A SUBSURFACE IRRIGATED, CONTROLLED TRAFFIC, NO-TILLAGE SYSTEM

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ABSTRACT

A subsurface trickle irrigation system was protected from damage for 21 months through use of a controlled traffic pattern and no-till agriculture. During this period, seven successive vegetable crops were grown without disturbing the irrigation system. Subsequent inspection of the system indicated that this combination of techniques would enable it to operate for periods greater than two years at acceptable levels without replacement. The experiment was conducted on two soils, a light volcanic ash soil and a heavy alluvial soil with less favorable physical properties, to assess the general applicability of the results.

Natural soil compaction over a 16-month period showed no significant effect on yields. Severe compaction imposed by tractor traffic resulted in a decrease in lettuce root weight of one-half, yet it had no significant effect on crop yield. Emitter plugging increased from an average of 23% in the non-compacted plots to 36% in the compacted plots with similar results in both shallow and deep (13 and 28 cm) lateral line placement. Plugging did not significantly reduce crop yields. Water movement along the trickle line and the intermittent nature of plugging may have reduced the influence of plugging on lettuce yields. The results from these experiments indicate that for shallow-rooted, short-duration, transplanted vegetable crops, such as lettuce and cabbage, acceptable yields can be obtained without extensive tillage if water and nutrients are adequately supplied.

Phosphorus fertilizer distributed through the trickle system was immobilized within 10 cm or less of the emitters. Because transplanted seedlings were placed directly over the emitters, this "banding" effect was more efficient than broadcast applications at similar rates in supplying nutrients to the first crop of lettuce.

The results of this research suggest that economy in time and expense may be achieved with a no-till, controlled traffic, subsurface trickle irrigation system. This method permits vegetable growers and others to exploit the benefits of reduced tillage, optimum soil-water conditions, and distribution of fertilizers through the irrigation system. In addition, phosphorus use efficiency may be increased by transplanting over the emitters. With this approach, growers can minimize the cost of lateral line repair and eliminate the cost of removing or replacing trickle laterals for each harvest cycle.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

Page

RESULTS AND DISCUSSION

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

INTRODUCTION

Irrigation has been used for centuries to maintain soil moisture for crop growth during dry seasons or in areas where crops would otherwise be lost due to moisture stress. Until recently, flood and furrow irrigation have been the techniques available to farmers. These methods are inefficient, however, and often permit crops to experience water stress between irrigation cycles. The resulting yield decline was recognized only after modern irrigation technology developed high frequency systems such as trickle irrigation. Following the introduction of trickle irrigation techniques and materials in the U.S. in the 1960's, land area under trickle irrigation has increased exponentially (Shoji, 1977). Studies worldwide have described numerous advantages to this type of system for general agriculture as well as for many specific circumstances, as detailed in a later section. Due to the relatively high cost of the materials needed, trickle irrigation was initially used for high value horticultural crops. As the materials became less expensive, application of this form of irrigation was found to be highly profitable for some field crops including sugarcane and pineapple in Hawaii.

In the mid 1970's, competition for water by industry, homes and agriculture left agriculture with a lower quantity and/or quality of water. Land prices also increased rapidly during this period requiring increased yields from a given area of agricultural land. These factors have resulted in an increased interest in trickle irrigation because of the high water use efficiency and ability to increase quality and quantity of crop yields.

During the 1970's, however, the cost of oil-based plastic products which make up virtually all components of the trickle irrigation system increased drastically. Increases in the cost of labor during this period also contributed to an increased cost of both manufacture and installation of trickle systems.

As a consequence of these increased costs it has become essential to minimize costs of maintenance and replacement of the system to keep the system economically attractive. Damage to lateral lines is largely a result of field operations, temperature and ultraviolet light. The need to remove or destroy the laterals during harvest and bed preparation is inherent in most cropping methods presently used. Placing the system underground may protect it during crop growth. Experience in the Hawaiian sugar industry showed that laterals buried as deep as 45 cm are still subject to damage during normal field operations (Martin, 1973). Their experiments, however, lacked any method of keeping heavy machinery from crossing the subsurface lateral lines.

Both controlled traffic and no-till cultivation are accepted soil management practices. These practices may provide a way to keep machinery traffic off irrigation laterals and to prevent tillage-related damage. If these practices permit extended use of subsurface lateral lines, other cost-reducing innovations may be possible.

A common method of increasing the cost effectiveness of trickle irrigation systems is to distribute fertilizers with the irrigation water. Of the fertilizers commonly injected into trickle irrigation lines, phosphorus has been studied most intensively because of its tendency to precipitate, plug emitters, and to be immobilized in the soil near the emitters.

In highly leached, high phosphate-fixing soils common to the tropics, high application rates of phosphate fertilizers are often required. Although "banding" of those fertilizers is a common method of increasing phosphorus uptake in crops, most research done with trickle-applied-phosphorus has been focused on moving this nutrient the greatest possible distance through the soil. The potential advantages of immobilization of phosphorus near the emitter, a self-banding effect, has yet to be studied.

The objectives of the present study were:

1. To determine if subsurface trickle irrigation lateral lines can be protected from damage through the use of no-till, controlled traffic soil management.
2. To determine if long-term continuous cropping in no-till, subsurface trickle irrigated, controlled traffic agriculture will significantly affect yields of selected leafy vegetables.
3. To assess the effect of mechanical soil compaction on the subsurface trickle system and determine whether deeper burial provides protection from the effects of compaction.
4. To assess the effect of mechanical soil compaction, depth of lateral line placement and irrigation frequency on crop yield.
5. To assess the merits of inorganic phosphate fertilizer application through the trickle irrigation system relative to standard broadcast application.

LITERATURE REVIEW

A. Trickle Irrigation

1. Advantages

Research and experience over the last 40 years have produced a long list of specific advantages derived from the use of this form of irrigation in all types of agriculture, including:

1. Reduced water stress in plants, resulting in increased yield and quality (Shoji, 1977).
2. Increased water savings (Gustafson et al., 1974; Hiler & Howell, 1972).
3. Increased soil erosion control.
4. Better ripening and fruit size uniformity (Hall, 1974).
5. Increased ease of automation (New and Roberts, 1974).
6. Greater field moisture control for better:
   - weed control (Shani, 1974)
   - disease control (Shani, 1974)
   - field trafficability (Hall, 1974)
   - harvesting conditions (Hall, 1974).
7. Increased plant growth and earlier maturity (Dan, 1974).
8. Increased crop density (Bach, 1972).
9. Increased control of fertilization (Shani, 1974).
10. Reduced labor, fuel and power requirements (Harrison and Myers, 1974).
11. Availability of irrigation for land that can not be irrigated by other methods (Grove, 1974).

12. Increased control of the root-zone environment permitting the use of higher salinity soil and water (Goldberg and Shmueli, 1970 and 1971).
13. Expanded use beyond irrigation including:
    - pesticide distribution (Chapman et al., 1978)
    - fertilizer distribution (Grobbelaar and Lourens, 1974)
    - soil fumigation (Uzrad and Goldberg, 1974).

2. Disadvantages

Disadvantages to the system include:

1. Cost
    - high initial cost of controls, pipes, lateral lines, installation labor, etc. (Hall, 1974)
    - frequent lateral replacement, increasing cost of materials and labor (Harrison and Myers, 1974)
    - frequent accidents inherent to complex systems
    - common requirement for replacement of entire systems due to faulty designs
    - frequent damage from ants, rodents and plants (Hall, 1972; Chang and Ota, 1976).
2. Salt accumulation from fertilizers and irrigation water (Goldberg et al., 1971; Goldberg and Shmueli, 1971; Tscheschke et al., 1974).
3. Emitter plugging caused by:
    - poor water quality (Pelleg et al., 1974)
    - poor filtration (Harrison and Myers, 1974)
    - poor system maintenance (Pelleg et al., 1974)

- biological growth (Ford and Tucker, 1974)
- chemical precipitation (Pelleg et al., 1974).

Through research, practical means have been developed to alleviate or eliminate many of these disadvantages. For example, management of the soils by regular leaching cycles can correct salt accumulations (Goldberg and Shmueli, 1970; Hoffman et al., 1974; Nelson and Davis, 1974). Filtration and water treatment can prevent, minimize or even correct emitter plugging (Pelleg et al., 1974; McElhoe and Hilton, 1974; Fraser, 1974). Ant damage can be reduced or prevented by installing ridges which deny ants access to the emitter (Chang et al., 1980). Incidence of faulty design should decrease with the availability of simplified design techniques (Wu and Gitlin, 1978a and 1978b) and subsurface placement can protect water transport systems from accident as well as from sun- and heat-related damage. As planning, construction, operation and maintenance become more routine, the disadvantages of trickle irrigation should continue to decrease. However, the rapid rise in the cost of petroleum-based products and of labor for both the installation and replacement of worn or damaged submains and lateral lines are continuing problems.

3. Subsurface Trickle Irrigation

Burial of the trickle irrigation system may provide a means to decrease replacement frequency, thus significantly decreasing the overall cost of materials and labor. The subsurface placement of trickle irrigation systems has a long history. The earliest commercial systems were buried, but because of frequent clogging caused by poor filtration, surface systems are far more common today (Shoji, 1977).

Since those initial attempts, investigations into subsurface irrigation have been relatively few and generally have not addressed the aspect of material protection. Important exceptions to this, however, have been efforts on the part of the Hawaiian sugar industry to protect lateral lines by burying them (Gibson, 1973; La Rue, 1973). In this industry fields are usually burned before harvesting. The cane is then harvested with heavy field equipment. Both of these practices destroy the surface placed tubing (Martin, 1973). Burying lateral lines protects them from field burning but burial as deep as 45 cm has not successfully protected them from damage by heavy machinery. Deeper placement has not been feasible because of poor water distribution and maintenance difficulties. The sugar industry's work suggests that subsurface placement does not protect lateral lines from farm machinery traffic unless traffic is also restricted.

B. Tillage

A subsurface trickle irrigation system is incompatible with conventional methods of tillage. If the trickle system is to be preserved, it must be protected from the damaging effects of compaction and tillage. Two common agricultural techniques used to minimize compaction and plowing are controlled traffic and no-till farming.

1. History of Compaction Studies

Both no-till and controlled traffic farming methods resulted from the reassessment of tillage practices in the United States in the 1950's and 1960's (Jones et al., 1968; Cooper et al., 1969). The adverse effects of field traffic on soil physical properties associated with tillage and crop protection operations were recognized in the early 1950's (Weaver and Jamison, 1951) and were the subjects of a book published by the American Society of Agricultural Engineers (Barnes et al., 1971).

Research into the effect of soil compaction on plant growth was also being conducted at this time (Shaw, 1952). Yield decline attributed directly or indirectly to soil compaction was reported for sunflower (Veihmeyer and Hendrickson, 1948), sugarcane (Trouse and Humbert, 1961), tomato and potato (Flocker et al., 1960; Timm and Flocker, 1966) and corn (Phillips and Kirkham, 1962; Raghavan et al., 1979). Nichols (1957) described the agronomic disadvantages of variable ripening times of crops caused by variability in field compaction. Poor soil aeration (Trouse, 1971; Taylor et al., 1972; Vorhees et al., 1975), mechanical impedance to roots (Gill, 1961; Trouse, 1978), increased drought susceptibility because of root restriction (Trouse et al., 1975; Cary and Rasmussen, 1979) and decreased soil moisture (Vomocil and Flocker, 1961) were given as causes for retarded growth and maturity of crops in compacted soil. No-till agriculture was introduced in the early 1960's as one method to correct these problems.

2. No-Till Agriculture

a. History

Excessive uncontrolled field traffic during seed bed preparation has been shown to nullify any advantages gained by the associated tillage operations (Kincade, 1972; Dumas et al., 1974). Tillage and plant protection operations require tractor and other machinery traffic which normally follow no set traffic pattern. No-till planting was introduced in the early 1960's to minimize field traffic and, therefore, soil compaction (Phillips and Young, 1973).

In a no-till system, all field preparation (pesticide and fertilizer applications, plowing, seed placement and soil packing) are completed in a single pass without plowing. The result is a crop planted into the stubble of a previous crop or into dead sod.

b. Advantages of no-till

Phillips and Young (1973) compiled a list of advantages of no-till agriculture. Advantages include:

- decreased wind and water erosion in stubble covered fields
- decreased crop lodging due to firm soil
- decreased labor, fuel and machinery costs by eliminating multiple passes over the field
- decreased rate of soil compaction from less traffic
- decreased time to planting by completing all operations in a single pass
- decreased irrigation requirements due to decreased evaporation and increased infiltration in stubble-covered fields
- improved soil structure in the absence of plowing
- increased soil organic matter from mulch decomposition
- increased land availability when erosion can be controlled.

c. Disadvantages of no-till

The disadvantages associated with no-till can, under certain conditions, be serious enough to preclude its use. Disadvantages include:

- decreased yields in easily-compacted or waterlogged soils (Beverlein and Bone, 1970)

- increased pest and disease problems due to harborage of organisms in the remaining crop litter (Triplett and Van Doren, 1969)
- increased difficulty in weed control (Phillips, 1972).

While no-till agriculture reduces field traffic, it does not eliminate machinery-related soil compaction. This may be one reason why controlled traffic agriculture was introduced shortly after no-till became widely known.

1.) Controlled traffic agriculture

a.) History

Cooper et al. (1969) reported that the first pass of a tractor in newly tilled soils caused ten times the compaction of subsequent passes. To overcome this problem they suggested a controlled traffic system where all traffic is restricted to previously compacted lanes, usually the wheel marks of a wide wheel span tractor. Tractors and machinery used in controlled traffic agriculture are designed with a given wide wheel span so that all field operations can be performed from platforms suspended above the bed while all the weight is carried by the wheels, which follow compacted traffic lanes.

b.) Advantages

Controlled traffic farming has several advantages in addition to those of no-till. These include:

(1) Traffic on well-packed lanes which permit better traction, reduced wheel resistance and easier access to the field under a wider variety of weather and soil conditions.

(2) With well defined traffic lanes, crops can be planted to avoid lateral compaction (Dumas and Trouse, 1974) and root restriction (Dumes et al., 1975).

(3) Mechanical soil compaction in the growing beds is avoided. If needed, this loose soil can be tilled with a minimum of energy input.

(4) The beneficial effects of deep tillage will be preserved for long periods (Trouse et al., 1975).

2.) No-till, controlled traffic and subsurface trickle irrigation

By keeping traffic in defined lanes, lateral lines can be protected by placing them between the compacted lanes. The soil between the lanes is protected from compaction, so that no plowing is necessary, although shallow cultivation for weed control is possible if laterals are buried. This combination of techniques should provide optimal conditions for crop control with minimum maintenance.

C. Phosphorus Placement through the Subsurface Trickle Irrigation System

The high distribution efficiencies of trickle irrigation can be exploited to achieve similar efficiencies in fertilizer application. By injection of fertilizer into a subsurface trickle irrigation system, fertilizers can be delivered directly to the crop's root zone, implying a potential for increased fertilizer use efficiency. This would be especially true of nutrients such as phosphorus which are rapidly immobilized by the soil. When used in conjunction with certain soils with high phosphate fixing ability, the maintenance of high

P availability adjacent to each emitter may be an effective solution to the problem of phosphate fixation.

1. Phosphate Fixation

Phosphate fixation in tropical soils has been recognized for nearly a century. Davis (1935) cited work done in 1902 which established that many tropical soils fix large amounts of applied phosphorus, removing it from the pool of plant-available nutrients. More than one-third of all soils in the lowland tropics are thought to be particularly high in their phosphate fixing ability (Kurtz and Quirk, 1965; Sanchez, 1976). Davis and other more recent researchers (Kurtz and Quirk, 1965; Shelton and Coleman, 1968; Rajan and Fox, 1972; Munns and Fox, 1976) characterized the reaction rates and possible chemistry of the soil-phosphate bond describing a fast, somewhat reversible reaction between this nutrient and soil aluminum and a slower, less reversible reaction with soil iron. Phosphate fixation was shown to have an inverse relationship with both a soil's native phosphate fertility (Fox et al., 1968) and amounts of phosphate fertilizer previously applied (Kamprath, 1967).

The ability of applied phosphorus to block the "fixation sites" in the soils (Fox et al., 1971) explained the observation by Young and Plucknett (1966) that increasing phosphate applications could, at some point, "quench" the absorptive capacity of the soil. Although "quenching" is an inaccurate representation of the true nature of the soil's reaction with phosphorus it is an attempt to describe the fact that, at some application rate, the plant-available phosphorus in equilibrium with sorbed phosphorus will be sufficient to produce optimal yields. The phosphorus application rate required for optimal crop yield is a function of the sorptive capacity of the soil and the level of available phosphorus required by the crop.

To achieve sufficient plant available phosphorus in the soil by broadcast application of phosphate fertilizers, several tons of phosphate fertilizers per hectare may be required on high phosphate fixing soils. In an attempt to find a more efficient method of fertilizer application, considerable research has been conducted using localized fertilizer application (Kratky and Tamimi, 1974; Fox and Kang, 1976; Memon, 1980). This method requires that fertilizer be applied to small volumes of soil at sufficiently high levels for plant availability, without requiring saturation of the entire volume with nutrients. This provides an advantage only when economics or availability of materials preclude fertilization of the entire cultivated soil volume to the critical level of plant requirements for optimal growth (De Wit, 1953; Nishimoto et al., 1977).

2. Phosphorus Application through Trickle Systems

Phosphorus application through trickle irrigation systems has been studied with conflicting results. Based on field results, the distribution of phosphorus through the trickle systems has been discouraged because precipitation of phosphorus causes emitter plugging (Sharratt, 1976). This disadvantage is particularly likely to occur in areas where irrigation water has high pH and high calcium concentrations. However, with caution and use of proper materials, plugging can be avoided and considerable economic advantage can be gained by using the trickle system to apply phosphorus (Rauschkolb et al., 1976; Kresge, 1978).

Keng et al. (1979) discouraged the use of phosphorus in trickle systems in Oxisols where its rapid fixation adjacent to emitters resulted in poor diffusion of phosphorus through the soil. Rolston et al. (1975b) showed that greater phosphate penetration through soil columns could be gained by use of organic phosphate. Rauschkolb et al. (1976) demonstrated in field experiments on loamy soil that at similar application rates, organophosphates diffused through 2.4 times larger volume than did orthophosphates. However, extractable phosphorus within this larger volume was only 18% of that found using orthophosphate sources. Rolston et al. (1975a) suggested there were advantages to applying phosphorus into limited soil volumes through the trickle system. They calculated that the application of 15 kg of P_2O_5 through 7200 emitters, each into a soil volume 8 cm in diameter, would result in localized applications of 1000 kg/ha--a number close to the phosphorus requirement for optimal crop yields in some important tropical soils. This suggests that localization of inorganic phosphorus fertilizers might be beneficial to crop growth by concentrating phosphorus in small volumes in a manner similar to conventional fertilizer banding.

Unfortunately, most phosphorus applications through trickle system have been to crops that cannot take full advantage of these systems because of economic or agronomic reasons. For example, in the Hawaiian sugar industry, "pineapple spacing" is commonly used to reduce lateral line cost by placing one line between every other row of sugarcane plants (Santo, 1976). In addition, the irrigation lines must be placed away from the sugarcane stools to prevent pinching during the growing cycle (Hilton, 1978). Rapid initial growth of sugarcane requires phosphorus placement immediately adjacent to the seed piece. Therefore, if phosphorus is to be applied to this crop through the trickle system, the sugar industry is forced to maximize phosphate diffusion through the soil toward the crop roots.

Other crops or cropping systems, however, may find considerable advantage in the fact that roots tend to concentrate around emitters (Goldberg et al., 1971) and that phosphorus can readily be banded in this same volume of soil.

MATERIALS AND METHODS

A. Main Experiments

Four separate components were combined to form an integrated cropping system. These components were: (1) subsurface trickle irrigation, (2) controlled traffic, (3) no-till and (4) continuous cropping. All have been studied separately elsewhere but the latter three, especially in combination, have received little attention in Hawaii. To test the combined benefit of these practices, experiments were initially established on a Typic Eutrandept, a light, fertile, relatively noncompacting soil. To assess the general applicability of this approach, similar experiments were installed on a Vertic Haplustoll, a clayey soil with less favorable physical properties.

To assess the integrated system's ability to sustain crop growth for extended periods without lateral line maintenance, the individual factors which may limit crop growth were also assessed. These factors include lateral line performance during extended burial and the effect of natural soil compaction on crop growth in the absence of tillage and traffic. Experiments were designed to permit the study of these individual factors while the overall ability of the integrated system was assessed by growing a large number of crops in succession using fast-growing leafy vegetables (Table 1). These crops were harvested six to eight weeks after transplanting and provided rapid generation of data with which to evaluate both the performance of the combined system and the soil's ability to sustain production.

1. Site Characteristics

Five experiments were conducted at the Lalamilo Experimental Farm in Kamuela on the island of Hawaii. The Waimea soil series on this

Table 1. Plot parameters for each experiment

			Plot			Lateral Line				
Site	Expt. No.	Description	Length (m)	Width (m)	Plots in Expt.	Emitter Spacing (cm)	Laterals per plot	Depth (cm)	Distance between Laterals (cm)	Total per Plot
Lalamilo	L_1	Longevity	6.0	1.2	18	45.4	2	13	61	26
	L_2	Compaction	2.4	0.3	48	30.2	4	Surface	30, 60	4
	L_3	Depth/frequency	6.0	1.2	18	45.4	2	13, 28	61	26
	L_4	Phosphorus	3.7	1.2	30	45.4	3	9	30	24
	L_5	Tube farm	3.3	1.2	10	30.2	2	13	61	100
Waimanalo	W_1	Longevity	6.0	0.9	18	30.2	2	13	31	40
	W_2	Compaction	2.5	0.3	48	30.2	4	Surface	30, 60	4

farm is a member of the medial, isothermic family of Typic Eutrandepts. This soil has a low bulk density (0.5 when newly plowed to 1.0 g cm^{-3} when compacted), good drainage, high water-holding capacity, high fertility and is relatively free of rocks. The site is located 850 meters above sea level and has an annual average rainfall of approximately 760 mm. Loose, fertile soil, high solar radiation and cool nights make Kamuela an important vegetable farming area (Appendix A).

Two additional experiments were installed on the heavy Waialua soil located at the Waimanalo Experimental Farm on the island of Oahu. This soil is a member of the very fine, kaolinitic, isohyperthermic family of Vertic Hapustolls. The soil is stony and very slowly permeable. The site is 24 meters above sea level and has an annual average rainfall of approximately 1400 mm. Typical weather includes long, hot, dry periods during the summer and fall interrupted by irregular rainfall. Heavy rain and flooding are common during the winter and spring. Corn, tomatoes and other heat tolerant field crops grow well at the Waimanalo farm (Appendix B).

2. Plot Preparation and Irrigation

The experimental plots were designed to create a controlled traffic pattern. Fields were prepared by disking and rototilling to a depth of approximately 20 cm. Tractors with the widest available front and rear wheel span were used with the wheel span defining the width of each plot in most experiments (Table 1). Furrows were cut to a 28 cm depth and backfilled, if necessary, to place the lateral lines at the desired depth. Kirkhill 16 mm diameter monowall tubing was placed with emitters (punched orifices of 0.03 mm diameter) facing upward. Adjacent lines were offset by one-half the distance of the orifice spacing as shown in Figure 1.

In addition to lateral lines, all submains and connections were placed at least 5 cm underground. The tractor wheels marked the traffic lanes, and throughout the experiment vehicular and foot traffic were confined to these lanes. Except for experiments L_2, W_2 and L_4 (the phosphorus and compaction experiments) where plots were level with the traffic lanes, each plot consisted of a bed raised approximately 30 cm above the traffic lane. This was found necessary to discourage foot traffic in the beds.

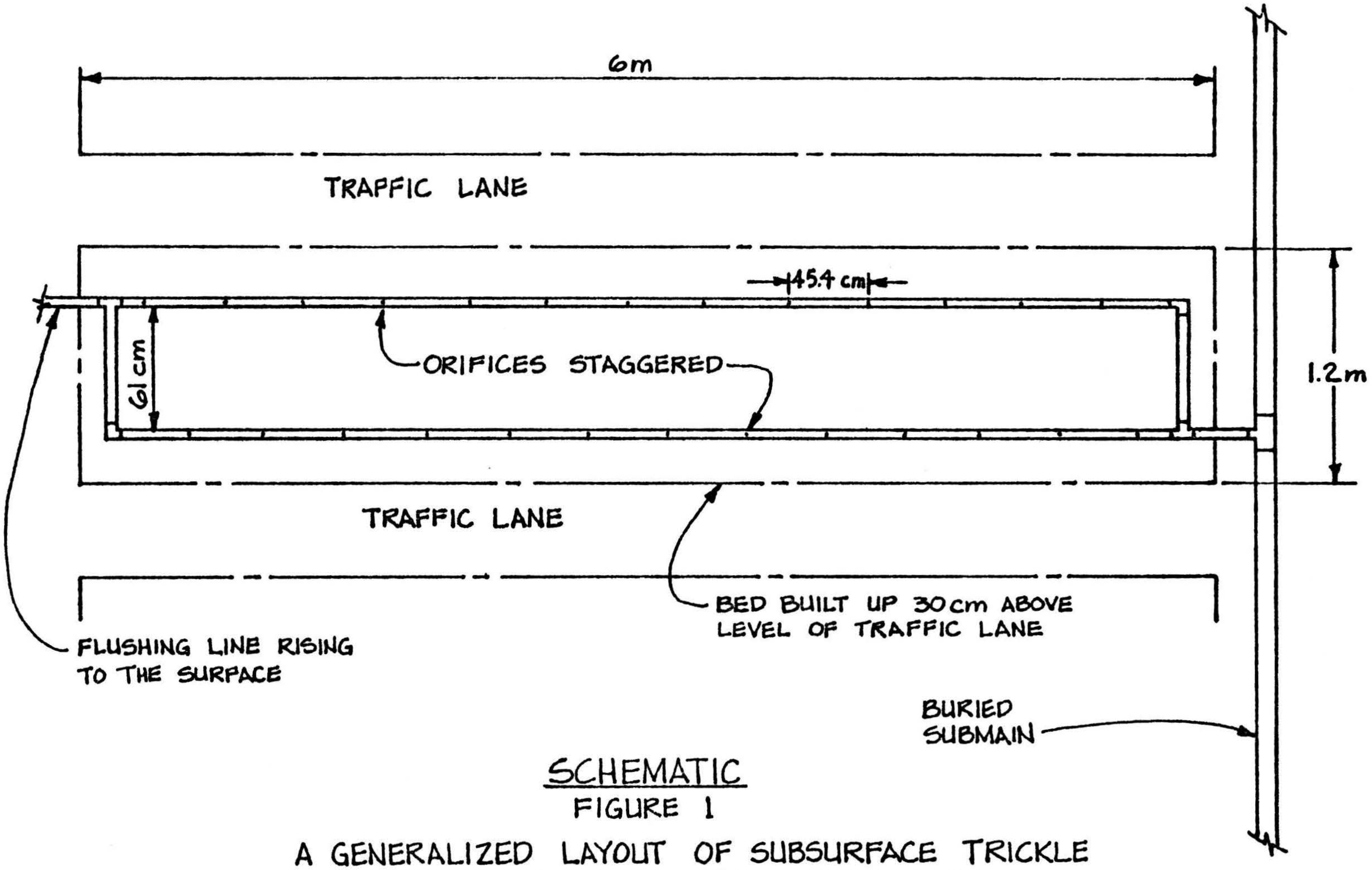
Municipal water of high quality was used for irrigation at both sites. Two pressure regulators were used in series to keep the pressure in the laterals at approximately 0.50 kg/cm^2. Thirty minutes per day provided the optimal irrigation level of 0.36 cm per day (Wu and Gitlin, 1977).

3. Soil Compaction

Soil compaction and its effect on the integrated system were studied in four ways.

a. Relationship between penetrometer resistance, soil water content and bulk density

This relationship was established to help study the effects of soil bulk density on the integrated system. To determine this relationship in the two soils studied, data were collected by taking three penetrometer readings within a small area using a Proctor penetrometer (Soil Test, Inc.) and standard procedures, and when three or more readings were somewhat similar, a core was taken from



SCHEMATIC

FIGURE 1

A GENERALIZED LAYOUT OF SUBSURFACE TRICKLE IRRIGATED PLOT. PARAMETERS VARY BETWEEN LOCATIONS AND EXPERIMENTS AS OUTLINED IN TABLE 1.

the undisturbed soil between the holes left by the penetrometer. Data were taken from the uncompacted plots, compacted plots and elsewhere to obtain as wide a range in bulk density and soil moisture as possible. Penetrometer readings for each sample were averaged and compared with the associated soil bulk density by regression analysis and plotted using a program being developed by Dr. R. Jones, University of Hawaii.

b. Natural compaction

Natural compaction was monitored throughout experiments L_1 and W_1 in both subject soils (Table 1). To do this, soil cores were collected from the protected plots for moisture and bulk density determination in order to monitor the rate of compaction of surface (0-3 cm) and subsurface (6-9 cm) soils in the absence of traffic. While sampling was easily accomplished in the Waimea soil, the plastic, rocky nature of the Waialua soil required that one plot at the Waimanalo site be excavated to the plow pan, the soil sifted through a 60-mm screen and returned to the plot. Samples from this plot provided far more consistent data with which to work.

During the sampling in loose soils it became evident that the samples were being compacted by the soil corer. To avoid this, samples were collected by pressing 3-cm brass rings (volume 68.7 cc) into the soil.

c. Compaction by varying passes of a tractor

The second method used to study compaction was to assess the effect of increasing tractor traffic on bulk density and crop yield in both soils (experiments L_2 and W_2). Thirty-two-cm wide strips of a prepared plot, 2.4 m long, were compacted using 2, 4 and 8 passes of a farm tractor. These treatments, each alternating with an uncompacted strip, were established in a randomized complete block design with six replications. Four lateral lines with 32-cm emitter spacing were placed on the soil surface, emitter downward, across all strips. Soil bulk densities and penetrometer readings were recorded to evaluate the effect of tractor traffic on soil compaction.

d. Severe mechanical compaction

A final study on the effects of compaction was prepared by mechanically compacting one-half of each plot in ongoing experiments after 16 months of continuous cropping. Thirty-six plots at the Lalamilo farm (experiments L_1 and L_3) and 18 at the Waimanalo farm (experiment W_1) were compacted lengthwise with 10-12 passes of a farm tractor directly over one of the two buried lateral lines in each plot. Soil bulk density, crop yields, emitter plugging rates and distribution as well as the weights of total roots and secondary roots (roots without the underground stump) from selected plots were recorded to evaluate the interrelationships of these components.

4. Lateral Line Performance under Subsurface Conditions

a. Assessment of lateral lines used in experimental plots

Kirkhill monowall lateral line performance was assessed by monitoring the percentage and distribution of emitter plugging at intervals during the study of the integrated system as well as the appearance of the lateral lines at the termination of each experiment. The condition of the emitters was determined by the wet spot which appeared on the soil surface shortly after the irrigation was started. In one experiment, plugged emitters were exposed and cleared by hand. Twenty plugged emitters, were examined in the laboratory with an optical microscope to determine the causes of plugging.

b. Tube farm

A tube farm (experiment L_5) was established at the Lalamilo farm to compare the performance of other lateral lines. Thirty-two-meter sections of 11 types of trickle irrigated laterals were buried at a depth of 13 cm (Table 2). Unreplicated 16-m long plots had two lateral lines each. Two crops of maize and assorted vegetables were initially grown on these plots after which the area was left fallow for the duration of the test. After 18 months the ground cover was killed with glyphosate, emitter plugging estimated and each line uncovered and examined.

5. Crop Performance

Six experiments were established to evaluate the long-term performance of the integrated system under different experimental conditions (Table 1).

a. The experiments

To compare the results between the two soils, two experiments were established at each site. The first (L_1 and W_1) was designed and managed to provide optimum conditions for the integrated system based on previous experience. Both experiments had 18 plots, 6 m long, but of different widths (1.2 m and 0.9 m at Lalamilo and Waimanalo, respectively) to properly accommodate the crops best suited for each location.

The second experiment established at both sites (L_2 and W_2) was a study of the effect of increasing tractor traffic on crop growth. Narrow plots, 0.32 m wide and 2.4 m long, were established with 2, 4 and 8 passes of a tractor in a randomized complete block design with six

Table 2. Lateral line materials tested under subsurface conditions

Source	Common Name	Type	Material	Wall Thickness*
T Systems corp	trickle tape	bi wall	polyvinyl	5 mil
T Systems crop	trickle tape	bi wall	polyvinyl	8 mil
Kirkhill	monotube	mono wall	polybutylene	15 mil
Chapin	twin wall	dbl wall	polyethylene	8 mil
Chapin	twin wall	dbl wall	polyethylene	4 mil
Chapin	twin wall	dbl wall	polyethylene	3 mil
Reed	biwall 19	biwall	polyethylene	19 mil
Reed	biwall 15	biwall	polyethylene	15 mil
Reed	biwall II	biwall	polyethylene	15 mil
Chapin	drip hose	biwall	polyethylene	12 mil
Anjac	(none)	biwall	polyethylene	19 mil

*1 mil = 1/100 inch = .025 mm

General comments: All plots had 32 m of lateral line with 100 emitters each (32 cm spacing). Plots were unreplicated.

replicates. A zero (uncompacted) treatment alternated with each compaction treatment resulting in a total of 48 plots.

Two other experiments (L_3 and L_4) were established at the Lalamilo farm to study crop performance in the integrated system. These were the depth/frequency and phosphorus experiments, respectively. These will be discussed in detail under the Supplemental Experiment subsection below.

b. Crop cultivars

At the Lalamilo site, head lettuce (*Lactuca sativa* var. Great Lakes R200 and Mesa) were transplanted during the winter and summer months, respectively. One rotation of head cabbage (*Brassica oleracea* var. Capitata) was also grown.

At Waimanalo, the more heat tolerant Anuenue lettuce cultivar was transplanted. Mustard cabbage (*Brassica chinensis* var. Hawaiian Waianae strain) was transplanted on three occasions when conditions for lettuce growth were particularly unfavorable.

c. Planting cycle

Seeds were sown in trays and kept in a fiberglass roofed seedling house or a glass house for one month prior to transplanting. The experiment was designed and timed so that the previous crop could be harvested, the beds prepared and the next crop transplanted within a two-day period.

d. Fertilizer application

Initial preplant fertilizers were applied to all but the phosphorus plots at the rates of 25 and zero kg/ha of P and K, respectively at Lalamilo and 120 and 100 kg/ha of P and K, respectively, at Waimanalo. Triple superphosphate was broadcast for the phosphorus applications while dissolved potash was applied through the trickle system. Additional nutrients were applied at rates determined to be necessary by the response of the previous crop (Table 3).

e. Crop harvest and sampling

To simplify sampling and permit more direct comparisons between treatments, the entire crop was harvested when approximately 80% of the crop was judged to be mature. Whole plant weights and plot-composite samples of the first wrapper leaf on each lettuce head were taken. Leaf samples were dried at 60°C, ground and analyzed for P, K, Ca, Mg, S, Si, Na, Cl, Mn, Fe, Cu and Zn by X-ray fluorescence spectrometry and for N using the micro Kjeldahl technique.

f. Plant protection

Glyphosate was applied as the general herbicide. Paraquat and hand weeding were used for purslane (Portulaca oleracea), burr clover (Medicago polymorpha), cheese weed (Malva parviflora) and other glyphosate-resistant weeds. Pronamide and CDEC were applied as pre-emergence herbicides. Methyl bromide was applied to control nutsedge (Cyperus rotundus) in two Lalamilo experiments. Diazinon was used to control insects (primarily cutworms, ants, and webworms) and DCNA was used to control bacterial rot. All pesticides were applied at recommended rates.

B. Supplemental Experiments

While monitoring the long-term performance of the integrated system, other experiments were conducted which focused on ways of maximizing the uses and efficiencies of this combined farming system.

Table 3. Crops, planting dates and nitrogen application rates for all major experiments

Crop	Planting Date	Total Nitrogen Application (kg N/ha)	Method
A. Longevity and depth/frequency experiments at Lalamilo (L_1 and L_3)			
lettuce	5/08/79	80 (urea)	3 equal applications, 2 week intervals (I)*
cabbage	8/02/79	40 (urea)	2 equal applications, 3 week intervals (I)
lettuce	10/18/79	none	
lettuce	1/16/80	150 (urea)	100 at planting, 50 at 4 weeks (I)
lettuce	3/26/80	none	
lettuce	7/10/80	50 (urea)	25 at 4 weeks (S)**, at 6 weeks (I)
lettuce	10/20/80	50 (urea)	at planting (I)
B. Phosphorus experiment at Lalamilo (L_4)			
lettuce	7/28/78	300 (urea)	at planting (I)
lettuce	10/13/78	none	
lettuce	1/23/79	170 (urea)	140 at 3 weeks, 30 at 7 weeks (S)
lettuce	6/06/79	100 (urea)	50 at planting, 50 at 6 weeks (S)
lettuce	1/10/79	100 (urea)	50 at 1 week, 50 at 6 weeks (S)
C. Longevity experiment at Waimanalo (W_1)			
Kai choi	5/05/79	80 (urea)	at planting (I)
lettuce	7/15/79	80 (urea)	at planting (I)
Kai choi	10/30/79	80 (urea)	at planting (I)
lettuce	12/27/79	75 (urea)	25 at planting, 2 and 4 weeks (I)
lettuce	2/27/80	75 (urea)	25 at planting, 2 and 4 weeks (I)
lettuce	5/02/80	120 (16-4-4)	at planting (S)
Kai choi	8/20/80	150 (16-4-4)	25 at planting, 125 at 2 weeks (S)
Kai choi	12/01/80	100 (16-4-4)	at planting (S)

*(I) = through the irrigation.
**(S) = sidedress.

Each series of plots was designed for a specific purpose although some were subsequently altered to provide certain additional information. The supplemental experiments are described below.

1. Depth/Frequency Experiment (L_3)

Experiment L_3 was established at the Lalamilo farm to determine the effects on yield of lateral line placement depths (13 and 28 cm) and irrigation frequency (four times per day, daily or every other day), using the optimum irrigation rates established by Wu and Gitlin (1977). Plots were arranged following a randomized complete block design (three replications). The 18 plots involved were constructed immediately adjacent to the L_1 experiment. Plot preparation, crops planted, planting and harvesting dates, total irrigation application and fertilizer applications were identical in these plots (Table 3). Standard analysis of variance and least significant difference tests were performed on the resulting yield data to determine statistical significance of the response to the treatments.

2. Phosphorus Application through the Subsurface Trickle Irrigation System

This experiment (L_4), located at the Lalamilo farm, was designed to assess the effectiveness of trickle applied inorganic phosphorus and broadcast applied fertilizer P.

In order to determine P rates, phosphorus isotherms (Fox and Kamprath, 1970) were prepared with samples taken from an area known to be P deficient. Phosphorus applications required for different levels of yield response were calculated from the isotherm (Fig. 2) and information on crop P requirements (Nishimoto et al., 1977).

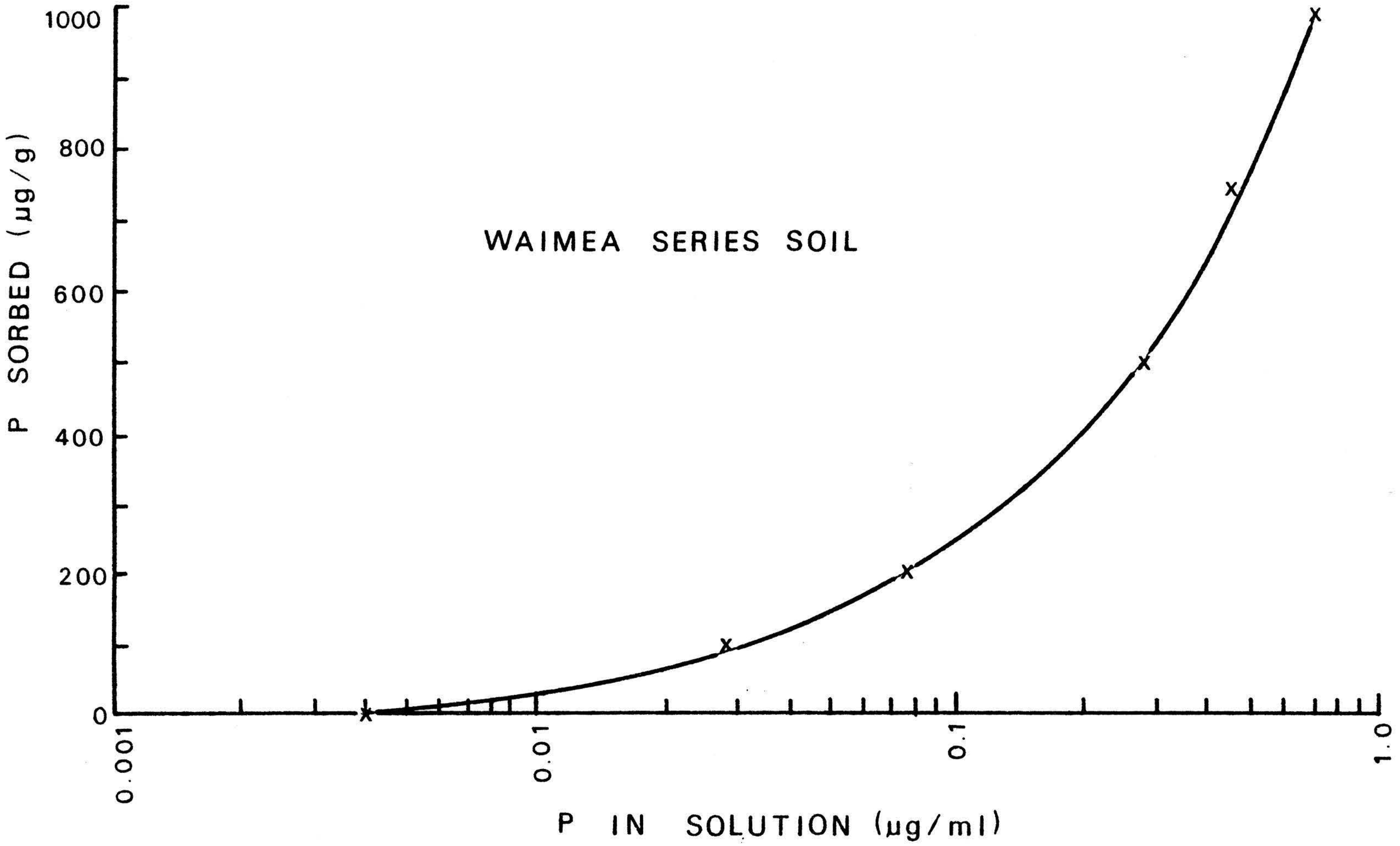


Figure 2. Phosphorus Adsorption Isotherm for a Low P Sample from the Lalamilo Experimental Farm.

To achieve low, medium and high yields of head lettuce, phosphorus levels equivalent to 0, 150, 600 and 1200 kg P/ha were applied to the 3.7-m by 1.2-m plots in a partial factorial (Table 4), randomized complete block design with three replications. Broadcast and trickle treatments were applied singly or in combination as shown in Table 4. Triple superphosphate (0-42-0) was applied for the broadcast treatments and a liquid urea phosphate fertilizer (15-27.2-0), from the Tennessee Valley Authority, was applied through the irrigation system.

To achieve the desired levels of N (300 kg/ha) and P (zero to 1200 kg/ha), urea phosphate was used in combination with dissolved urea and phosphoric acid (Table 4). These amendments were applied one day prior to planting the first crop. Nitrogen was applied to subsequent crops (Table 3) but no phosphorus was applied, permitting a study of the residual effects of the initial application.

Lettuce was transplanted directly over each emitter. Emitters were located by the wetted areas that developed on the surface soil shortly after an irrigation cycle began.

a. Sampling and analysis of soil phosphorus

Soil samples were taken in plots with trickle-placed phosphorus fertilizer in a 13 cm wide, 19 to 25 cm deep grid with the lateral line positioned on the left edge of the grid. Samples 2x2 cm square and approximately 6 cm long were taken horizontally from predetermined positions within the grid (Fig. 3) to determine the movement of phosphate into the soil. Phosphate levels were analyzed by the modified Truog method (0.02 N H_2SO_4 + 3 g/l $(NH_4)_2SO_4$ in a 1 hr, 1:100 extraction) using ascorbic acid color development (Watanabe and

Table 4. Phosphorus and nitrogen sources used to achieve desired treatment levels

Treatment	Application Rate (kg P/ha)		Triple Super-phosphate		Urea Phosphate**		Phosphoric Acid (85%)		Urea***	
	Trickle	Broadcast	kg/plot*	kg/ha	kg/plot	kg/ha	kg/plot	kg/ha	kg/plot	kg/ha
1	0	0	0	0	0	0	0	0	0.29	625
2	150	0	0	0	0.56	1253	0	0	0.11	233
3	0	150	0.33	741	0	0	0	0	0.29	625
4	600	0	0	0	0.89	2000	0.60	1344	0	0
5	150	450	0.99	2222	0.56	1253	0	0	0.11	233
6	0	600	1.32	2963	0	0	0	0	0.29	625
7	1200	0	0	0	0.89	2000	1.59	3578	0	0
8	600	600	1.32	2963	0.89	2000	0.60	1344	0	0
9	150	1050	2.30	5185	0.56	1253	0	0	0.11	233
10	0	1200	2.63	5926	0	0	0	0	0.29	625

*Plot size = 4.44×10^{-4} ha

**Urea phosphate analysis = 15-27.2-0

***Required to maintain all plots at 300 kg N/ha

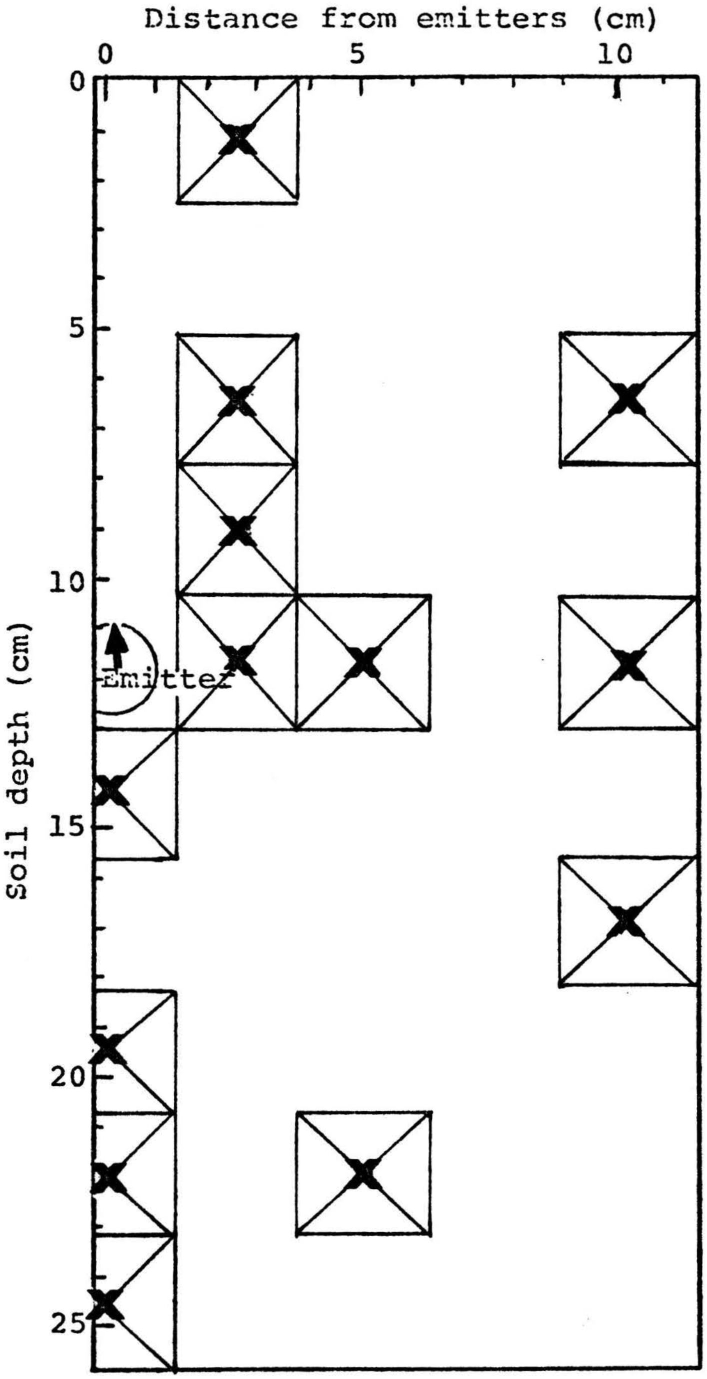


Figure 3. Soil sampling locations around a subsurface emitter.

Olsen, 1965). These data were used in a contouring program (Bridges and Becker, 1976) to draw isarithmic maps of P concentrations (Burgess and Webster, 1980) using cubic spline interpolation.

b. Yields and phosphorus in plant tissue

Yield and tissue-P response data were collected and analyzed as described in the Crop Performance section.

3. Water Movement from an Emitter

To monitor water movement from an emitter, two sets of modified gypsum resistance blocks (Larson Company's sensors) were placed 1 cm and 9 cm directly below the lateral line. The sensors in each set were placed 10 cm apart, over a distance of 50 cm from an operating emitter.

Two additional sets of sensors located at the same depths but spaced 7.6 cm apart for 38 cm from the operating emitter, were installed perpendicular to the lateral lines in the plane of the bed. Adjacent emitters were taped closed and irrigation withheld for two days before data were collected. Two sets of data were taken from this unreplicated study, one immediately after installation and one a month later.

RESULTS AND DISCUSSION

The purpose of this research was to combine a controlled traffic farm operation with a subsurface trickle irrigation system to minimize soil compaction, reduce the need for plowing and to eliminate the need to remove and re-install laterals with each crop cycle. The goal of this research is to develop a cropping alternative which would help growers increase profits and take some of the drugery out of farm work.

The research was based on two assumptions. The first was that a soil will remain loose and uncompacted and the second was that the laterals will remain functional. In Hawaii and other parts of the tropics where crops may be grown continuously, six or more transplanted, fast growing crops can be harvested from a parcel of land each year. The feasibility of adopting the combined system depends to a large degree on the duration over which these assumptions hold. To test these assumptions, compaction of tilled soil in the absence of traffic was measured over time and lateral line performance was monitored in four continuous cropping experiments. A subsurface "tube farm" was installed to permit the performance of several lateral line materials to be compared.

A. Soil Compaction

1. Penetrometer Resistance and Bulk Density

The advantages of using penetrometer resistance rather than bulk density measurements in assessing soil compaction are twofold. First, the resistance measurements are more sensitive to compaction, and second, each measurement is easier to obtain. However, because penetrometer readings usually vary with soil moisture content, soil samples for moisture determinations must be made for each set of penetrometer readings.

In the Waimea soil, stepwise multiple regression analysis showed that the natural log of penetrometer resistance values is significantly related to soil bulk density ($R^2 = 0.66$). Adding soil-water content to the regression equation increased the coefficient of determination very little. This suggests that, for this soil, penetrometer readings can be compared directly to bulk density within the gravimetric water content range of 35 to 60% (Fig. 4).

In the Waialua soil, difficulty in sampling due to the plastic nature of the soil resulted in a non-significant relationship between soil-water content, bulk density and penetrometer resistance.

2. Natural Compaction in Two Soils

Natural soil compaction was monitored by taking surface (0-3 cm) and subsurface (6-9 cm) bulk density samples at both sites over a period of several months. In the Waimea soil, where samples were taken over a 17-month period, natural compaction was found to be significantly related to time (Fig. 5). Here, soil compaction rate and bulk density at the 0-3 cm depth did not differ significantly from the 6-9 cm depth.

Mean surface penetrometer resistance in the protected Lalamilo plots increased very little over 59 weeks of sampling from an initial value of 0.55 to 3.6 kg cm^{-2}. This shows that these soils remain friable and easy to work. Soils do not become hard to the touch until they reach a bulk density above 0.80 g cm^{-3} or a penetrometer resistance above 5.0 kg cm^{-2}.

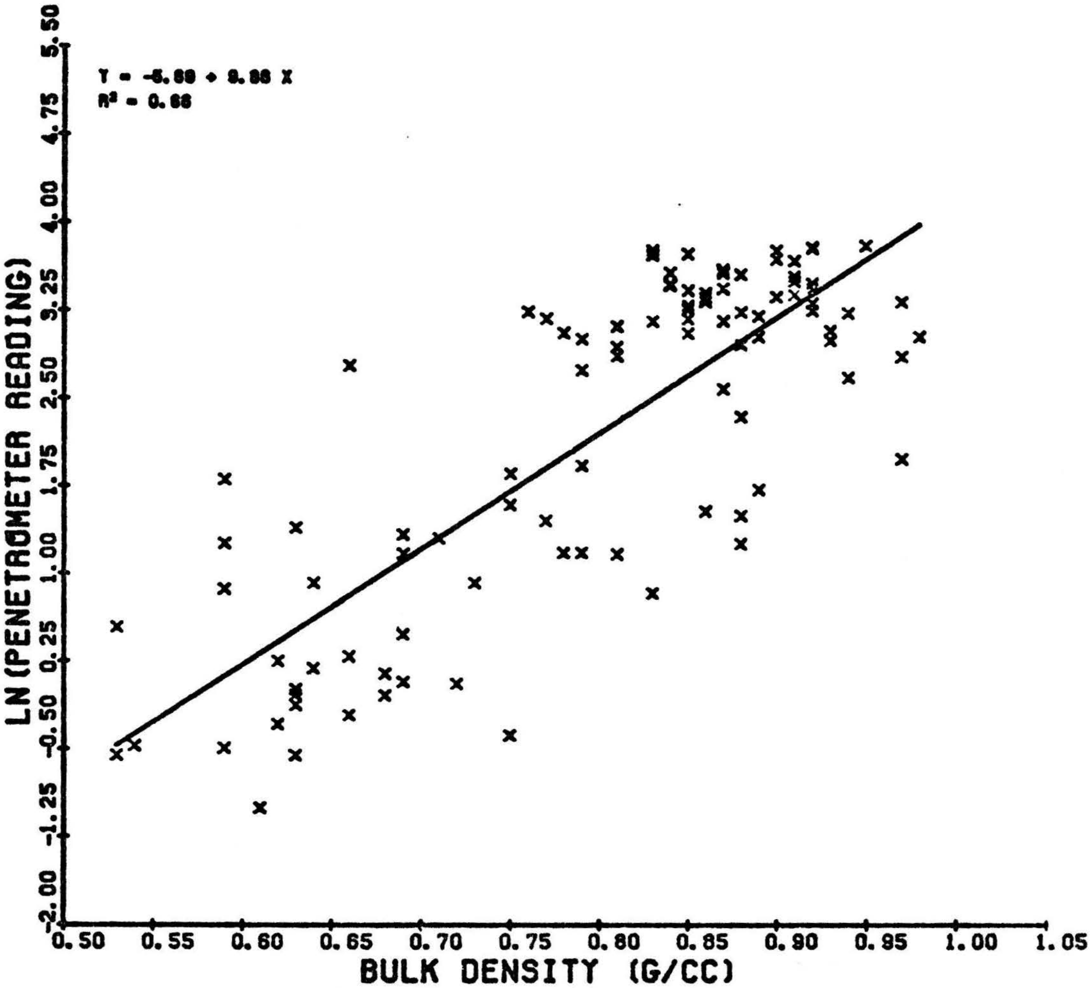


FIGURE 4. AN AVERAGED VALUE (θ, FROM 0.35-0.60) OF THE RELATIONSHIP BETWEEN THE NATURAL LOG OF PENETROMETER RESISTANCE AND BULK DENSITY (5-8 CM DEPTH) IN A WAIMEA SOIL.

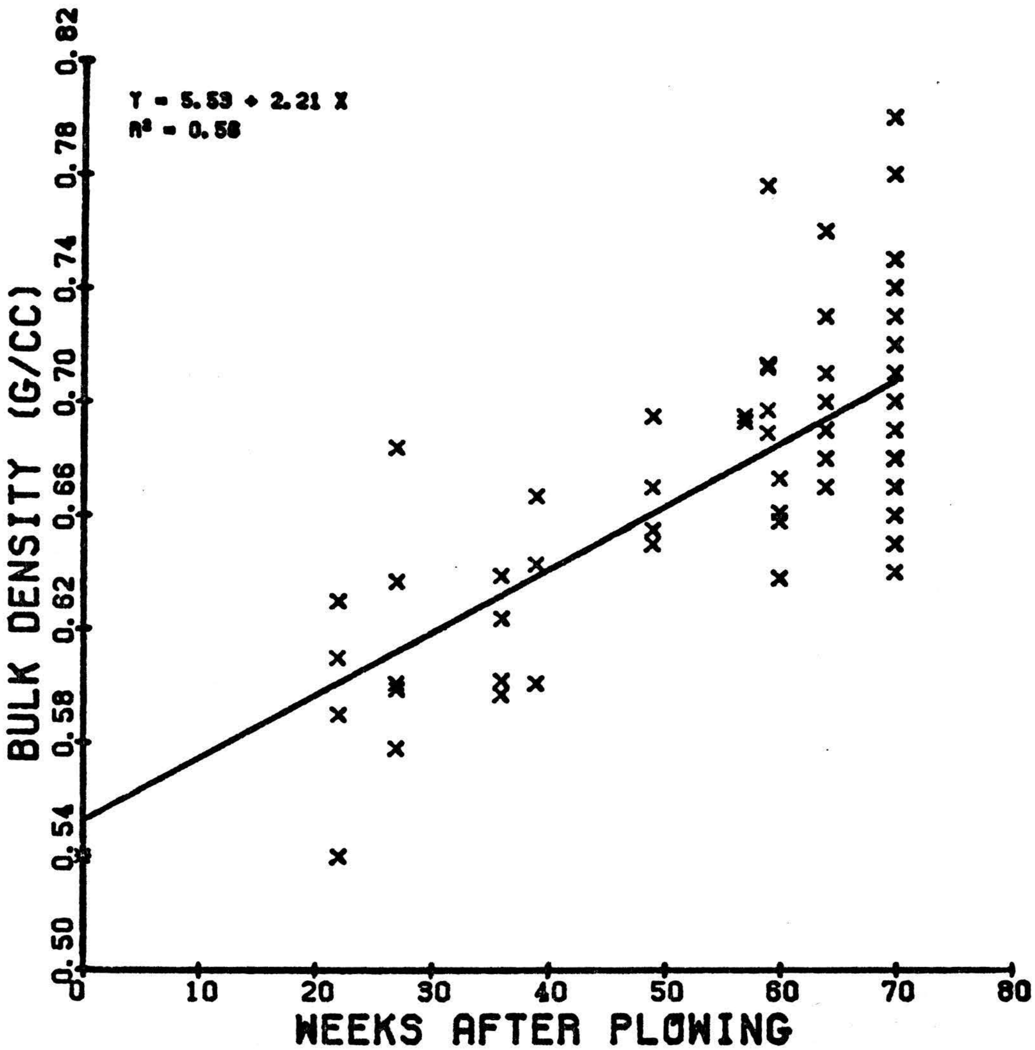


FIGURE 5. COMPACTION IN A WAIMEA SOIL OVER A 70 WEEK PERIOD WHILE PROTECTED FROM TRAFFIC.

No significant relationship between soil bulk density and time from plowing was found from samples taken in most of the experimental plots at the Waimanalo site due to the sticky, plastic nature of the soil. Sampling was partially successful in the sifted plots, however, where natural compaction over a 48-week period appeared to be relatively rapid compared with the Waimea soil (Fig. 6). Observations in the field showed that in less than one year, natural compaction of the Waialua soil resulted in a loose surface soil underlaid by a relatively dense, slowly permeable layer. The dense subsurface layer causes irrigation water that intercepts it to move laterally into the traffic lanes. More frequent, lower volume irrigation is required for this soil to accommodate the low permeability of the subsoil.

3. Effect of Mechanical Compaction

To study the effect of compaction on the integrated system, soils at both locations were compacted with multiple passes of a tractor wheel.

a. Traffic and its effect on bulk density and penetrometer resistance

To assess the importance of tractor wheel traffic on the two soils, soil samples and penetrometer resistance measurements were taken in newly plowed soil and in the wheel path after a prescribed number of passes by a farm tractor. The results of these samples are shown in Table 5.

Surface bulk density and penetrometer resistance increased in both newly plowed soils as a result of tractor traffic. The first two passes of a tractor on each of these soils produced significant

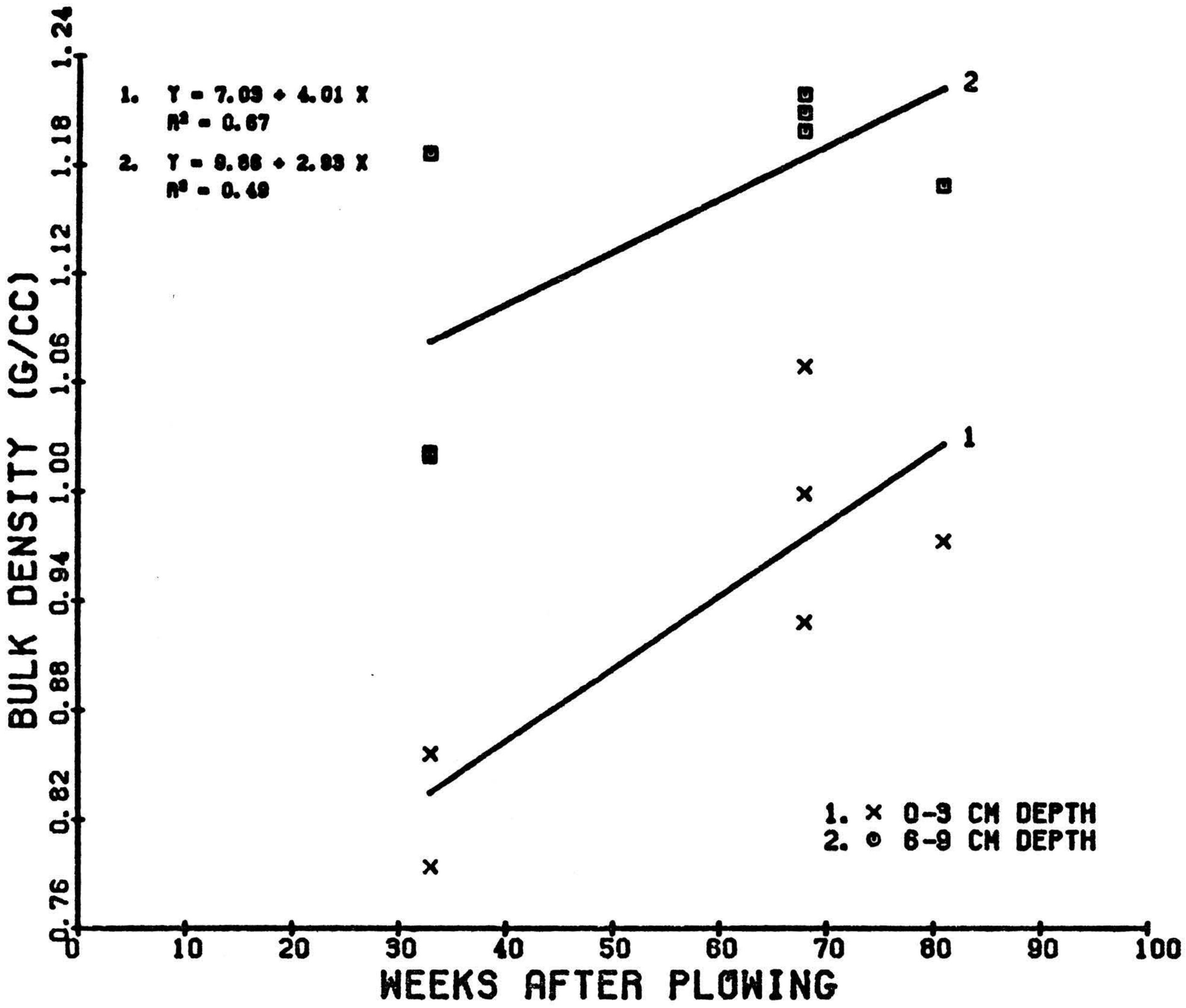


FIGURE 6. COMPACTION IN A WAIALUA SOIL OVER AN 81 WEEK PERIOD WHILE PROTECTED FROM TRAFFIC.

Table 5. Surface bulk density and penetrometer resistance as a function of the number of tractor passes

Number of Passes	Waimea Soil (θ_g† = 0.50)		Waialua Soil (θ_g† = 0.35)	
	Surface Bulk Density (g cm^{-3})	Penetrometer Resistance (kg cm^{-2})	Surface Bulk Density (g cm^{-3})	Penetrometer Resistance (kg cm^{-2})
0	0.65 a*	1.39 a*	0.94 a*	1.70 a*
2	0.85 b	22.3 b	1.33 b	23.2 b
4	0.85 b	24.2 b	1.34 b	24.3 b
8	0.87 b	27.0 c	1.40 b	25.6 b
	LSD = 0.04	LSD = 2.32	LSD = 0.08	LSD = 4.20

*Means with the same letter are not significantly different at the 5% level using the least significant difference test.

†θ_g = gravimetric water content of soils during compaction and sampling.

increases in both bulk density and penetrometer resistance, but no further significant increases in bulk density or penetrometer resistance were obtained even with eight passes of the tractor wheel. The relative effect of the first two passes in the Waimea soil is shown graphically in Fig. 7.

In different experiments (L_1 and W_1) samples were taken to compare profiles of bulk density in compacted and non-compacted soils at both locations (Table 6). These plots had been under continuous cultivation for 81 weeks. The compaction treatment was imposed on one-half of each plot at both locations eight weeks prior to sampling.

B. Subsurface Trickle Irrigation in Uncompacted Soils

1. Condition of Trickle Irrigation System Materials after Extended Burial

a. Continuous cropping experiments

Kirkhill monowall lateral line was used in all continuous cropping experiments at both sites. As each experiment was terminated, the irrigation system was uncovered and examined. Although lateral line strength was not measured quantitatively, an inspection of laterals after periods of up to 22 months showed that they were very similar in appearance to tubing which had been stored indoors. The only exception to this was fire ant (Solenopsis geminata) damage at the Waimanalo farm, discussed below. Buried polyvinal chloride (PVC) submains, although somewhat more brittle than new samples, retained their flexibility and strength far better than sections of similar pipe exposed to sunlight. These observations suggest that burial can substantially increase the working life of these plastic materials.

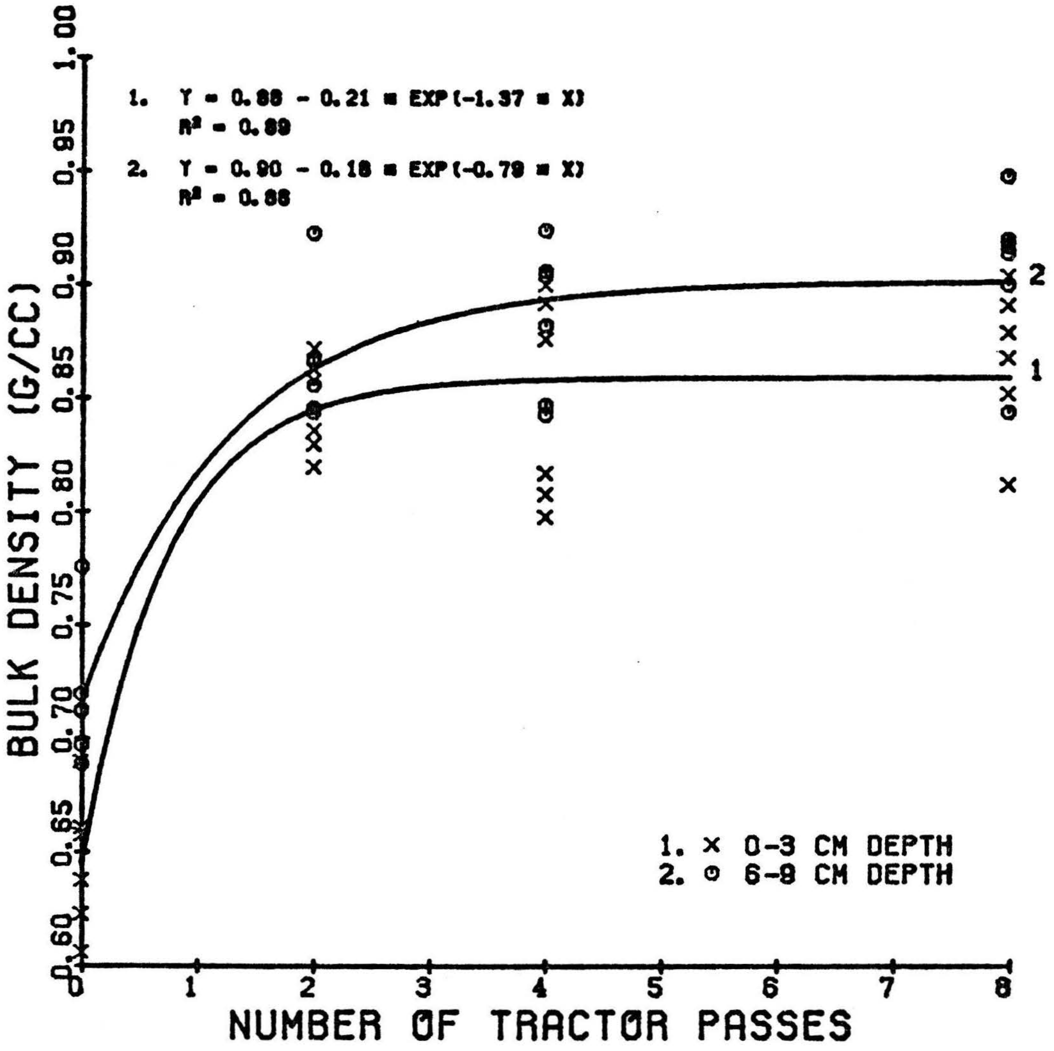


FIGURE 7. RELATIONSHIP BETWEEN BULK DENSITY AND THE NUMBER OF TRACTOR PASSES FOR WAIMEA SOIL

Table 6. Bulk density profiles of non-compacted and compacted Waimea and Waialua soils

Depth (cm)	Waimea Soil (g cm^{-3})		Waialua Soil (g cm^{-3})	
	Uncompacted $\bar{x}$ (n = 7)	Compacted $\bar{x}$ (n = 4)	Uncompacted $\bar{x}$ (n = 3)	Compacted $\bar{x}$ (n = 3)
0-3	0.65	0.92	1.01	1.07
3-6	0.69	0.90	1.12	1.26
6-9	0.73	0.87	1.23	1.31
9-12	0.74	0.84	1.24	
12-15	0.77			

b. Tube farm

Manufacturers produce irrigation lateral lines from at least three different materials and in varying thicknesses. To evaluate the effects of material composition and thickness on long-term performance of buried trickle lines, observations were made on 11 different commercially available lateral lines. After growing two crops of maize and assorted vegetables over the buried laterals, the area was fallowed. Purple nutsedge (*Cyperus rotundus*), burr clover (*Medicago polymorpha*), purslane (*Portulaca oleraceae*), sow thistle (*Sonchus oleraceus*), Fuji "grass" (*Galinsoga parviflora*), Spanish needle (*Bidens pilosa*), and various true grasses (mostly *Setaria* sp.) comprised the majority of the weeds covering the area during this period. Although foot traffic was discouraged around the tube farm, some compaction from this source occurred during the 18-month test period.

After 18 months of use, these materials appeared new except for damage by ants, nutsedge and farm operation. The condition of each lateral line is summarized in Table 7.

2. Sources of Damage to Subsurface Lateral Lines

a. Damage from farm laborers

Field experience showed that education of farm laborers and proper bed preparation are as important to lateral line preservation as is proper use of farm machinery. In the first experimental plots lateral lines were placed at a depth of 10 cm or less in beds which were level with the traffic lanes. These factors and the inexperience of the farm labor force with subsurface systems resulted in occasional foot traffic within the beds and damage to the lateral lines during

Table 7. Condition of 11 types of lateral lines after 18 months of burial

Lateral Line Characteristics			Wall Thickness*	Condition on Recovery
Common name	Type	Material		
trickle tape	bi wall	polyvinyl	5 mil	3 small holes (ants), 1 large hole (rodents?), 9.6% plugged
trickle tape	bi wall	polyvinyl	8 mil	no holes, 11.7% plugged
monotube	mono wall	polybutylene	15 mil	no holes, 5.7% plugged
twin wall	dbl wall	polyethylene	8 mil	2 holes (ants), 29.5% plugged
twin wall	dbl wall	polyethylene	4 mil	11 pierced by nutsedge, 7 nutsedge tubers inside, 24% plugged
twin wall	dbl wall	polyethylene	3 mil	21 pierced by nutsedge, 19 nutsedge tubers inside, plugging undetermined
biwall 19	biwall	polyethylene	19 mil	no holes, 9.5% plugged
biwall 15	biwall	polyethylene	15 mil	no holes, 40.5% plugged
biwall II	biwall	polyethylene	15 mil	no holes, 26% plugged
drip hose	biwall	polyethylene	12 mil	1 hole in high pressure wall (ants), 20% plugged
(none)	biwall	polyethylene	19 mil	no holes, 26% plugged

*1 mil = 1/100 inch = 0.025 mm

General comments: All plots had 32 m of lateral line with 100 emitters each (32 cm spacing). Plots were unreplicated.
Lateral line material was found to be visually quite similar to unused sections of line. No quantitative tests were run.

hand weeding and transplanting. These problems were overcome in later experiments by raising the beds, by placing the lateral lines slightly deeper ($\geq$13 cm), and by the workers becoming more familiar with the subsurface trickle system.

b. Ant damage

Ant damage occurs whether lateral lines are placed on the surface or are buried. Damage is generally in the form of enlargement of the emitter orifices although in some cases new holes are made. The damage also tends to be concentrated in areas close to ant colonies. In the Waimanalo experiment (W_1) fire ants (Solenopsis geminata) were the main cause of emitter damage beginning six months after tube installation. This species has previously been identified as the most damaging to irrigation tubing (Chang and Ota, 1976).

The most frequently damaged plots were those bordering the experiment, apparently from ants migrating from adjacent grassy areas, although interior plots were also occasionally damaged.

Ant damage was not as important a problem in the Lalamilo plots, presumably because the less damaging bighead ant (Pheidole megacephala) is the only ant species found in the Kamuela area which is known to damage lateral lines (Vincent Chang, personal communication).

Control of this pest with the insecticide Diazinon was poor. The chlorinated hydrocarbons, the only effective systemic insecticides, have been restricted from use in all but two agricultural crops in Hawaii and will soon be removed from the market altogether. No new products approaching their effectiveness seem to be forthcoming but a promising mechanical method of protecting in-line emitters has recently been developed by entomologists at the Hawaiian Sugar Planters' Association (Chang et al., 1980).

c. Purple nutsedge damage

Purple nutsedge (*Cyprus rotundus*) damage to trickle irrigation laterals has long been a concern of Kamuela farmers (Kuni Fujii, personal communication). The sharp point of the rhizomes and aerial stems can penetrate a range of materials, including asphalt.

Of the materials tested in the tube farm, only the two thinnest were punctured by nutsedge. The Chapin 3-mil polyethlene double wall material was punctured 21 times along a 32-meter section. In 14 of these cases, single or multiple tubers were growing inside the line. The Chapin 4-mil double wall lateral line was punctured 11 times, a in 7 locations tubers were growing inside. The punctures ranged from 0.5-1.5 mm in diameter. The Chapin 8-mil double wall polyethylene line was not punctured by nutsedge, indicating that this is an adequate thickness for this material.

The polyvinyl lateral was undamaged even at 5-mil thickness suggesting that this material is more resistant to nutsedge damage. All other materials remained undamaged by nutsedge.

To further test the ability of horizontally growing nutsedge rhizomes to penetrate lateral line materials, 80 nutsedge tubers were planted within a wire mesh cylinder, buried vertically, which held a single layer of lateral line material (900 cm^2 surface area) within 6 cm or less of each tuber. One cylinder was used for each of the 11 materials previously tested and was buried for 90 days as the nutsedge plants grew. As in the previous experiment only the Chapin 3-

and 4-mil materials were punctured after six months of dense nutsedge growth (11 and 8 punctures, respectively), confirming the results from the tube farm.

3. Plugging under Subsurface Conditions

a. Distribution of plugging over time

Plugging of lateral line emitters at the Lalamilo farm was surveyed by noting the number and position of moist spots within each plot. Following the initial lettuce crop in the phosphorus plots, a survey showed that 26% of the emitters were plugged and 7% possibly plugged. The pattern indicated that plugging was random within the plots as well as among the plots (Fig. 8). Here, 47% of the plugged emitters occurred between operating emitters. Twenty days after the first plugging survey, each plugged emitter was uncovered for verification and unplugging. The results of this second survey are shown in Fig. 9 and compared with results of the earlier survey in Table 8. These results suggest that a substantial amount of plugging (at least 27% of plugged emitters) is intermittent over time. If intermittent plugging is a common occurrence, calculations of uniformity and emitter flow variation based on plugging percentage or water flow rates (Braltz et al., 1978) may need to take this fact into account.

After a second crop of lettuce was grown and harvested from these plots, another visual plugging survey was conducted. At this time, approximately three months after each emitter was cleared by hand, the plugging rate was 18%. Allowing for a few exceptions, plugging within and among the plots again appeared to be random (Fig. 10) with approximately one-half (54%) of all plugged emitters occurring between

Rep III	Rep II	Rep I
OXXO??X?	OOOOXXOO	XOOXOXOX
OOOOOOXO	OOXXOOXO	OOOOOOOX
OOOO??OO	OOXOOXOO	OOOOOOOO
OO?OOOOO	OXOOOOOX	OOOOXOOO
OXOOO?OX	OO?XOXOO	OOXXOOOO
OOOOOOOO	?O?OOOOX	OXXXOOOX
?OOXOOOX	OOOOX?OO	OOOOOOOO
O?O??OOO	OOOOOOOO	OOOXOOXO
OOOO?OOO	OOXXOOOO	XOOXOOOO
OOOOXOX?	X??XXOOX	OOOOOOXX
OX?XOOOO	O?OOOOOX	OXOOXOXX
OOOOXOOO	OO?XOOOO	OXOXOOOO
OOOXOOXO	OOOOOOXO	XOXXOOXO
OOOOOXXO	?OXO?OOO	OXXOOXXX
OO?OOOOO	XOOOOOOO	OOOXOXXO
OXOXXXXX	OOOOO?OO	OOOXOOOO
XOXXOXXX	OOOXXOXX	OOXXOOOO
XXOOOOOX	X?X?OOOO	XXOOOXOO
XXXOOOXX	XO?OO?O?	XOXOOOOO
OOOOXXOO	OOOOOO?O	XOOXXOOX
OOOXO??X	OOOOOOOO	OOOOOOOX
XOO?OOOO	XX?OOOOO	OXXOXOXO
XOOOOOOX	O?OX?OOO	OOOOXXOO
O?OOOOOX	OOOO?OOO	OOO?OXOX
XXXXXOXO	?OOOO?XO	OXXXX?OO
XXXXXOOX	O???OOXO	OXXOXXOO
OX?OOO?O	OOOOXOOO	OOXXOOXO
OXX?XXXO	XO?OXXXO	OOOXOXOO
OXXOOXOX	OO?XXOXX	OXOXOOOO
OOOOOOOO	XOOX?XOO	XOXOOOOO

Symbol	Emitter status	Number of emitters	% of total emitters
O	open	478	66
X	plugged	189	26
?	uncertain	53	7

Figure 8. Location of plugged emitters in a subsurface trickle irrigated experiment 10 weeks after installation at the Lalamilo farm (Experiment L_4, 720 total emitters).

```
Rep III                   Rep II                    Rep I

-O--OO-O                  ----//--                  O-------
--------                  ------O-                  --------
----xx--                  --------                  --------

--x-----                  --------                  -------x
-O---O-O                  --OO----                  -x-----x
--------                  O-O----/                  --O-----

O-------                  ----OO--                  --------
-xxxO---                  --x-----                  ------Ox
----x---                  ---O----                  O--O----

------//                  -xx-----                  ------O-
--x-----                  -O---x--                  -Ox-O-OO
--------                  --/-----                  -O-/----

--------                  ------O-                  O-O/--O-
x-x-----                  ----x---                  -O/--OOO
---O----                  --------                  ---O-OO-

--------                  -----x--                  --------
---O----                  --------                  x-OOx---
--------                  OO-O----                  -O--x---

/-------                  O-O--O-O                  ---x---x
----/---                  ------O-                  ----O---
-----/O-                  --------                  -------O

---O----                  OOO-----                  --O-/--x
--------                  xO-Ox/--                  -------x
-/------                  ----/---                  ---O----

-O--/-/-                  O-----OO                  -O---O--
--O--x-O                  xOOO--Ox                  --/-//--
-//---/-                  ----/---                  --------

---O/--x                  /-/---O-                  -----O--
--------                  --O-----                  xOxO----
--------                  ----/---                  --/-x---
```

Symbol	Condition	Number of emitters	% of total emitters
-	unchanged from previous inspection	571	79
x	newly plugged	37	5
/	newly partially plugged	30	4
O	newly opened	82	11
	Total emitters plugged	155	22
	Total emitters partially plugged	31	4

Figure 9. Changes in emitter plugging 20 days after initial inspection of the subsurface trickle irrigation system at the Lalamilo farm (Experiment L_4, 720 total emitters).

Table 8. A comparison of the condition of individual lateral line emitters on two examinations 20 days apart in experimental plots at the Lalamilo farm

Initial Data Taken		Data Taken 20 Days Later	
Condition	Number and % of total emitters	Condition of the same emitters	Number and % of total emitters
Plugged	189 (26)	Plugged	138 (19)
		Partial	0
		Open	51 (7)
Uncertain	53 (7)	Plugged	12 (2)
		Partial	9 (1)
		Open	32 (4
Open	478 (66)	Plugged	25 (4)
		Partial	0
		Open	453 (63)

Rep III	Rep II	Rep I
OOOOOOOO	OOOOOOOO	/OXOOOOO
OOOOOOOX	OOOXXXXO	O/OO/OOX
OOXOXOOO	OOXOOOOO	OXOOOOOO
OOOOOOOO	OOOOOXOO	OOOOOXOX
XOOOOOXX	OXXXXXXO	OOOXOOXX
OOOOXOOO	OOOOOOOX	XXOOOXOO
OOOO/OOO	XOOOOOOO	OOOOOO//
XOOOXOOO	OXOXOOOO	OOOXOOXO
OOOOOOOO	OOOOOOOO	OOOOOOOO
OOOOOOXX	OOOOXOOO	OOOOOOOO
OOOOOOOO	OOOOOOOX	XXOOOO/X
OOOOOOOO	OOOOOOOO	OOOXOOXO
OXXOOOOO	XXOOOOOO	OOOXOOOO
XXXOOOOO	XOOOXOXO	OOXXOOXO
XOOOOOOO	OOOOOOOO	OOOOOOOO
XXOXOOOX	OOOOOOOO	OOOOOOOO
OOXOOXOX	OOOXXOXX	OOOOOXXX
OOOOOOOO	OOOOOXOO	OOO/OOOX
XOOOOOOO	OOOOOOOO	OOXXXOOO
OOOOOOOO	OOOOOO/O	OOOXXOOX
OOOOOOOO	OOOOXOOO	OOOOOOOO
OOOOOOOO	OOOXOOOO	OOXOOOOX
OOOOOOOO	OOXOOOOX	OOOOOOOO
XOXOOOOO	OOOOXOOO	OOOOOOOX
OOOXXOXO	OXXOOOOO	OOOOOOOO
OOXXXOOX	XOXOXOOX	OXOOOOXO
OOOOOOXO	O//OOOOO	OOOXOXXX
OOOOXOOO	OOOOOO/O	OOOOOOOO
XXXOOXOX	OOOOOOXX	OOOOOXOO
XXOOOOXO	XOOOOOOO	XOXOOOOO

Symbol	Emitter status	Number of emitters	% of total emitters
O	open	578	80
/	partially plugged	12	2
X	plugged	130	18

Figure 10. Location of plugged emitters in a subsurface trickle irrigated experiment at Lalamilo farm three months after each previously plugged emitter was manually unplugged (Experiment L_4, 720 total emitters).

operating emitters. The lower rate of plugging recorded in the second survey suggests that the high rate of initial plugging may have been caused by soil or foreign particles introduced into the system during installation or during fertilizer injection.

Comparing the results in Fig. 10 with those of the previous figures, over half (81 out of 142) of the emitters that were manually unplugged had become plugged again. This indicates that the method of unplugging is only partially effective and/or certain emitters are prone to plugging. If the latter is true, a study of the size and shape of emitters prone to plugging may prove profitable.

To determine the number and relative position of plugged emitters after extended undisturbed use, a survey was made of plots that had been continuously cropped with six vegetable crops over an 18-month period (Figs. 11 and 12). Of the tubes that were not subjected to compaction (see compaction studies described below), 23% of the emitters were plugged. Depth of burial did not have an effect on the number or distribution of plugged emitters (see depth/frequency studies discussed below).

The distribution of the plugged emitters was different in these plots, however. Seventy-two percent of the plugged emitters were immediately adjacent to one or more plugged emitters, one-third of which (34.5% of all plugged emitters) were in groups of four or more. Four plugged emitters in a row represent a two-meter length without irrigation. Because of the short length of the plots (6 m), little can be said about plugging distribution in long laterals.

Rep III		Rep II		Rep I	
XOOOOOOOOXOOO† OOOOOOOOOOOOO	S*	?/X////OXXXOO XOXOX/XXX///X	D	/////O/XXX/// OOXOOOOOOOOOO	D
OOO/XXX?OOOOO OO?XOOXXOO?XO	S	XXOOOOOOOOOOO XXXXXXO?OXXXX	S	OO/OOOO//O/// O///OOO//OOOO	D
OO?XXOOOOOOOO XOOXOXXOOOXOO	D**	?OOOOOOOOOOOO XOOOOOOXXXOOO	D	OOOOOOOOOOOOO OOOOOOOOOOOOO	S
XXXXXOXOOOOOO XOOXXOOOOOOXX	S	/OOOOOO/OOOOO OOOOOOOOOOOOO	S	XOOXOOOOOOOOO O?????????OOO	S
XOOOOOOOOOOOO XXOOOOOOOXOOX	D	Line broken	D	OXOOOOOOOXOOO //OX/O/XXX?OO	D
X??OOOOOOOOOX OOXOOO?OOOOOO	D	OOOOOOOOOOOOO OOO?OOOOXXOOO	S	Line broken	S

†The first row in each plot has been protected from mechanical compaction for 18 months. The second has been mechanically compacted.

*S = Shallow (13 cm) line burial

**D = Deep (28 cm) lateral line burial

Symbol	Emitter status	Number of emitters	% of total emitters
O	open emitters	283	68
/	partially plugged	36	9
X	plugged	76	18
?	uncertain	21	5

Figure 11. Location of plugged emitters in a subsurface trickle irrigated experiment at Lalamilo farm 18 months after installation (Experiment L_3, 416 of 468 total emitters).

Rep III	Rep II	Rep I
OOOOXOOOOOOOO†	OOOOOOOOOOOOO	OOOOOOOOXXXOO
XXOOXXO?OXOOO	OO?OXOO?OOOXO	OOOOOOOXOXOXO
OOOOOOOOOOOOO	XOOOOOXXOXOOO	XOOOOOOOOOOOO
XXXXXOOXOXXOX	XOO?XXOXOOXXO	OOOOOXOOXXXXX
XOOOOOOOOOOOO	XOOOOOOOOOOOO	XOOOOXXXXXXXO
XOXXOOXXOXOXO	O?XOXO?OOOOOO	OOOOOO//OOOXX
OOOOOOOOOOXXX	OOOOOOOO/OOOO	OXOOXXXOOOOOO
XXXXXXOOXOOOX	??OOO?X?XOO/X	OXOXXXXOXXOOX
OXXOXOXOOOOOO	OOXOOXOOOOXXO	XXXXXXO/XXXOO
OXXOOXXOOXXOX	XXXXXXXXXXOXO	OOOXXOOOXXXOO
XXXXXXXX D*	XXOOOOOOXOOXO	XXXOOXXXOXXOO
XXOOOX	XXXXXXXXXXXOO	XOOXXXXXOXXOX

†The first row in each plot has been protected from mechanical compaction for 18 months. The second has been mechanically compacted.

*Damaged

Symbol	Emitter status	Number of emitters	% of total emitters
O	open emitters	271	59
/	partially plugged	5	1
X	plugged	170	37
?	uncertain	10	2

Figure 12. Location of plugged emitters in a subsurface trickle irrigation experiment at Lalamilo farm 18 months after installation (Experiment L_1, 456 of 468 total emitters).

b. Causes of emitter plugging

An optical microscope was used to examine 20 plugged emitters taken from the Lalamilo plots. Particles of soil, approximately the size of the orifice or slightly larger, caused 40% of the plugging. Another 40% was attributed to bacterial slime alone or slime combined with fine inorganic material. A mixture of larger particles and bacterial slime caused the remaining 20%. Although soil was often found clinging to the outside of plugged emitters, visual inspection indicated that plugging in all instances was from inside the lateral line.

c. Effect of mechanical compaction on plugging

To determine if compaction had an effect on the plugging rate of subsurface lateral line emitters, a survey of plugged emitters was taken after one-half of each plot in two experiments (18 plots each) had been compacted by 10 to 12 passes of a farm tractor. The influence of depth of lateral line placement and vehicular compaction on emitter plugging was also measured in this experiment (Table 9). These data show that mechanical compaction increased emitter plugging by more than 50% relative to that in non-compacted plots. Depth of lateral line burial had no effect on emitter plugging in this experiment. No distinct pattern on plugging was apparent, as might be expected if compaction pinched off entire sections of lateral line tubing. This suggests that plugging was caused by packing of the soil into individual emitters.

C. Crop Performance in the Integrated System

The previous experiments showed that, while natural compaction is slow in the upper 8 cm of the Waimea soil, this

Table 9. Percentage of plugged emitters in compacted and non-compacted portions of experimental plots in Waimea. Compaction was accomplished by 10 to 12 passes with a farm tractor

Plot Parameters		Number of Plots	Plugged Emitters Mean (%)	Plugged Emitters Range (%)
A. Experiments L_1 and L_3				
Overall		72	29	0-59
Compact (Bulk density = 0.92 g cm^{-3})		36	36	0-84
Loose lanes (Bulk density = 0.69 g cm^{-3})		36	23	0-73
B. Experiment L_3				
28-cm depth:	Compact	9	30	8-69
	Loose	9	22	0-54
13-cm depth:	Compact	9	30	0-84
	Loose	9	20	0-73

process results in a relatively dense subsurface (>6 cm) later in the Waialua soil. Except for ant damage at the Waimanalo site and some emitter plugging in all experiments, the subsurface trickle irrigation system continued to perform well at both sites for nearly two years with no sign of deterioration.

Crops were planted in rapid succession, when possible, during the experimental period. Although the integrated system permits transplanting a crop the day after harvesting, only about one-half of the crops were transplanted within a week of harvest.

1. Crop Growth in Protected Plots

Up to seven successive transplanted vegetable crops were grown in three experiments conducted at the Lalamilo farm. Except for the first crop of head lettuce in the tandem experiments (L_1 and L_3) neither soil biotic factors nor natural compaction of the soil appeared to have any adverse effect on crop production (Table 10). The exception was apparently the result of previous methyl bromide soil sterilization immediately before planting. This procedure caused butt rot (Dr. John Cho, personal communication) which affected 86% of the oversized lettuce plants. One rotation of head cabbage was then transplanted to permit the soil biota to re-establish natural competition with the Erwinia sp. bacteria which cause this disease.

The last crop in the L_4 experiment was exceptionally poor. This was the result of two weeks without irrigation (water inadvertently turned off) and severe weed infestation. Other than those exceptions, average yields fluctuated, but showed no trend that indicated a decline in the ability of the integrated system to support crop growth.

Table 10. Mean crop yield in relation to harvest dates and soil bulk density in experiments at the Lalamilo farm

A. Longevity and Depth/Frequency (L_1 and L_3) experiments

Crop Number	Crop	Harvest Date	Mean Whole Plant Weight (kg)		Weeks of Operation	Surface Bulk Density (g cm^{-3})
			Longevity (L_1)	Depth/Frequency (L_3)		
1	lettuce	6/27/79	2.02	1.67	9	0.54
2	cabbage	10/2/79	3.14	2.20	24	0.59
3	lettuce	12/26/79	1.17	0.91	35	0.58
4	lettuce	3/25/80	1.66	1.66	48	0.57
5	lettuce	5/29/80, 6/3/80	1.34	1.00	57	0.64
6	lettuce	9/12/80	1.47	1.32	72	0.69
7	lettuce	12/26/80	1.17	-	87	

B. Phosphorus plots (L_4)

Crop Number	Harvest Date	Mean Whole Plant Weight (kg)	Weeks of Operation
1	9/19/78	1.31	7
2	1/03/79	0.91	15
3	4/04/79	0.98	28
4	8/04/79	1.16	51
5	3/08/80	0.59	76

Although vegetable crops did not grow well at the Waimanalo site, the last crop (20 months after the installation of the irrigation system) was judged to be excellent by local farmers (Table 11). Therefore, natural compaction and disease build-up were not identified as problems at this location either. Thus, even in this heavy soil the system operated adequately for nearly two years.

2. Plant Growth in Mechanically Compacted Plots

Two experimental approaches (half-plot compaction and single-row compacted strips between uncompacted strips) in five experiments (L_1, L_2, L_4, W_1 and W_2) were used to study the effect of tractor traffic on crop growth.

At the Lalamilo farm, the main effect of compaction on crop growth was on the size and shape of plant roots. Head lettuce roots were collected from all plants in two selected plots at the Lalamilo site. Differences in root weight were highly significant between compacted and non-compacted soils (Table 12). These differences were visually apparent with compaction resulting in deformed, short, thickened secondary roots. The roots were largely confined to the hole made by the planting tool. The yield reduction was not as pronounced as the root weight reduction. Plots a and b had yield reductions of 26.7 and 17.5%, respectively, relative to yields in the uncompacted portion of their respective plots. Although root development was reduced in all compacted rows, the average crop yield from 36 compacted plots was only 6% less than that for uncompacted plots. Yields were higher in 13 of the 36 compacted plots than in the adjacent non-compacted plots. Therefore, although compaction resulted in significantly reduced root size, yield was not significantly reduced.

Table 11. Mean yields of successive crops at the Waimanalo farm

Crop Number	Crop	Harvest Date	Mean Yield (gm/plant)	Weeks of Operation
1	Kai Choi	6/14/77	56	7
2	Lettuce*	8/20/79	lost	16
3	Kai Choi	12/17/79	537	34
4	Lettuce	2/20/80	96	43
5	Lettuce	4/08/80	132	49
6	Lettuce	6/03/80	183	57
7	Kai Choi	9/30/80	lost	70
8	Kai Choi	1/13/81	405	89

*The Anuenue cultivar was used in all lettuce plantings.

Table 12. Mean lettuce root weights from two selected plots, half of each plot being compacted just prior to planting

	Surface Bulk Density ($g\ cm^{-3}$)	Plot a				Plot b			
		Crop Yield (kg)	Wet Whole Root (g)	Wet Rootlet (g)	Dry Rootlet (g)	Crop Yield (kg)	Wet Whole Root (g)	Wet Rootlet (g)	Dry Rootlet (g)
Noncompact	0.65	1.61	29.9	21.6	2.72	2.02	31.9	18.2	2.92
Compact	0.92	1.18	16.9	9.6	1.28	1.67	19.6	8.7	1.39
Difference	0.27**	0.43*	13.0**	12.0**	1.44**	0.35 ns	12.3**	9.5**	1.53**
% difference	42.0%	26.7%	43.5%	55.6%	52.4%	17.3%	38.6%	52.2%	52.4%

*,**Significant at 5% and 1% level, respectively, for 13 observations each.

In the Waimanalo experiments, no significant differences in bulk density were found between compacted and non-compacted soil in either experiment. This may be attributed to the swelling nature of this soil. In both treatments root development was similar and no significant differences between crop yields were found.

The results from the Waimea soil show that for lettuce grown on this soil, poor root development due to compaction is not detrimental to yield if water and nutrients are adequately supplied. Although a trickle irrigation system can provide these requirements, compaction in the beds should be avoided for other practical reasons, including emitter location and accessibility as well as ease of transplanting crops.

3. The Effect of Emitter Plugging on Crop Growth

In experiments L_1 and L_3, emitter plugging in a given plot (26 emitters) was as high as 56% while single line plugging (13 emitters) was as high as 85% (Figs. 12 and 13). The weather during this period was dry (Appendix), providing 44 mm of the predicted 240 mm water requirement for optimum production at this site for the 63 day crops (Wu and Gitlin, 1977). Regardless of these facts, there was no statistically significant relationship between the percent of plugged emitters and lettuce yield. This lack of statistical significance may be due to a number of factors including a flat yield-response curve to water application (Wu and Gitlin, 1977), intermittent emitter plugging (discussed previously), water supplied from emitters adjacent to the plugged emitters (discussed below), and high natural yield variability.

D. Effects of High Frequency Irrigation on Crop Yield

One of the major advantages of the trickle irrigation system is its ability to provide high frequency irrigation, minimizing water stress in crops. High frequency irrigation usually refers to daily or alternate day scheduling, although higher frequencies are possible. To determine if lettuce would respond to high frequency irrigation, an experiment was installed at the Lalamilo farm to compare yields under frequencies of once every two days, daily and four times per day. Four crops were successfully grown under this irrigation regime. In three of the four crops, the highest frequency resulted in significantly poorer yields than the less frequent treatments (Table 13). The same results were found for wet and dry seasons (crops 2 and 4, respectively). These data suggest that there is no advantage in irrigating head lettuce at this site more frequently than once every two days.

E. Lateral Line Depth

Depth of lateral line placement had no significant effect on size of mature plants. However, depth did make a substantial difference in field operations. The deeper (28 cm) lateral lines did not always result in a wetted surface area corresponding to each working emitter, making emitter location for planting, plugging surveys or repair more difficult. As a result, newly transplanted seedlings did not always receive a readily available supply of water, frequently resulting in heavy post-transplant seedling loss. Therefore, during dry periods, sprinkle irrigation was sometimes used during the first week after transplanting to permit proper root establishment.

Table 13. The effect of irrigation frequency on whole plant yield of head lettuce from four successive crops at the Lalamilo farm

Crop number	1	2	3	4
Harvest date	12/26/79	3/25/80	6/3/80	9/12/80
Effective rainfall*	183 mm	250 mm	175 mm	44 mm
Treatments	Yield (kg/plant)	Yield (kg/plant)	Yield (kg/plant)	Yield (kg/plant)
4 irrigations/day	0.69 b**	1.46 b*	0.86 b**	0.96 b**
1 irrigation/day	0.93 a	1.74 a	1.11 a	1.61 a
1 irrigation/2 days	1.11 a	1.79 a	1.03 ab	1.54 a
Least significant difference	0.21	0.26	0.23	0.31

*Soil water holding capacity = 50 mm. Rainfall in excess of this within a 2-day period is considered lost.

**Treatments followed by the same letter are not different at the 5% level.

F. Phosphate Placement through the Subsurface Trickle Irrigation System

1. Phosphate Distribution in the Soil

Soil samples were taken in a grid pattern around the emitter at the Lalamilo site 55 days after phosphorus was applied as shown in Fig. 3. One plot was sampled a second time 15 weeks after the first sampling and 161 days after fertilizer application to determine the redistribution of phosphorus. Figures 13 to 17 show the distribution of modified Truog extractable phosphorus in treatments where all phosphorus was applied through the trickle system. Figures 18 and 19 show phosphorus distribution in treatments where the phosphorus was applied by broadcast application as well as through the trickle system. Table 14 shows the modified Truog extractable phosphorus levels in the control and broadcast-only plots 55 days after fertilizer application. Figures 18 and 19 show that the broadcast fertilizer (as triple superphosphate) is concentrated near the surface and was incorporated in a soil volume approximately one-half that originally anticipated.

These results show that in the Waimea soil, trickle applied phosphorus concentrates near the emitters at depths easily reached by the lettuce root system, and that there is considerable residual phosphorus within this zone nearly one-half year after application. The high phosphate zone remains intact in this no-till system and ranged in volume from an estimated 0.02 to 0.12 m^3 for the 24 emitters in each plot. This is 5 to 30% of the 0.4 m^3 volume occupied by the broadcast fertilizer. Even so, extractable phosphate levels near the emitters, although higher than levels in similar broadcast treatments, do not seem to reflect the magnitude of this concentration factor. Since these high concentration zones surrounding the emitters can easily be located,

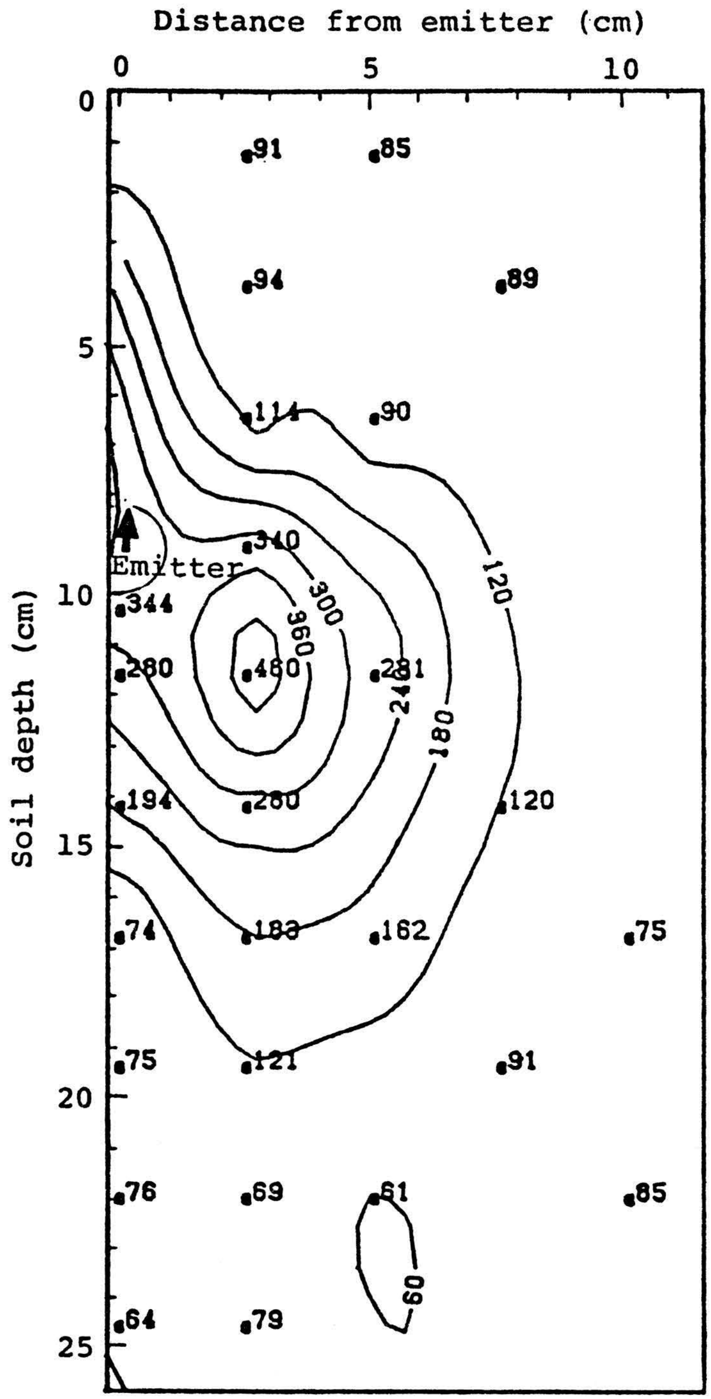


Figure 13. Iso-concentration lines (ppm P) of modified Truog extractable phosphorus 55 days after phosphorus equivalent to 1200 kg/ha was applied through the trickle system.

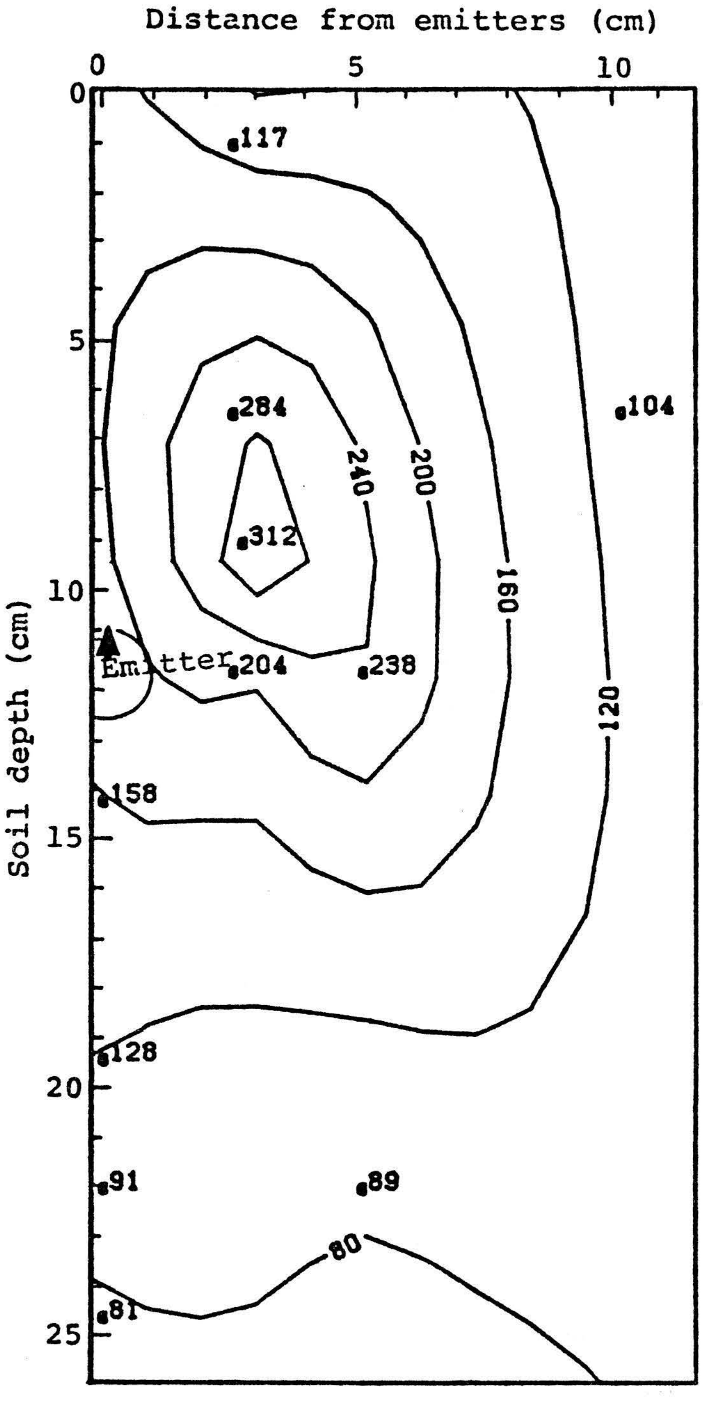


Figure 14. Iso-concentration lines (ppm P) of modified Truog extractable phosphorus 55 days after phosphorus equivalent to 1200 kg/ha was applied through the trickle system (replicate sample).

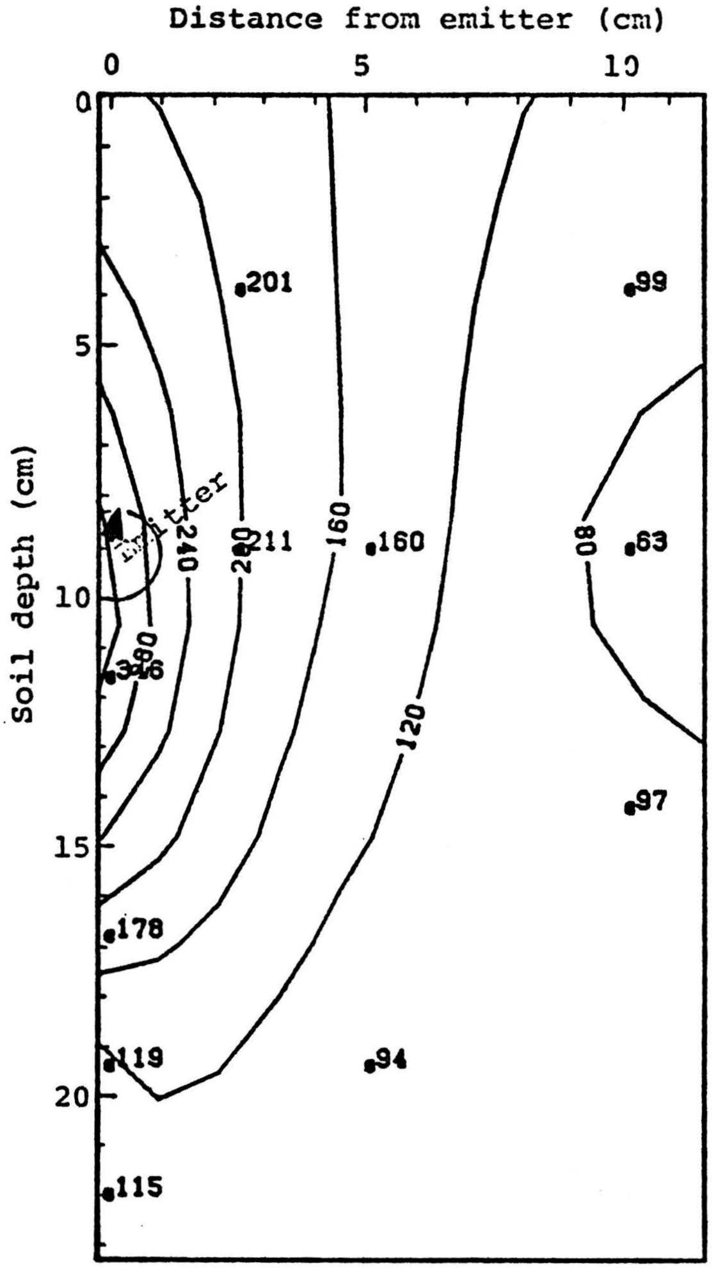


Figure 15. Iso-concentration lines (ppm P) of modified Truog extractable phosphorus 161 days after phosphorus equivalent to 1200 kg/ha was applied through the trickle system.

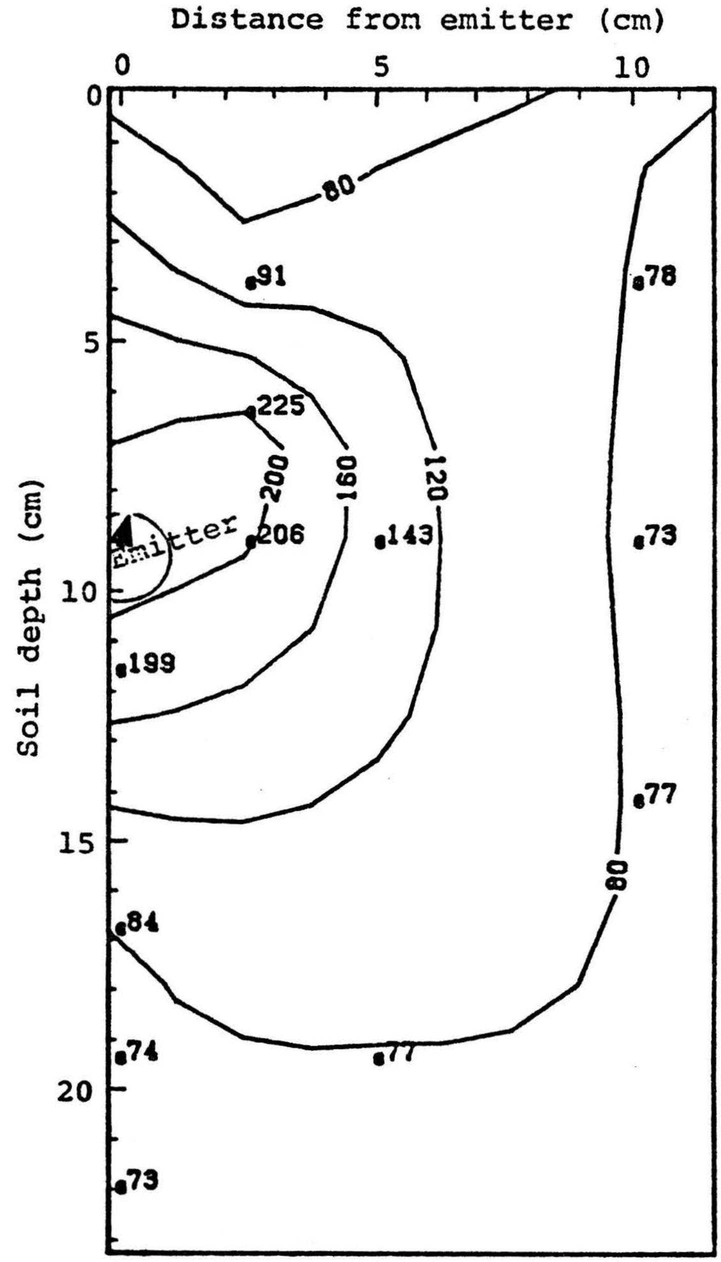


Figure 16. Iso-concentration lines (ppm P) of modified Truog extractable phosphorus 55 days after phosphorus equivalent to 600 kg/ha was applied through the trickle system.

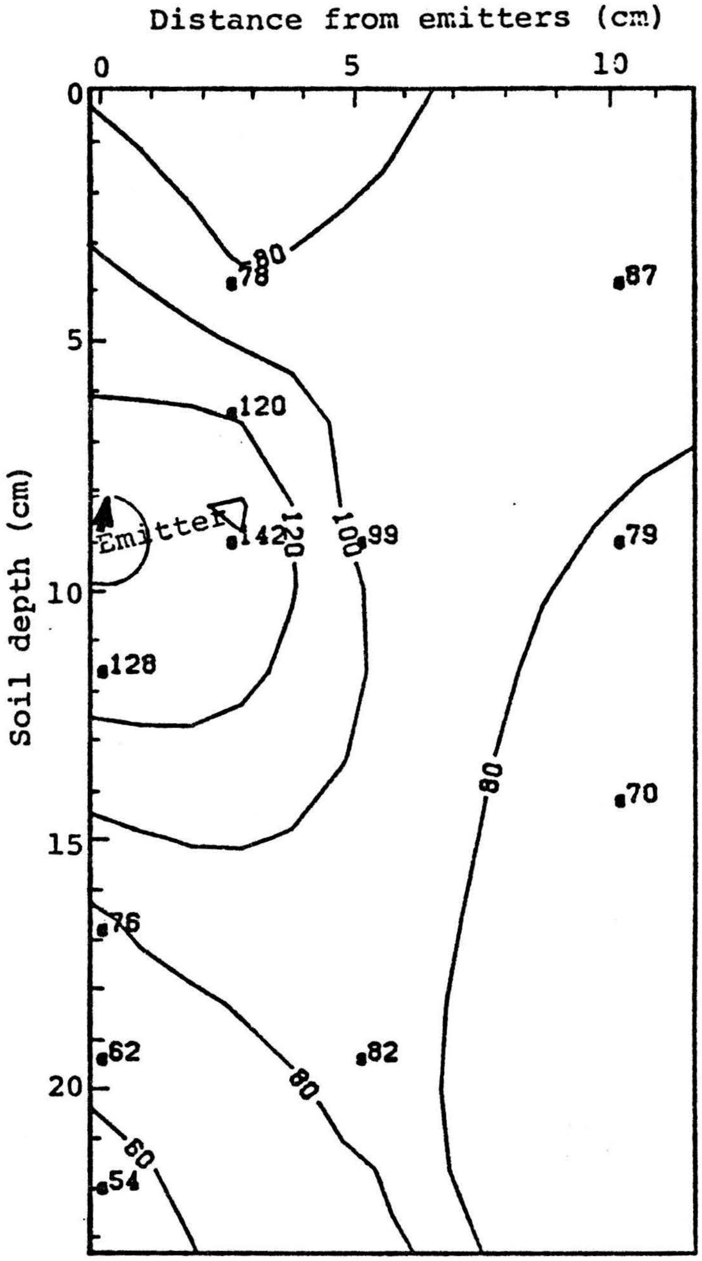


Figure 17. Iso-concentration lines (ppm P) of modified Truog extractable phosphorus 55 days after phosphorus equivalent to 150 kg/ha was applied through the trickle system.

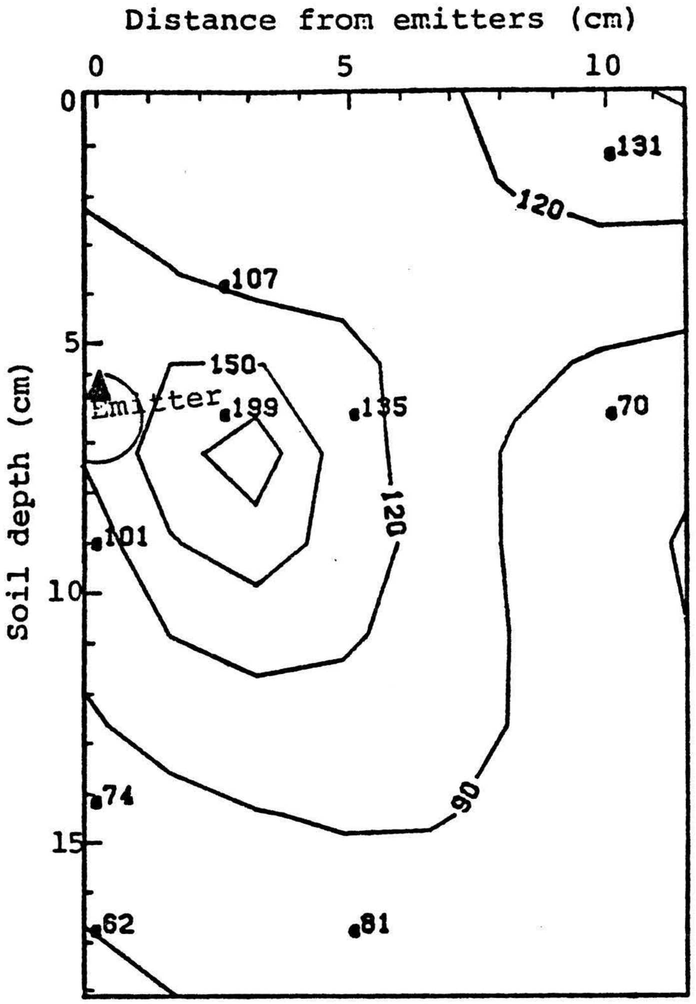


Figure 18. Iso-concentration lines (ppm P) of modified Truog extractable phosphorus 55 days after phosphorus equivalent to 150 kg/ha was applied through the trickle system and 450 kg P/ha was applied by broadcast.

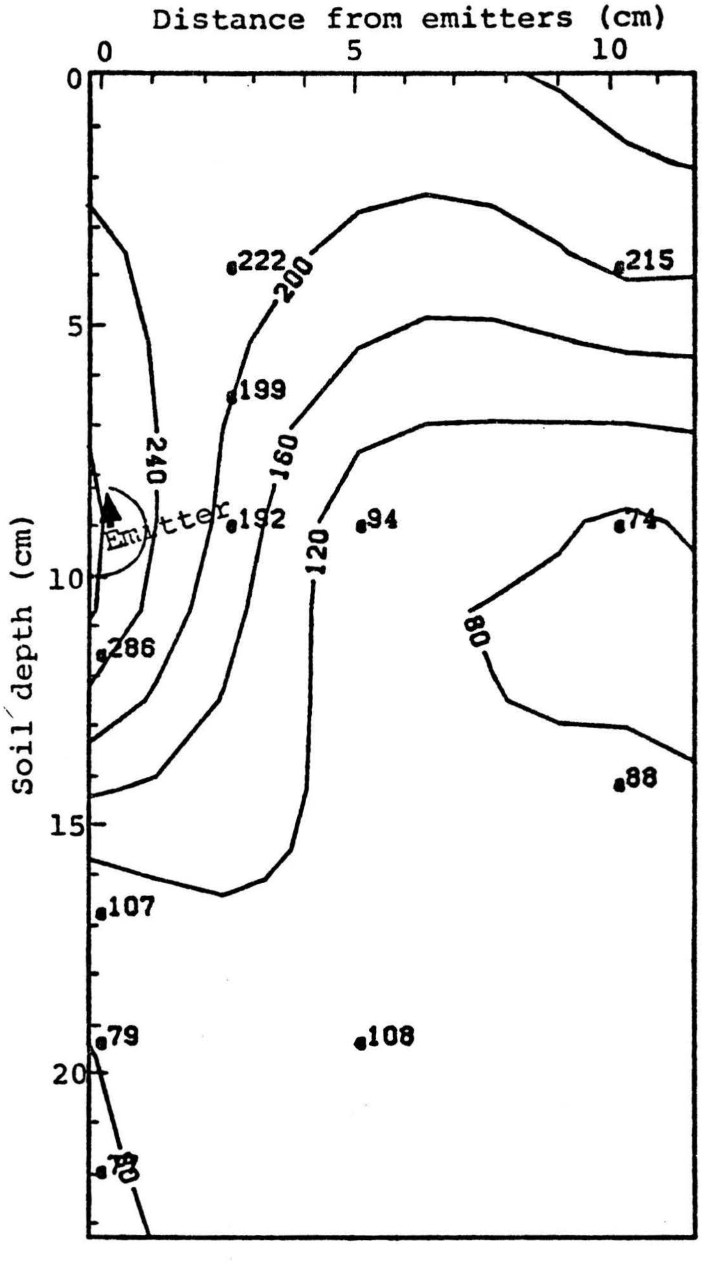


Figure 19. Iso-concentration lines (ppm P) of modified Truog extractable phosphorus 55 days after phosphorus equivalent to 150 kg/ha was applied through the trickle system and 1050 kg P/ha was applied by broadcast.

Table 14. Modified Truog extractable phosphorus levels in single Waimea soil plots where phosphorus was applied only as a broadcast treatment 55 days before sampling

Broadcast Rate (kg P/ha)	ppm P in Surface Soil (0-3 cm)
Control	79
150	99
600	141
1200	207

subsequent transplants can be placed directly over each emitter, thus taking advantage of water availability and residual phosphate (Memon, 1980).

2. Crop Response to Phosphate Fertilizer Treatments

The Waimea soil is naturally fertile with adequate potassium, phosphorus and other nutrients for most crops (Dr. Bernard Kratky, personal communication). Therefore, an area of the Lalamilo farm thought to be low in phosphorus was chosen for this experiment. Although soil samples taken prior to the experiment showed low levels of 0.01 M $CaCl_2$ extractable phosphorus (Fig. 1), the data from the previous section show background levels of 70 to 90 ppm modified Truog extractable phosphorus. Levels of 50 ppm modified Truog extractable phosphorus are considered sufficient for most agronomic crops (Tamimi, 1977), but higher levels are undoubtedly required for optimal production of lettuce. Lettuce, with its limited root system, shows a marked response to extractable soil phosphorus when compared with other crops (Fox et al., 1977) and would therefore be expected to require high soil phosphorus levels for optimal growth.

More information is available on critical levels of lettuce tissue phosphorus than for soil extractable phosphorus. Recommended levels of tissue phosphorus differ depending on age of the plant (Zink and Yamaguchi, 1962), plant part sampled, method of analysis and other factors, but studies on mature leaf phosphorus suggest minimum levels of 0.2% with optimum yields obtained in the rage of 0.3-0.4% (Table 15). To determine the effect of two methods of fertilizer application on

Table 15. Critical phosphorus levels for lettuce.

% P in Plant Tissue			Tissue Sampled	Source
Low	Sufficient	High		
0.2	0.3		leaf	Soil Improvement Committee (1973)
	0.35		wrapper leaf	Nishimoto et al. (1977)
0.19	0.20-1.50	151	base of mature bottom leaves	Bauerle (1975)
			midrib of wrapper leaf:	Lorenz and Maynard (1980)
0.2	0.4		at heading	
	0.25		at harvest	
	0.35-0.70		wrapper leaf	International Minerals and Chemical Corp.
	0.37		wrapper leaf	this study

crop growth, three consecutive crops of head lettuce were transplanted with each plant positioned directly over an emitter.

a. Phosphorus in plant tissue

Data from the first crop planted one day after fertilizer application show that trickle application of 600 kg P/ha produced significantly higher tissue phosphorus levels than those found in the 600 kg P/ha broadcast treatment (Table 16). In the first crop, the highest tissue phosphorus levels were found in trickle application treatments. Response to low application rates were inconclusive due to the high native phosphorus level in one of the two control plots, high variability in the data and loss of one of the three replications.

The second crop shows greatly depressed tissue P levels as a result of both water and nitrogen stress. This may also explain the mixed results obtained from tissue analysis.

The third crop shows no significant differences in tissue phosphorus levels above the 150 kg P/ha application rate regardless of application method or rate, even though samples taken just prior to planting (Fig. 15) indicate high levels of residual soil phosphorus.

Plants tend to respond to phosphorus applied early in their growth (Lochwing, 1951), therefore, the high levels of tissue phosphorus from the trickle applied treatments in the first crop was probably a response to readily available phosphorus immediately following its application. Since soil phosphate availability decreases substantially within a few months after application (Yost and Fox, 1977), the lower levels of tissue P in the last crop is not unexpected and indicates the need for additional phosphorus.

Table 16. Phosphorus levels in head lettuce (first wrapper leaf) tissue in response to phosphate application rate and method

	Broadcast (kg P/ha)	Mean % P in Tissue	Trickle (kg P/ha)	Mean % P in Tissue	Combination Broadcast-trickle (kg P/ha)	Mean % P in Tissue
Crop 1	0	.30 c*	0	.30 c	0	.30 c
53 days after	150	.33 bc	150	.30 c	-	
fertilizer	600	.35 bc	600	.50 a	450 + 150	.39 abc
application	1200	.38 abc	1200	.52 a	600 + 600	.45 ab
LSD = 0.15					1050+ 150	.42 abc
Crop 2	0	.21 ef*	0	.21 ef	0	.21 ef
150 days after	150	.22 cdef	150	.20 f	-	
fertilizer	600	.25 bcd	600	.26 abc	450 + 150	.25 bcde
application	1200	.28 ab	1200	.26 bcd	600 + 600	.25 cdef
LSD = 0.05					1050 + 150	.30 a
Crop 3	0	.30 d*	0	.30 d	0	.30 d
250 days after	150	.32 bcd	150	.31 cd	-	
fertilizer	600	.36 a	600	.34 abc	450 + 150	.35 ab
application	1200	.35 ab	1200	.34 abc	600 + 600	.37 a
LSD = 0.03					1050 + 150	.35 a

*Values followed by the same letter within any one crop are not significantly different at the .05 level by the least significant differences test.

b. Lettuce yield

To establish the critical phosphorus level for lettuce, the relationship between yield and P concentration was examined (Fig. 20). Although the linear correlation is highly significant, the resulting regression line is not helpful in determining the critical phosphorus level. The Cate-Nelson method (Sanchez, 1976) provides an estimate of the critical level of head lettuce at the Lalamilo farm. The latter analysis in Fig. 20 shows that the critical level for plant tissue phosphorus is about 0.37%. This level was only exceeded in the first crop.

Table 17 shows lettuce yield response to the phosphate treatments in the three successive crops. As with tissue P, the yield of the trickle applied 600 kg P/ha application was significantly greater than the broadcast treatment at that level.

The second crop was lost to nitrogen and water stress. The third crop, grown with proper care, showed no significant differences in yield between the control and all but two of the other treatments. Apparently the differences in tissue P found six to eight months after fertilizer application (Table 15) are not sufficient to produce a yield response.

The data in Table 15 show that the Waimea soil requires high phosphate fertilization. Further, considerable savings in fertilizer cost is possible by applying P through the trickle system into the root zone of a crop at moderate levels rather than by large broadcast applications. Although trickle applications resulted in high residual phosphorus near the emitter, it was not effective in increasing phosphorus uptake or crop yield six months after application of up to

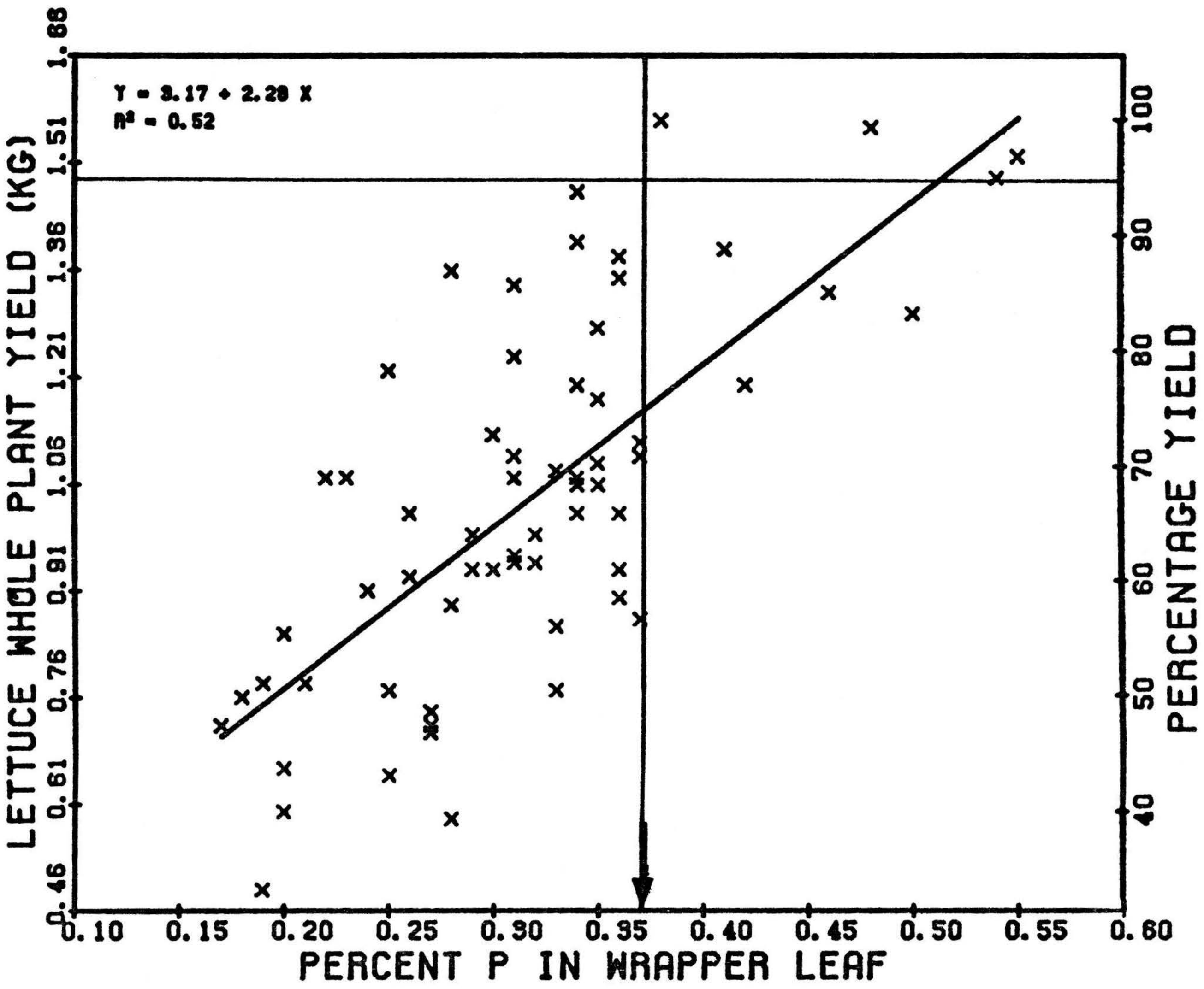


FIGURE 20. REGRESSION AND CATE-NELSON ANALYSIS ON THE EFFECT OF PLANT TISSUE P ON LETTUCE YIELD

Table 17. Whole plant yields in head lettuce in response to phosphate application rate and method

	Broadcast (kg P/ha)	Mean Yield (kg)	Trickle (kg P/ha)	Mean Yield (kg)	Combination Broadcast-trickle (kg P/ha)	Mean Yield (kg)
Crop 1	0	1.16 fg*	0	1.16 fg	0	1.16 fg
53 days after	150	1.20 cdefg	150	1.02 g		
fertilizer	600	1.10 fg	600	1.41 abcd	450-150	1.29 cdef
application	1200	1.43 abc	1200	1.54 ab	600-600	1.58 a
LSD = 0.50					1050-150	1.35 bcde
Crop 2	0	0.02 a*	0	0.82 a	0	0.82 a
159 days after	150	0.93 a	150	0.88 a	-	
fertilizer	600	0.76 a	600	1.06 a	450-150	0.93 a
application	1200	1.00 a	1200	0.88 a	600-600	0.34 a
LSD = 0.69					1050-150	0.91 a
Crop 3	0	0.85 c*	0	0.85 c	0	0.85 c
250 days after	150	1.01 abc	150	0.87 bc	-	
fertilizer	600	1.01 abc	600	1.07 ab	450-150	1.01 abc
application	1200	1.03 abc	1200	0.92 abc	600-600	0.88 bc
LSD = 0.47					1050-150	1.12 a

*Values followed by the same letter within any one crop are not significantly different at the .05 level by the least significant differences test.

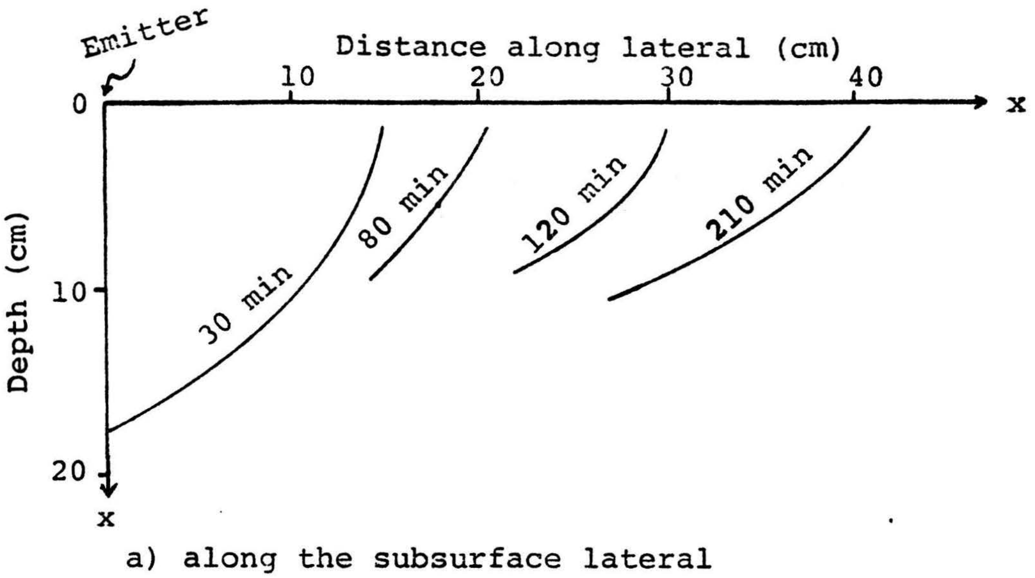
1200 kg P/ha. This suggests that the high residual levels of extractable phosphorus near the emitters might best be exploited by subsequent applications in the same volume.

G. Water Distribution in a Subsurface Trickle System

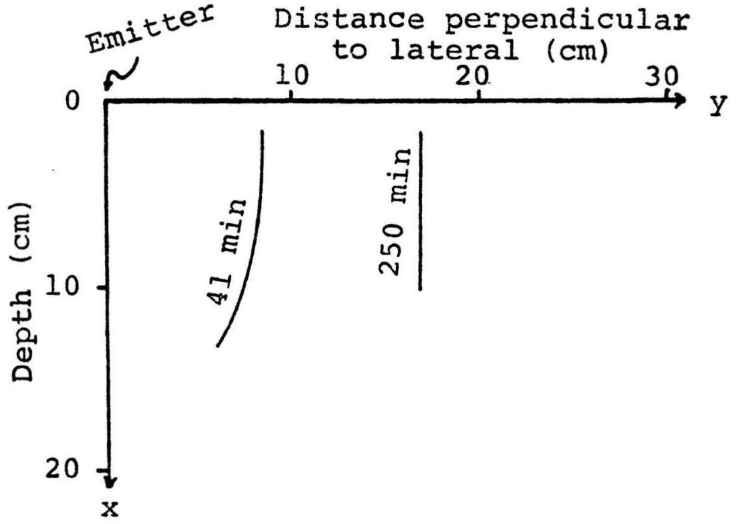
A grid of resistance blocks was buried along and at right angles to a subsurface lateral line to study horizontal water movement from a single operating emitter. Readings showed that after 105 minutes, water from a single continuously functioning emitter had saturated soil 30 cm from the emitter downslope along the lateral line but had moved only 8 cm perpendicular to the line. After five hours of irrigation, the wetting front perpendicular to the lateral line had not yet reached the sensor 24 cm from the emitter (Figs. 21 and 22).

The tendency of the water to flow freely along the outer surface of the lateral line depends on soil permeability, soil moisture, lateral line slope within the soil and rate of water application. Even at the low flow rate of a single emitter (0.25 liter/min.) in a friable, moderately dry soil (ψ = 40 centibars), the difference between water movement perpendicular to the lateral and along the lateral line was pronounced.

At higher flow rates this effect may be much more pronounced. On several occasions, when a hole was dug to repair a damaged, leaking subsurface lateral line immediately following an irrigated cycle, water was observed flowing from around the lateral lines into the hole at substantial flow rates, indicating a large free-water reservoir along and immediately adjacent to the lateral line. This is evidently due to water flowing freely along a soil surface formed around the subsurface lateral line by the expansion and contraction of the lateral during the

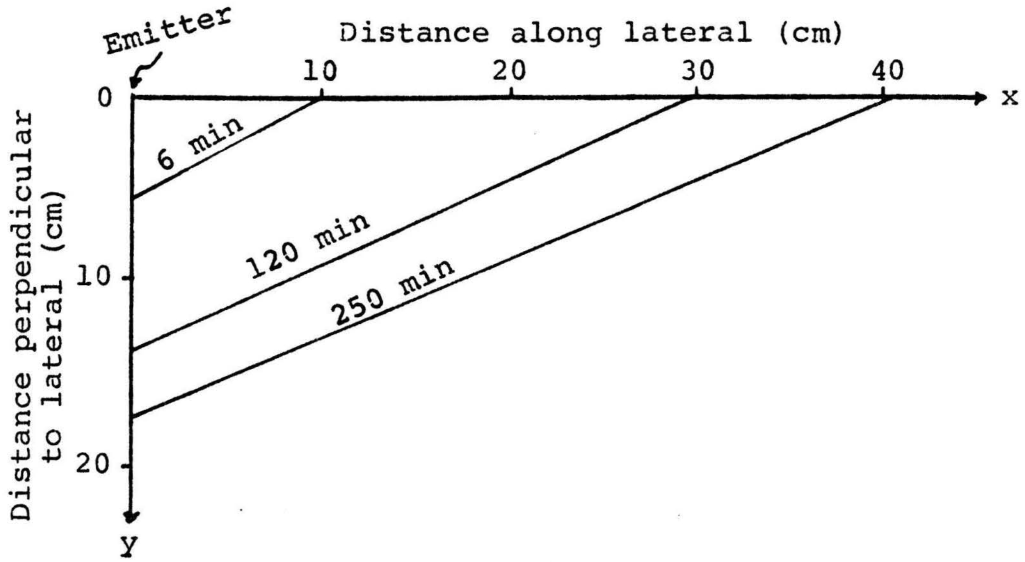


a) along the subsurface lateral

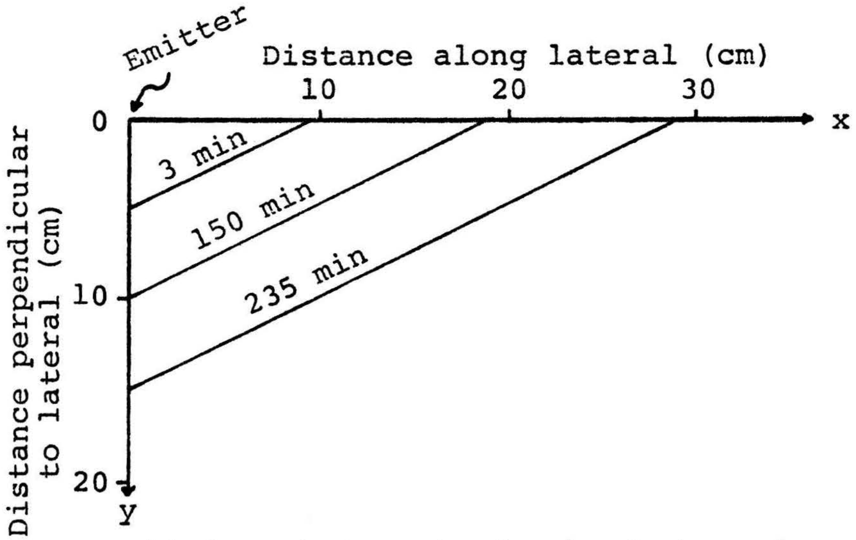


b) perpendicular to the subsurface lateral

Fig. 21. Movement of the wetting front in the horizontal and vertical directions as it is influenced by a subsurface lateral line.



a) 1 cm below the depth of the subsurface lateral line



b) 9 cm below the depth of the subsurface lateral line

Fig. 22. Relative horizontal movement of the wetting front at two depths along (x direction) and perpendicular to (y direction) a subsurface lateral line.

irrigation cycle. Preferential water movement of this type may permit considerable lateral movement, particularly in sloping fields. This may be important in supplying water to plants located near an adjacent plugged emitter and may reduce the damaging effects of plugging.

CONCLUSION

This study demonstrates that controlled traffic agriculture, already widely practiced in the United States, is readily adaptable to vegetable farming in Hawaiian soils. By restricting the tractor wheel to specific lanes, equipment can be operated under more adverse weather conditions and tillage requirements in the planting beds are substantially reduced. Both of these factors become increasingly important as the number of crops harvested each year increases. The major disadvantage of minimum tillage agriculture in Hawaii, as elsewhere, is the need to maintain more strict control over weeds.

Because of the advantages of controlled traffic agriculture, this method of farming has its greatest potential in Hawaii in small farm vegetable production. Farmers who plow their fields four to five times a year may, under most conditions, reduce tillage to once every two or more years.

Controlled traffic farming provides an additional advantage for trickle irrigated crops. Although trickle irrigation, once in place, provides optimal water management in the field with the minimum of labor, many vegetable farmers avoid its use because trickle lines must be removed and replaced with each harvest and planting operation to make way for tillage and traffic. This study shows that, with proper bed preparation, proper depth of lateral line placement, and by confining traffic to traffic lanes and thus eliminating the need for tillage, the time, expense and drudgery of removing and replacing the drip lines can also be eliminated. Subsurface placement of laterals also reduced rat damage, material degradation from solar radiation, and accidental damage to the lateral line.

Combining controlled traffic with a subsurface trickle irrigation system permits the farmer to take further advantage of the trickle irrigation system. A trickle irrigation line placed 13 cm below the surface can be used to distribute fertilizer within the root zone of each plant. Each emitter is readily located by a wet area that forms directly over it shortly after an irrigation cycle begins. By transplanting directly over the emitter, a plant is assured of water and injected nutrient availability. The proximity of the plant roots to the fertilizer source permits nutrients immobilized by the soil, such as phosphorus, to be distributed through the trickle line and concentrated near the emitter. Moderate levels of phosphorus applied in this manner provides significantly more phosphorus to the crop than if the same amount is broadcast-applied.

Emitter plugging is a major problem associated with subsurface trickle irrigation. There are indications, however, that the intermittent nature of some plugged emitters and the flow of water and nutrients along the outer wall of the subsurface trickle tube may lessen crop water stress as determined by the number of plugged emitters or by flow rate. Plugged subsurface emitters can be located by the absence of the wetted area and, if desired, may easily be unplugged by digging through the soil which has been kept friable through controlled traffic management.

Finally, in a well-fertilized field provided with adequate water, good crop performance can be attained even in compacted soils. Lettuce transplanted in rows compacted by 10 to 12 passes of a tractor wheel produced heads comparable in size and quality to those grown on the non-compacted control plots, even though root size and weight of plants in the compacted rows were significantly reduced by the compaction treatment.

This study indicates that there is great opportunity for exploiting controlled traffic farming in Hawaii. The small vegetable farmer who now practices continuous cropping can achieve greater economy of time and energy by adopting this system.

APPENDIX

APPENDIX A

Table 18. Monthly temperature and rainfall data for the Lalamilo experimental farm, Kamuela, Hawaii

Month	Temperature (°C)			Monthly Rainfall (mm)
	Max.	Min.	Avg.	
July 1978	21.1	16.5	18.8	58
Aug.	22.6	17.1	19.9	37
Sept.	22.9	16.1	19.5	13
Oct.	23.9	15.2	19.6	40
Nov.	20.9	14.3	17.6	73
Dec.	19.8	13.4	16.6	100
Jan. 1979	19.0	11.4	15.2	
Feb.	19.8	12.4	16.1	175
Mar.	20.4	11.5	16.0	47
Apr.	21.4	13.0	17.2	88
May	21.8	14.3	18.1	64
June	19.6	15.2	17.4	49
July	21.8	15.3	18.6	50
Aug.	23.6	15.7	19.7	34
Sept.	23.9	16.3	20.1	39
Oct.	23.9	15.9	19.9	38
Nov.	21.9	13.9	17.9	319
Dec.	21.6	13.2	17.4	68
Jan. 1980	21.4	10.8	16.1	280
Feb.	21.6	12.2	16.9	80
Mar.	19.4	14.6	17.0	349
Apr.	19.8	14.7	17.3	161
May	22.1	15.5	18.8	143
June	22.1	15.9	19.0	40
July	23.4	16.5	20.0	43
Aug.	24.0	15.8	19.9	21
Sept.	24.3	16.7	20.5	18
Oct.	23.8	16.6	20.2	65
Nov.	24.7	15.6	20.2	22
Dec.	24.0	12.2	18.1	35
Jan. 1981	23.1	10.9	17.0	18

APPENDIX B

Table 19. Monthly temperature and rainfall data for the Waimanalo experimental farm, Waimanalo, Hawaii

Month	Temperature (°C)			Monthly Rainfall (mm)
	Max.	Min.	Avg.	
May 1979	27.4	20.7	24.1	33
June	27.9	21.9	24.9	14
July	28.9	22.4	25.7	8
Aug.	29.7	23.0	26.4	24
Sept.	29.6	23.3	26.5	21
Oct.	29.2	22.3	25.8	79
Nov.	26.6	20.9	23.8	106
Dec.	26.3	19.3	22.8	318
Jan. 1980	25.6	18.6	22.1	373
Feb.	25.7	17.4	21.6	137
Mar.	25.1	20.2	22.7	36
April	25.8	20.6	23.2	66
May	27.2	21.4	24.3	244
June	27.4	22.4	24.9	44
July	28.2	22.8	25.5	37
Aug.	28.6	22.8	25.7	65
Sept.	28.9	23.2	26.1	41
Oct.	28.7	22.1	25.4	25
Nov.	27.8	20.8	24.3	21
Dec.	27.1	18.9	23.0	349

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