considerations of the desirable irrigation system characteristics and the size and design of the experimental area. The purpose of the experiment was to determine the response of this crop to phosphorus fertilizer under different irrigation water regimes in an ecological environment where the crop is rarely cultivated. Fertilizer P was band-applied.

The plant measurements made were leaf number, plant height and number of nodes per plant on a weekly basis for the first seven weeks after seedling emergence. Irrigation scheduling procedures were the rigid interval-type, but, gravimetric soil moisture determinations were taken throughout the cropping season to aid in scheduling and provide indications as to whether or not plants experienced any water deficit and hence stress during any part of the irrigation cycles.

The plant response data taken during the seven weeks stated above, the yield and nutrient content of plant foliage harvested after 90 days of growth were found to be in parallel with data reported in the quoted literature. The dry matter yield-fertilizer P response curve was curvilinear (convex) and fitted nicely to the Mitscherlich's model - the "law of diminishing returns." A linear regression fit was not necessary. However,
in fitting the yield-seasonal water use data to the Stewart (1977) yield-evapotranspiration model, it became useful. Curves of both model validations could be a useful tool in yield predictions under a given set of agronomic management specifications. There was not enough data for fitting irrigation water and fertilizer P jointly to a multivariate model. There is no denying the truth that the experiment was designed so that proper account could be taken of the likelihood that any functional relationship examined with these quantities of test variables (5 levels P, 3 levels W, and 5 levels S) might be limited to the given range of experimental conditions. Extrapolation to other levels, crops and for that matter, another environment is consequently, limited.

It was demonstrated that irrigation is necessary for optimum cowpea yield even though the total water supply (irrigation plus rainfall) during the irrigation season could exceed the seasonal water requirement of the crop. In this study, the distribution of rainfall was important and critical in the control plot. Reducing the amount of irrigation water applied per irrigation set by irrigating more frequently with less water was found advantageous because in addition to improving yield in comparison to normal interval schedules at any given fertilizer level, water was evidently saved (Table XV) as water use efficiency was increased. Irrigating three times within the normal irrigation cycle (e.g every 3 days in July) left the soil persistently excessively wet; this partly accounts for the depressed yield under this scheduling technique (S3).
High frequency irrigation, thus, offered many opportunities with regard to water conservation besides improving yield but, a limit exists. For this crop on the test site, S5, irrigating twice (every 4 days in July) within the interval with half the design consumptive use (43mm/day) gave maximum yield at any P level, when all treatment plots are under consideration. Methods for determining when cowpeas should be irrigated to achieve reductions in water use while maintaining dry matter yield optimum can be further developed from these findings.

In this study, the importance of irrigation water as a factor limiting the yield response of cowpea appeared to be erased by the effect of factor, scheduling procedure. In an irrigation area where uncertain rainfall (such as in the case from late Spring to late Summer in Vancouver) varies the number of irrigation required, the decision on when to apply these irrigations is obviously critical if water is to be used efficiently. Without the aid of information on soil water supplies and crop-soil studies such as this, deciding when to irrigate and how much water to apply at each irrigation set, under these conditions must be very difficult. This probably leads farmers to irrigating with more water and in some cases, more frequently than essential, to be on the safe side. Scheduling irrigations in such areas based on concepts investigated in this work would ensure that irrigations are applied only when necessary and with just some fraction of the design irrigation depth, leaving room for sporadic yet significant rains and thereby maximizing the efficiency of
irrigation water usage.

As expected, cowpea being a legume, was found to respond well to fertilization of soil with phosphorus. The data obtained might be limited to the soil-crop-climatic conditions in question but it did report the importance of maintaining a high level of P fertilization in order to obtain the yield potential with optimum soil moisture.

For all plots (irrigation schedules), 0 and 50 kg/ha phosphate produced forage that was lower in quantity than plants fertilized with 60, 70, and 80 kg/ha of the same nutrient. These are indications that the former two levels of P namely, P1 and P2, were markedly low. Furthermore, it was observed that yields in the control plot at all P levels were quite close, pointing to the fact that if no irrigation is contemplated, there is no need to apply fertilizer; once crop is to be irrigated, the need for phosphorus fertilizer addition to ensure optimum yield becomes apparent as is noticeable in the superior yields of irrigated plots over the control (S1) and the stage-of-growth plot (S4) at any specified P level.

Some deductive conclusions could be drawn from the yield-fertilizer data as a basis for phosphorus fertilizer recommendation for forage production from cowpea in this climatic situation.

Referring to the tables and graphs on dry matter yield and P-Uptake by cowpea, it is clear that there is no significant difference between P4 and P5 — in three out of the five scheduling regimes, the latter P level was less productive.
From an agronomic point of view, it could be said that P5 must have been the toxic level or at least it set up soil reactions detrimental to the crop. Economically speaking, since at this level, the crop did not indicate convincingly that it can produce more dry matter or absorb P at least up to P4 level plants, it is not economically justifiable applying 80 kg/ha phosphate. Based on environmental considerations, it is obvious that application of as much as 35 kg/ha P (P5) will result in a lot of P residues in soil (without higher yield than P4) at site of application either as the applied monocalcium form or some transformed products thereof. Crop recovery of applied fertilizer P is a low 15-25% (Veits, 1972; and Hagin and Tucker, 1982) while this element has a low mobility in soil (William, 1971 and Hagin and Tucker, 1982) but can be carried with runoff or subdrain discharges to constitute a source of pollution elsewhere remote from the farm location. The foregoing deductive statements leave no basis for not rejecting P5 as an excessive level. Since experimental data suggest comparable yields between P4 and P5 but significantly higher yields than P1 - P3, P4 (30.6 kg/ha P or 70 kg/ha phosphate) can be considered an optimum level of fertilizer for irrigated cowpea production under the crop-soil situation studied.
5.2 Conclusion

It must be reiterated that irrigation on the study plots was supplementary. None of the data indicated plant dependence on irrigation for growth, but for optimum dry matter yield in the presence of fertilizer, irrigation became important. The data demonstrated beneficial plant growth responses from irrigation. The analysis of results supports the view that the time of application of irrigation water is more important in determining its productivity than the total quantity used.

The importance of this study may be acknowledged from two perspectives: The results

1* Allow the farmer to estimate yields if rainfall does not come regularly during the growing season or

2* Give the farmer the management alternatives to select the energy, water application, phosphate fertilizer and yield levels that should produce maximum or optimum production levels of cowpea on his farm.

Poor rainfall distribution with respect to evapotranspiration distribution and low water-holding capacities of most soils cause irrigation to be needed in many semi-arid and humid areas, particularly in intensive agriculture. Rainfall occurs sporadically during the growing season and disrupts any preplanned schedule or falls a few days after a full irrigation regime. In order to make effective use of
rainfall that occurs during the irrigation season, it is important that less irrigation water be applied than the soil will hold within the rooting zone so there will be room to hold a reasonable amount of rainfall without deep percolation occurring. For the cowpea used in this investigation, the evidence generated from the study is that the crop be irrigated with 21.59mm per irrigation set of 3 hours. This is half the designed application depth of 43.18mm (1.7 in.) for a set time of 6 hours and an average irrigation interval of 9 days for the relevant cropping months of June to September, inclusive.

For reasons already discussed in section 5.1, and under the preceding recommendations of irrigation amount and schedule, the fertilizer P level requirement that will produce the best combination of production variables for optimum cowpea dry matter yield and fertilizer utilization is 30.6 kg/ha P.

5.3 Recommendations for Further Studies

This study was undertaken to ascertain the performance of cowpea with the purpose of optimizing irrigation water and phosphorus fertilizer levels that will produce maximum yield. The results of the experiment illustrate that a complex relationship exists between water management practices and fertilizer response. A better understanding of this relationship is important if the objective of developing soil and water management practices leading to more efficient use of fertilizer P and water is to be accomplished. In this respect, further investigations in the following directions become
imperative:

1. It is not known from these studies whether the levels of the soil and plant parameters which were established as indicators of irrigation need and optimum yield are applicable for cowpeas in other soil and environmental conditions in British Columbia. Consequently, as in many field experiments, it is important to evaluate similar treatments as in this study, in the different environmental conditions present in this area for which recommendations are to be made. Likewise, for an obvious reason, namely, that conditions vary from year to year, it is important to know the effect of years on the different treatment combinations since recommendations are usually made for future years. Both temporal and spatial repetitions would go a long way towards improving the scope of inference made from the experiment so far.

2. The necessity of coordination of irrigation and fertilization practices was demonstrated by comparing yields of P fertilization and irrigation frequency treatments with the yields resulting when either variable was increased independently. To further improve the reliability and scope of inference of the experiment, a number of refinements are suggested: first, it is necessary to increase the number of irrigation water levels; secondly, within the present range of 50 - 70 kg/ha of
phosphate, the incremental rate should be made 5 kg instead of the 10 kg implemented in the study being reported now; and lastly, but not the least important, there is a need to increase the number of replicates. Unfortunately, these suggested refinements are limited largely by the funds and time available for experimentation; the compactness of the specified irrigation system and hence experimental design reduce this fear and improve the feasibility of these suggested studies.
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APPENDIX A - METEOROLOGICAL DATA USED IN IRRIGATION DESIGN

UBC., Vancouver Weather Station,
Lat. 49 15 N, Long. 123 15 W, 87 m. (1951 - 1980 Normals)

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<td>SNOW</td>
<td>20.5</td>
<td>6.1</td>
<td>4.0</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>3.1</td>
<td>20.8</td>
<td>54.7</td>
<td>mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>172.8</td>
<td>132.8</td>
<td>116.0</td>
<td>69.1</td>
<td>59.5</td>
<td>43.0</td>
<td>37.0</td>
<td>52.5</td>
<td>72.2</td>
<td>133.4</td>
<td>162.5</td>
<td>207.9</td>
<td>1257.7</td>
<td>mm PRECIP.</td>
</tr>
</tbody>
</table>

Vancouver International Airport, B.C.
Lat. 49 11 N, Long. 123 10 W, Elevation 3m Altitude (1951 - 1980 Normals)

<table>
<thead>
<tr>
<th></th>
<th>REL. HUMID.</th>
<th>VAPOUR PRESS.</th>
<th>SEA-LEVEL PRESS.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>KPa</td>
<td>KPa</td>
</tr>
<tr>
<td></td>
<td>80 78 72 68 65 66 65 68 72 78 72 83 73</td>
<td>0.68 0.77 0.78 0.89 1.09 1.31 1.51 1.55 1.39 1.13 0.86 0.77 1.06</td>
<td>101.64 101.67 101.61 101.7 101.7 101.7 101.8 101.7 101.7 101.7 101.6 101.69</td>
</tr>
</tbody>
</table>

Source: Canadian Climate Normals, Ministry of Environment, Ottawa.
* Evaporation losses were neither controlled nor measured.
* Sprinkler operation during the test (and Experiment) was 206.7 KPa
APPENDIX B contd.
SPRINKLER UNIFORMITY TEST RESULT

Time of catch = 50 min
Diameter of can = 10.5 cm

<table>
<thead>
<tr>
<th>IRRIGATION LINE-SOURCE</th>
<th>SPRINKLER</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEAN VOLUME OF CATCH(ml)</td>
<td>244.25 154.25 44.75</td>
</tr>
<tr>
<td>DEPTH OF WATER CAUGHT/can (cm)</td>
<td>2.83 1.78 0.52</td>
</tr>
<tr>
<td>IRRIGATION DEPTH FOR TIME SET OF 6hr. (mm)</td>
<td>169.8 106.8 31.2</td>
</tr>
</tbody>
</table>

SPRINKLER COEFFICIENT OF UNIFORMITY (Christiensen, 1942) = 48%.
(Note that there was no lateral overlap, therefore, the coefficient of uniformity given above is apparently the water distribution pattern peculiar to the system).
APPENDIX C - PLANT ANALYSIS: AUTOANALYSER PLOT
**APPENDIX E - SOME GRAVIMETRIC MOISTURE DETERMINATION RESULTS**

Soil samples were taken with an auger. Sampling depths: 0-30cm, 30-60cm.

Gravimetric soil moisture contents recorded as %

<table>
<thead>
<tr>
<th>PLOT I</th>
<th>PLOT IV</th>
<th>PLOT II</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cm</td>
<td>35.47</td>
<td>36.18</td>
</tr>
<tr>
<td>30 cm</td>
<td>33.20</td>
<td>30.68</td>
</tr>
<tr>
<td>60 cm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**July 4th:** IRRIGATION W1 W2 W3 W2 W1
Whole plot irrigated to field capacity. Note special lateral movements made to ensure 'overlap' along the main.

| 0 - 30 cm | 32.61 |
| 30 - 60 cm | 30.25 |

**July 9th:** Irrigation to field capacity.

**15th July, 3 days after the rains from 10 to 12th July 1983.**

| 0 - 30 cm | 35.47 |
| 30 - 60 cm | 33.20 |

**26 - 28/7 rain**

| 0-30 | 47.70 |
| 30-60 | 50.60 |

| 0-30 | 50.60 |
| 30-60 | 49.18 |

**July 25th:** Irrigation.

| 0-30 | 40.6 |
| 30-60 | 33.8 |

| 0-30 | 35.5 |
| 30-60 | 35.5 |

**Showers on 2/8**

| Moisture determinations on the following day - 3/8. |
| 29.37 | 31.50 |
| 36.07 | 40.14 |

| 28.06 | 28.51 |
| 30.78 | 34.19 |

After irrigation on 6/8

| 49.7 | 48.7 |
| 52.7 | 52.7 |

| 50.1 | 50.6 |
| 50.8 | 48.4 |

After irrigation

| 49.1 | 43.0 |
| 51.6 | 48.8 |

No rain since August 2nd.

| Before irrigating on 14/8/83. |
| 20.58 | 22.48 |
| 25.44 | 28.93 |

| 24.20 | 25.14 |
| 26.5 | 25.5 |

| 28.0 | 29.8 |
| 30.7 | 30.9 |

| 34.2 | 35.1 |
| 35.6 | 36.9 |

| 30.0 | 31.7 |
| 38.4 | 36.7 |

| 33.0 | 34.3 |

| 34.3 |
APPENDIX E contd.

<table>
<thead>
<tr>
<th>PLOT III</th>
<th>PLOT V</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1 W2 W3</td>
<td>W3 W2 W1</td>
</tr>
<tr>
<td>W3 W2 W1</td>
<td>W1 W2 W3</td>
</tr>
</tbody>
</table>

July 15th, 3 days after rains of July 10-12th

| 32.11 | 35.76 | 30.76 | 32.86 |
| 34.80 | 33.85 | 32.30 | 34.80 |

Before irrigation of plots III and V on July 22nd

| 25.4 | 26.0 | 25.1 | 25.9 | 28.53 | 29.6 | 29.4 | 27.7 | 30.9 | 29.2 | 30.3 | 29.7 |
| 28.1 | 26.7 | 26.7 | 30.4 | 28.5 | 31.7 | 30.4 | 31.7 | 34.5 | 30.1 | 33.5 | 32.6 |

After irrigation of both plots on the same day.

| 33.1 | 34.6 | 30.3 | 31.0 | 35.0 | 32.3 | 32.9 | 36.6 | 43.8 | 44.5 | 36.6 | 31.5 |
| 39.2 | 38.9 | 39.7 | 39.3 | 30.3 | 30.5 | 38.6 | 39.1 | 40.5 | 40.0 | 38.9 | 39.6 |

July 25th, 1983.

Before irrigation

| 20.8 | 28.1 | 30.6 | 31.1 | 27.3 | 21.35 |
| 30.1 | 31.7 | 34.7 | 32.9 | 30.4 | 30.80 |

After irrigation

| 28.1 | 32.8 | 39.1 | 40.4 | 33.7 | 28.23 |
| 33.81 | 31.7 | 42.5 | 42.5 | 34.8 | 32.45 |

Plot V not scheduled to be irrigated.

Note: Appendix E is only illustrative and not the whole bulk of gravimetric soil moisture determinations carried out during the experiment. Whenever there was a rainfall event, soil sampling was implemented by taking samples from two depths and on either side of each lateral set in any plot; however, when a plot was irrigated, it was necessary to estimate soil moisture contents at W1, W2 and W3 on both replicates of a plot (Figure 4 of Chapter 3).