EFFECT OF SUPPLEMENTAL IRRIGATION ON SOIL CHEMICAL PROPERTIES AND GROWTH OF *ACACIA SALIGNA* IN NORTH-WESTERN KENYA

BY

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DECLARATION

CANDIDATE

I do declare that this thesis and the work reported herein are my original work and ideas. It has not been presented for an award of degree in any other University. However any assistance from friends and colleagues is acknowledged.

07/05/2001

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DEDICATION

Dedicated to the mzee Nicholas Otuto's family and in particular to

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SYMBOLS AND ABBREVIATIONS

ASAL	Arid and semi-arid lands
BWIP	Brackish water irrigated plots
Ca	Calcium
Ca^{2+}	Calcium ion
$CaCl_2$	Calcium chloride
CEC	Cation exchange capacity
Cl	Chloride ion
CO_2	Carbon dioxide
CO_3^{2-}	Carbonate ion
EC	Electrical conductivity
$EC_{25°}$	Electrical conductivity at 25°C
ECe	Electrical conductivity of saturation paste extract.
ECw	Electrical conductivity of water
ESP	Exchangeable sodium percentage
FWIP	Fresh water irrigated plots
H_2O	Water
HCl	Hydrochloric acid
HCO_3	Hydrogen carbonate ion
H_2SO_4	Sulphuric acid
IR	Infiltration rate
K	Potassium
K^+	Potassium ion
KCl	Potassium chloride
LSD	Least significant difference
Mg^{2+}	Magnesium ion
Mn	Manganese
N	Nitrogen
Na	Sodium
Na^+	Sodium ion
NaCl	Sodium chloride
NH_4Ac	Ammonium acetate
NIP	Non-irrigated plots
OH	Hydroxide ion
PI	Permeability index
RSC	Residual sodium carbonate
SAR	Sodium adsorption ratio
SAR_{adj}	adjusted sodium adsorption ratio
SO_4^{2-}	Sulphate ion
ψ	water potential
ψ_g	gravitational potential
ψ_m	matrix potential
ψ_{pl}	plant/shoot water potential
ψ_s	Solute potential
ψ_{soil}	Soil water potential
Σ	Summation
USDA	United States Department of Agriculture
VPD	Vapour pressure deficit

ABSTRACT

The aim of the experiment was to evaluate the effects of supplemental irrigation using brackish (3.15 dsm^{-1}) and fresh waters (0.30 dsm^{-1}) on soil chemical properties and growth of *Acacia saligna* grown on runoff collection fields. The experiment involved supplementing natural precipitation and harvested runoff with irrigation using the two water quality levels during dry spells. The irrigation treatments were applied in a randomised complete block design with three replicates to one year old *Acacia saligna* trees which, had been raised under harvested runoff.

Tree growth and biomass accumulation were determined using stem girth method. The double ring infiltrometer with a falling head was used to measure the rates of water infiltration into the soil. Tree phyllodes were wet digested and cation contents determined using an atomic absorption spectrophotometer while chloride was determined using a chloridometer.

Irrigation with brackish water increased the levels of soil Mg^{2+} and ESP but depressed the average and final rates of water infiltration into the soil. Supplemental irrigation with fresh water improved the soil permeability to water. Supplementary irrigation with the two water types did not affect both the ionic content of phyllodes and the growth and biomass accumulation of *Acacia saligna* trees. *Acacia saligna* tolerated salinity of irrigation water of 3.15 dsm^{-1} and excluded chloride ions from its phyllodes.

Natural precipitation and harvested runoff water sufficed to grow *Acacia saligna* without supplemental irrigation during the dry spells under conditions at our experimental site. The brackish water of 3.15 dsm^{-1} can safely be used for supplemental irrigation of *Acacia saligna* during dry spells at the experimental site. Long-term studies need to be conducted to evaluate the sustainability of these results given the highly variable rainfall pattern of the region, which often leads to several dry months.

CHAPTER ONE

INTRODUCTION

One of the major problems facing the world today is that of meeting the agricultural needs of an ever-increasing population from a limited arable land. The solution to this problem lies in bringing under-utilised lands such as the Arid and semi-arid lands (ASAL) into agricultural production. Worthington (1976) estimated 60% of the world surface to fall under ASAL. In Kenya over 83% of the landmass is in the marginal and semi-arid zones (Braun and Mungai, 1981).

Agricultural land utilisation in the ASAL is however limited by insufficient and erratic precipitation coupled, especially in the tropics, with high evaporative demand. North-western Kenya in particular is characterised by an average annual precipitation of 220-300 mm. The availability of water from this low precipitation to plants if further reduced by the tendency of the water to be lost to the atmosphere as evident in the precipitation to potential evapotranspiration (P/ETP) ratio of between 0.07 and 0.2. Furthermore, the rainfall is concentrated over short periods giving a growing season of one to twenty nine days a year (FAO, 1993). These conditions result in low and insufficient soil moisture incapable of taking, even the fast-maturing crop species and varieties, to maturity. Even though trees are more tolerant to drought than annuals, their productivity is greatly impaired during these long dry spells.

A number of strategies have been employed to tackle this problem of limited soil moisture in ASAL. These strategies include supplemental application of water, dryland farming (water conservation techniques), and growing drought tolerant species.

Even though, irrigation is the major way of supplementing the usually insufficient precipitation in ASAL, these (ASAL) regions are dry and water for irrigation is limited. Furthermore, bringing water for irrigation from long distances lead to increased cost of producing plants in ASAL. Thus, attempts have been made to use underground water for irrigation. However, many of the underground waters available in ASAL are usually brackish or even saline. The use of such brackish and saline waters for irrigating planted fields invariably leads to salinity and/or sodicity problems in the long run. The use of runoff water is another option of dealing with the limited water in ASAL.

Runoff water following rainfall events is a common feature of ASAL. Harvesting of this runoff water for plant production is a viable undertaking. It has been practised in Negev desert, Israel (Evenari *et al.,* 1982), Iran (Koswar, 1991) and Turkana, Kenya (Fallon, 1963).

Under runoff farming, runoff water is trapped and let to percolate into the planted fields. This water is thereafter accessible to the field plants. However, as drought progresses following rainfall and runoff events, the top depths of the field dry up first and access of the harvested runoff water becomes limited only to deep-rooted plants. This makes deeply rooted plants especially trees best suited to runoff farming.

Multipurpose fast growing trees establish themselves quickly enough before the moisture in the topsoil is depleted following the occasional rainfall and runoffs. Furthermore, trees do withstand long dry spells and are able to resume active growth during the next rainy season. The multipurpose trees have high economic values supplying products such as timber, fuelwood (including charcoal), fodder, medicinal substances, gums and resins,

tannin, and essential oils and waxes. Trees also contribute to soil conservation by reducing runoff and wind erosion. Moreover, trees maintain and improve soil fertility through incorporation of organic matter into the soil and pumping of nutrients from lower soil layers. Growing of halophytic trees has been used to rehabilitate salt affected soils by reducing soil alkalinity and salinity and increasing soil organic carbon (Malcolm, 1993). Equally important though less obvious is the provision of shade to both people and animals by trees. A number of multipurpose trees have been identified One such tree is *Acacia saligna*.

Acacia saligna (= *Acacia cyanophylla*) is a small (2-9 m high) evergreen, multipurpose, leguminous tree native to the south-west of Western Australia (Crompton, 1992). *Acacia saligna* is adapted to the ASAL and saline conditions of Australia (Crompton, 1992) North Africa (Tiedeman and Johnson, 1992) and Israel (Degen *et al.*, 1995).

Acacia saligna has been used, to supply forage, tannin and fuelwood; to maintain soil fertility and control soil erosion; and as ornamental and windbreak. *Acacia saligna* provides a reserve of high protein animal feed used during droughts. The tree increases the soil nitrogen through N-fixation (Tiedeman and Johnson, 1992) and through decomposition of high nitrogen-containing litter which, is produced in large quantities (Witkowski, 1991). Because of its adaptability to dry and salt-affected regions, *Acacia saligna* presents a great potential for ornamental use under these conditions where most other ornamental species do not readily fit.

In this study *Acacia saligna* was grown under natural precipitation and harvested runoff that was supplemented with irrigation using fresh and brackish underground waters in

between the rainfall and runoff events. Harvested runoff water was expected to supply soil moisture and also wash down salts from irrigation water beyond the trees' root zone.

1.1 The Problem.

1.1.1 Hypothesis

The study tested the following hypotheses:

(a) Water stress affects plant growth and productivity.

(b) Sodicity and low salt levels reduce soil permeability to water resulting in low soil moisture and hence reduced water availability to plants.

(c) High salt levels in the soil lowers the soil water potential and thus reduces effective water availability to plants.

(d) Salinity and sodicity cause specific ion toxicity of ions such as Na^+ and Cl^-.

(e) Sodicity raises the soil pH causing nutritional imbalances especially of calcium and magnesium and reducing availability of other nutrients such as phosphorus, manganese, boron and iron to plants.

1.1.2 Objectives.

The objectives of the study were to:

(a) assess the effects of supplemental application of water on the growth and biomass accumulation of *Acacia saligna*.

(b) assess the effects of quality of the waters of irrigation on soil chemical properties.

(c) assess the effects of irrigation water quality on the salt levels of the phyllodes of *Acacia saligna*.

CHAPTER TWO
LITERATURE REVIEW

2.1 Tree Growth and Productivity

Trees like all plants grow by a process of continuous synthesis of large complex molecules from simpler and smaller ions and molecules. The growth and productivity of trees depend on the accumulation of these complex compounds into biomass. The building blocks for tree growth are acquired through nutrients uptake from growth media (soil) and photosynthesis.

A conventional method used to measure tree growth and biomass yield (productivity) is the determination of dry weight. To obtain dry weight, the tree or its parts are dried and thus destroyed. The destructive nature of this method limits its use in monitoring the growth and biomass accumulation of a tree over a period of time. Furthermore, because of high variability of trees grown under water limited conditions, a large number of trees grown would have to be sampled to obtain a representative data on the extent of growth and biomass accumulation. Some models, which have been established and tested, could be used in non-destructive measurements of tree growth.

Biometric relationship between accumulated biomass (dry weight) and trunk diameter has long been recognised and forms the basis of the pipe model theory (Shinozaki *et al.*, 1964a; 1964b). This relationship enables the prediction of tree growth and accumulated biomass from trunk diameters of trees. A linear correlation between above ground biomass yield and trunk diameter has been reported for *Acacia salicina* and *Eucalyptus occidentalis* (Lovenstein and Berliner, 1993) and *Acacia saligna* (Droppelmann and

Berliner, 2000). Results on *Acacia saligna* (from the same fields used for our study) showed that the above ground biomass yield per tree was linearly correlated to the square of the basal diameter at a height of 0.2m (Droppelmann and Berliner 2000):

$$BM = 0.168(BD)^2 \quad (1)$$

Where BM is above ground dry matter (kg/tree)
BD is basal diameter (cm) at 0.2m height

2.2 Tree Growth and Productivity under Arid and Semi-Arid Lands (ASAL)

The single most important factor limiting growth and productivity of plants in ASAL is water. Water is involved in plant growth at different levels: expansive cell growth, photosynthesis both as a substrate and in the regulation of stomatal aperture, and as a medium in which various biochemical and physiological processes leading to growth do occur. Plants rely on food supplied by photosynthesis for their growth.

Plants growing under ASAL suffer some water stress in the course of their development. Plant water stress though usually associated with low soil moisture, develops whenever water loss exceeds absorption for a long enough duration to cause a decrease in plant water content and sufficiently perturb plant growth and developmental processes (Kozlowski et al.,1991). Therefore besides low levels of soil moisture enhanced plant transpiration and reduced absorption and xylem conductance of water up the plant, also result in plant shoot water deficit.

2.2.1 Water and Tree Growth and Productivity:

Within a cell, cytoplasmic materials are cradled in a matrix of water making up to 80-90% of the fresh weight of fully hydrated tissues. Cell growth occurs in three stages: cell division, cell enlargement, and cell differentiation. Cell enlargement acts as a sink for water taking up large quantities of water. Water uptake by cells is the primary cause of irreversible enlargement of cells (Cosgrove, 1986). The growth of single cells is quantitatively related to cell turgor (Levitt, 1980). Furthermore, cells do not divide until they have attained a certain size. Water status through its effects on cell enlargement therefore also affects cell division.

The relationship between water availability to trees and diameter growth measured as width of annual rings laid down each growing season forms the basis of the science of dendrochronology. Kozlowski *et al* (1991) suggested that lack of turgor inhibits enlargement of xylem initials and that tree water deficits directly affects the development of cell walls of xylem derivatives. Insufficient water supply to trees results in few and small-sized xylem cells in the stem. Tree water status as determined by predawn water potential at seedling stage has been found to correlate well with the height at maturity of Douglas-fir trees (Waring and Schlesinger, 1985).

Besides these long term effects of tree water deficits, midday effects when transpiration exceeds water absorption do occur. Reduced shoot elongation and stem shrinkage occur at midday on hot sunny days (Kozlowski *et al.* 1991).

2.2.2 Photosynthesis

Plants depend on food supplied by photosynthesis for their growth. Photosynthesis in trees mainly occurs in the leaves. Transpired water and carbon dioxide (CO_2) for photosynthesis leave and enter the leaves respectively through stomata.

The stomatal mechanism has been extensively reviewed (Permadasa, 1981). Stomata open in response to light (except for plants with Crasulacean acid metabolism) and low levels of internal CO_2. Leaf water potential has a profound effect on stomatal opening and closing. Low leaf water potential cause stomata to close. This effect of low leaf water potential over-rides the effects of both low internal CO_2 levels and bright light (Permadasa 1981; Salisbury and Ross 1986). A favourable plant (and in particular leaf) water status is therefore necessary for the opening of the stomata and flow of CO_2 for photosynthesis into the leaves.

Lowered photosynthetic rates have been reported for water stressed plants. Ni and Pallardy (1991) working with seedlings of four tree species reported reduced net photosynthesis with decreasing leaf water potentials. Similar observations have been reported for mature 'Valencia' orange (*Citrus sinensis*) (Vu and Yelenosky, 1988), eight-year-old orchard lychee (*Litchi chinensis*) (Batten *et al.*, 1994) and one-year-old interior spruce (*Picea glauca*) (Eastman and Camm, 1995).

Besides reduction in photosynthetic rates, tree water stresses also limit expansive growths of leaves and hence leaf area. This reduction in leaf area is one of the damaging effects of water stress on tree growth and productivity. Kozlowski *et al.* (1991) suggested that increased leaf area resulting from irrigation of trees was more important for tree growth

and productivity than an increase in photosynthetic rate per unit leaf area. A good correlation between leaf area and stem biomass among trees has been reported (Ridge *et al.* 1986)

Tree photosynthesis is a function of both the leaf area and the duration over which the leaf area is maintained. Plant water stress leads to premature senescence and shedding off of leaves (Levitt, 1980) Premature leaf senescence and shedding off reduces the effective leaf area and therefore photosynthetic area.

2.2.3 Runoff Harvesting for Agricultural Utilisation

Low and unreliable precipitation and lack of irrigation water hinder productive plant growth in ASAL. However, the long dry spells in ASAL are usually interrupted by flood producing heavy downpours. Up to 53 million m^3 of water in form of surface runoff is estimated to flow across Iran annually into the Caspian sea, Persian Gulf, Oman sea, and numerous lakes and swamps (Koswar, 1991). In Northern Kenya, surface runoff produces many seasonal streams and rivers. Harvesting this runoff water could to an extent alleviate the water shortages in these regions.

Runoff harvesting involves conveying the runoff water into a plot surrounded by walls (Evenari *et al.*, 1982, Lovenstein *et al.*, 1991). The trapped water then percolates into the soil and becomes available for plant growth. Runoff farming is not a new concept. The practice dates back to over 4000 years in the Negev desert, Israel (Evenari *et al.*, 1982). In Turkana, Kenya, harvested runoff was already being used to grow sorghum by 1952 (Fallon, 1963). Runoff farming has been used to grow grapes and apricot fruits of good yield and quality in Negev desert (Evenari *et al.*, 1982) and at the University of Arizona

(Mielke and Dutt, 1981). *Acacia saligna* yielded up to 9.8 tonnes ha^{-1} per year of lopped material under runoff irrigation in the Negev desert (Israel) with a long term annual average rainfall of 115mm (Sauerhaft, 1997).

Besides supplying water for plant growth, harvesting runoff water has many advantages. Runoff water carries with it manure and other organic matter into the trapping plots. In Iran, Koswar (1991) noted that management of runoff water could be used to achieve a number of goals. These included meeting the water requirement of crops and trees, artificially recharging acquifers, reducing gully erosion, leaching saline soils, and preventing water-logging of agricultural lands and population centres downstream of the floodwater spreading area.

2.3 Salinity and Plant Growth and Productivity

Soil salinity refers to high levels of soluble salts in the soil solution and encompasses sodicity problems. Salts in the salt-affected soils originate from inherent saline materials in the soil (Carter, 1975), shallow saline water tables (Otieno, 1990) and saline irrigation waters (Wakindiki, 1993). In this study it was envisaged that irrigating plants with brackish water would accelerate the development of salinity.

Irrigating with saline water contributes to soil salinity (Wakindiki, 1993) All irrigation waters contain some dissolved salts (Ayers, 1985; Mass, 1993). Irrigation waters have been classified into various classes based on their suitability for irrigation. The classification has been based on total salt concentration as measured by electrical conductivity (ECw), residual sodium carbonate (RSC) content, and sodium adsorption ratio (SAR) (US Salinity Laboratory staff, 1954). Ayers (1985) added toxic levels of ions and miscellaneous effects on susceptible plants to the above criteria Ayers' (1985) classification is the most widely

used and is produced here (Table 1).

Table 1: Guidelines for interpreting water quality for irrigation

Problem	Degree of problem		
	No problem	Increasing problem	Severe problem
Salinity			
(affects crop water availability)			
EC_w (dsm^{-1})	< 0.75	0.75-3.0	> 3.0
Permeability (of water into the soil)			
EC_w (dsm^{-1})	> 0.5	0.5-0.2	< 0.2
adj SAR			
montmorillonite	< 6.0	6.0-9.0	> 9.0
Illite-vermiculite	< 8.0	8.0-16.0	> 16.0
Kaolinite-sesquioxide	< 16.0	16.0-24*2	> 24.0
Specific ion toxicity			
(affects sensitive plants)			
Sodium (adj SAR)*2	< 3.0	3.0-9.0	> 9.0
Chloride ($meqL^{-1}$)*2	< 0.75	0.75-2.0	> 2.0
Miscellaneous effects			
(affects susceptible plants)			
NO_3-N or NH_4-N ($mg\ L^{-1}$)	< 5.0	5.0-30.0	> 30.0
HCO_3 ($me\ L^{-1}$) [overhead sprinkling]	< 1.5	1.5-8.5	> 8.5
pH	[Normal range of 6.5 – 8.4]		

Source (FAO Irrigation and drainage Paper No.29 R1 1985)

*1 Lower limit, intermediate range and upper limit are used when EC_w < 0.4 dsm^{-1}; EC_w – 0.4 to 1.6 dsm^{-1} and EC_w > 1.6 dsm^{-1}

*2 Most tree crops and woody ornamental are sensitive to Na^+ and Cl^-.

When sprinkler irrigation is used on sensitive crops, Na^+ or Cl^- in excess of 3.0 $meql^{-1}$ under certain conditions has resulted in excessive leaf absorption and crop damage

Critical salt levels both in water and soil, affecting plant growth and productivity vary with other factors such as plant species, water-holding capacity of soils, and composition of salts (Carter, 1975; Ayers 1985).

2.3.1 Effects of Irrigation Water Salinity on Soil

Carter (1975) reviewed the development of salinity problem in the plants root zone. Evapotranspiration removes water in the pure state leaving behind salts and other substances. This results in greater concentration of salts in the remaining solution unless leaching occurs.

The introduction of salts into the soil be it from irrigation water or fertiliser, results in chemical reactions especially the exchange of bases. Shalhevet and Kamburov (1976) described a number of processes, which occur as irrigation water percolates into the soil and gets lost through evapotranspiration and deep seepage. The important ones of these processes are the accumulation of salts in the plants' root zone and the exchange of cations between irrigation water and soil exchange complex.

(a) Ion Exchange Equilibrium

Shainberg (1975) reviewed the ion exchange equations relating to the distribution of cations on the adsorbed and soil solution phases. Exchangeable ions occur in the soil exchange complex, which is in constant contact with the soil solution. As irrigation water percolates into the soil, it becomes part of and interacts with the soil solution. This interaction causes ion exchange reaction between the soil exchange sites and the 'new' soil solution. A new ion exchange equilibrium is then established in the soil.

The ion exchange reaction common under ASAL is that between adsorbed calcium (Ca^{2+}) and magnesium (Mg^{2+}) (which are the principal cations found in the normal soils under these regions, Shainberg, 1975) and sodium (Na^{+}) from the irrigation water:

$$2Na^{+}_{(l)} + Ca^{2+}_{(s)} \rightarrow 2Na^{+}_{(s)} + Ca^{2+}_{(l)} \qquad (2)$$

Where the subscripts (l) and (s) represent the soil solution and the soil exchange complex respectively.

(b) Soil pH:

The pH values of irrigation water and soil solution are governed, to a large extent, by the amount and proportion of CO_3^{2-} and HCO_3 ions. The soil pH has been shown to correlate well with the contents of soil soluble CO_3^{2-} and HCO_3 (Kanwar and Mehta, 1970) and with RSC of irrigation water and SAR of soil solution (Paliwal and Maliwal, 1968).

(c) Permeability/Infiltration

The most important soil physical property affected by high levels of soluble salts and/or sodicity is permeability of the soil to water. Ayers (1985) noted that a permeability problem occurs if the irrigation water does not enter the soil rapidly enough to replenish the soil with water needed by the crop before the next irrigation and/or precipitation.

Soil permeability to water is a function of the mean pore radius (r^2). Low concentration of salt in the soil bulk solution and high levels of adsorbed Na^{+} cause dispersion (Yousaf *et al.*, 1987; Ali *et al.*, 1987; Shainberg *et al.*, 1981) and swelling (McNeal *et al.*, 1966, McNeal, 1968) of clay particles. Both dispersion and swelling of susceptible soil colloids reduce the mean pore radius of the soil and thus permeability of the soil to water.

Reduced soil permeability to water therefore results from the utilisation of irrigation water with low salt and/or high sodium levels (Ayers, 1985; Shainberg *et al.*, 1981, Yousaf *et al.*, 1987, Ali *et al.*, 1987). High CO_3^{2-} and HCO_3^- content in irrigation water reduce the levels of Ca^{2+} and Mg^{2+} through precipitation and tend to increase the relative proportion of Na^+ in the water (Eaton, 1950) thus contributing to reduction in soil permeability.

Using total salt concentrations and levels of Na^+, CO_3^{2-} and HCO_3^- the potentiality of soil permeability problem resulting from irrigation has been evaluated. Permeability index (PI) was defined and used by Doneen (1975) to classify water into suitability classes.

$$PI = \frac{[Na+\sqrt{(HCO_3)}] * 100}{(Ca+Mg+Na)} \quad (3)$$

Where ionic concentrations are in $meqL^{-1}$

Adjusted sodium adsorption ratio (SAR_{adj}) has been used by many (e.g. Ayers, 1985) to predict permeability problem expected from irrigation and is given by:

$$SAR_{adj} = \frac{Na}{\{1/2(Ca + Mg)\}^{0.5}} \; |1 + (8.4 - pHc)| \quad (4)$$

Where:

Na, Ca and Mg are the concentration of the ions in meq L^{-1}.

$pHc = (pK_2 - pK_c) + p(Ca + Mg) + pALK$.

pK_2 = negative logarithm of second dissociation constant for H_2CO_3 and corrected for ionic strength of the water

pK_c = negative logarithm of the solubility product constant of $CaCO_3$ and corrected for ionic strength of the water.

pK_2-pK_c = negative logarithm of total cation concentration (Ca^{2+} + Mg^{2+} + Na^{+}) in meq L^{-1}

$p(Ca^{2+} + Mg^{2+})$ = negative logarithm of concentration in meq L^{-1} of calcium plus magnesium

pAl K = negative logarithm of concentration in meq L^{-1} of carbonate plus bicarbonate

(d) Salt affected soils

Shainberg (1975) defined salt affected soils as those that contain excessive concentration of soluble salts and/or exchangeable sodium (Na^{+}). Based on these two factors (concentration of soluble salts and exchangeable sodium) US salinity laboratory staff (1954) classified soils as non-saline, saline, sodic, and saline sodic (Table 2).

Table 2. US salinity laboratory classification system of salt-affected soils:

	ECe < 4 dsm $^{-1}$ at 25^{0}C	ECe > 4 dsm $^{-1}$ at 25^{0}C
ESP < 15%	Non-saline soils	Saline soils
ESP > 15%	Sodic soils	Saline-sodic soils

Source (US Salinity Laboratory staff, 1954)

Non-saline soils refer to soils with no harmful salinity effects. Saline soils have quantities of soluble salts sufficient to interfere with growth of most crop plants but do not contain enough exchangeable Na^{+} to appreciably alter the soil characteristics. Sodic soils have a pH of between 8.5 to 10 and contain high enough quantities of exchangeable Na^{+} to interfere with growth of most crop plants but not appreciable quantities of soluble salts

The properties of saline-sodic soils vary with the concentration of salts in the solution. At high salt concentration, these soils have properties similar to those of saline soils flocculated particles leading to relatively high permeability and pH below 8.5. The high salt concentration inhibits hydrolysis of adsorbed Na^+ (Yousaf *et al.*, 1987). When the salts concentration in the soil solution is lowered as would happen with leaching, the properties of these soils change markedly and become similar to those of sodic soils. The exchangeable sodium hydrolyses and pH rises to levels above 8.5, clay particles disperse leading to poor soil permeability, drainage and aeration

2.3.2 Effects of salinity on trees

All plants grow on and obtain nutrients from a growth medium (soil). Trees are therefore affected by salinity in the soil. Water availability and specific ion toxicity are the main processes by which salinity directly affects trees (Ayers, 1985).

Water is important for the growth of trees Soil salinity therefore by affecting water availability to trees affects their growth and productivity too. Trees draw water from the soil Water is driven from the soil through the tree to the atmosphere by a negative water potential (ψ) gradient (Kramer, 1983). The solute osmotic potential (ψ_s) and matrix potential (ψ_m) are the important components of soil ψ with regard to plant water uptake from the soil and are additive in their effects. Salinity lowers the soil ψ through an osmotic effect caused by reduction in ψ_s. The ψ_s is the most variable component of soil ψ under conditions of good soil moisture. It therefore has the greatest effect on tree water uptake under such conditions (Rhoades and Merril, 1976). The decrease in ψ_s is proportional to salinity level in the soil (Ayers, 1985; US salinity laboratory 1954). The US salinity laboratory staff (1954)

presented a formula for estimating the osmotic effect (reduction in ψ_s) from the levels of salts in the soil as measured by electrical conductivity of saturation paste extract (ECe).

$$\psi_s \approx -36\ ECe_{25°C} \qquad (5)$$

Where ψs = solute potential in kPa

$ECe_{25°C}$ = electrical conductivity of saturation paste extract in dsm^{-1}

Besides lowering soil ψ_s salinity has been reported to increase tree resistance to water movement in the halophyte *Atriplex halimus* (Kaplen and Gale, 1972) and citrus (Zekri, 1991). Zekri (1991) reported that both root conductance to water and transpiration were reduced.

Regardless of salt composition in the soil solution, salinity has been reported to reduce photosynthesis per unit leaf area for trees such as citrus (Lloyd *et al.*, 1990) olive (Bongi and Loreto, 1989), *Eucalyptus* sp. (van der Moezel *et al.*, 1989) and *Acacia saligna* (Shaybany and Kashirad, 1978). Mass (1993) also reported decreased leaf area and canopy volume for citrus. This lowered the total photosynthetic capacity of the citrus trees.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Experimental Site, Field Layout and Treatments:

3.1.1 Experimental site.

The experiments were conducted at Kakuma, (3^0 34' N, 34^0 51' E and 620 m above sea level) in Turkana district, north-western Kenya between July 1997 and May 1998. The area is semi-arid with highly unreliable bimodal rainfall, which has a long-term average of 220-300 mm annually. The long rains generally occur between April and July and the short ones November and December. The mean temperature is 28^{0}C. The soils are Endosodic calcaric fluvisols according to FAO classification systems (Ute, 1996). The soils were loamy sand in texture with silt and clay being restricted to the top 30 cm (Fig. 1 Page 19). The main vegetation includes *Dobera glabra, Acacia tortolis* and *Prosopsis chilensis*.

The beginning of the experiment was preceded by a long dry spell from January to June 1997. Rains occurred during July and August (Fig.2 Page 20) followed by two dry months before the rains resumed in November 1997. July and November 1997 also had harvested runoff floods of 135 and 285 mm respectively of standing water. December 1997 to March 1998 was dry with light showers in January. Rainfall resumed in April and measurements were then terminated.

The monthly average temperatures increased through the months of July to October (Fig.2 Page 20). There was a slight drop during November followed by further increases that peaked up in February. The last five months of the experimental period were generally dry with mean temperatures above 30^{0}C.

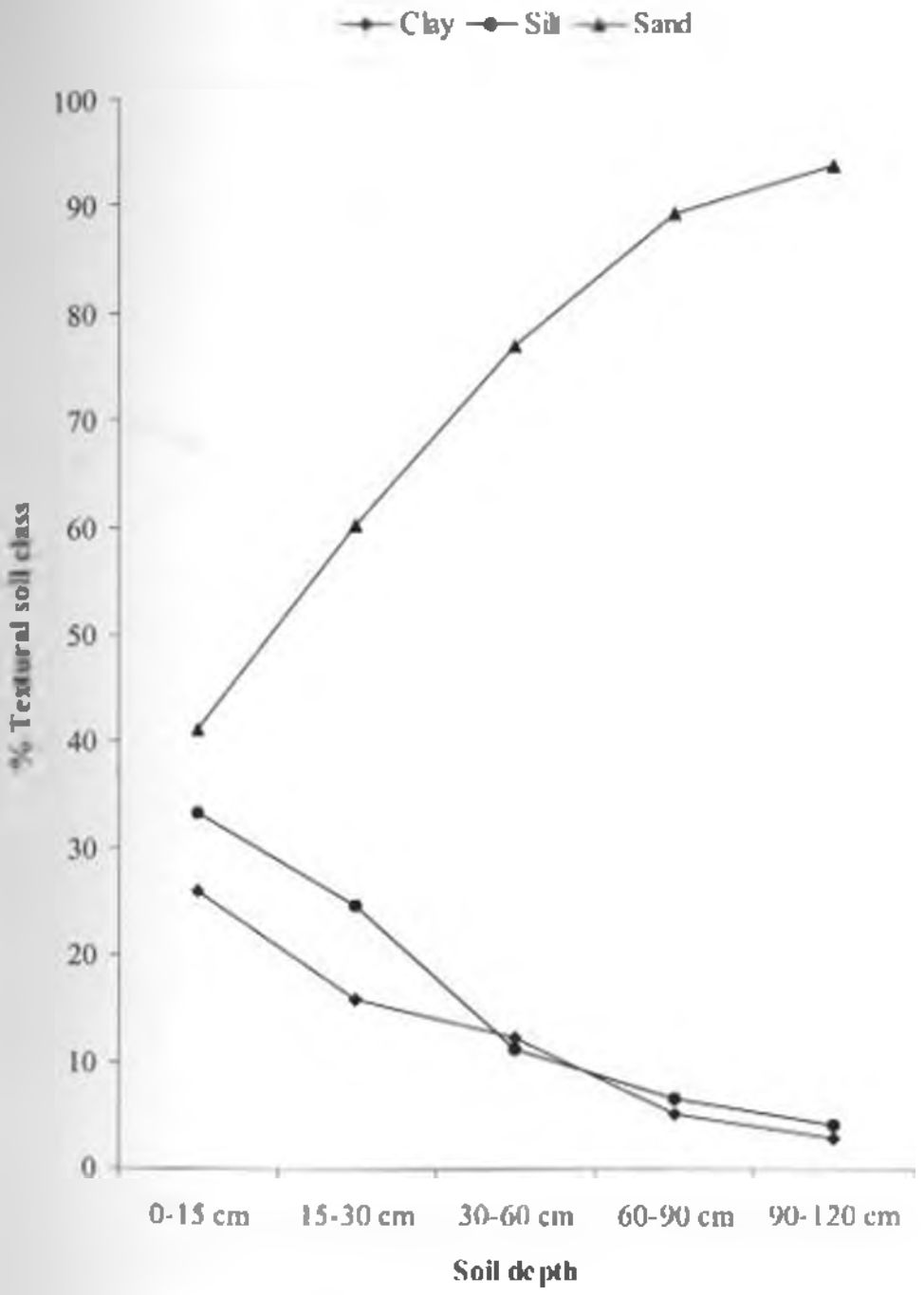


Fig. 1.Variation of soil texture down the soil profile

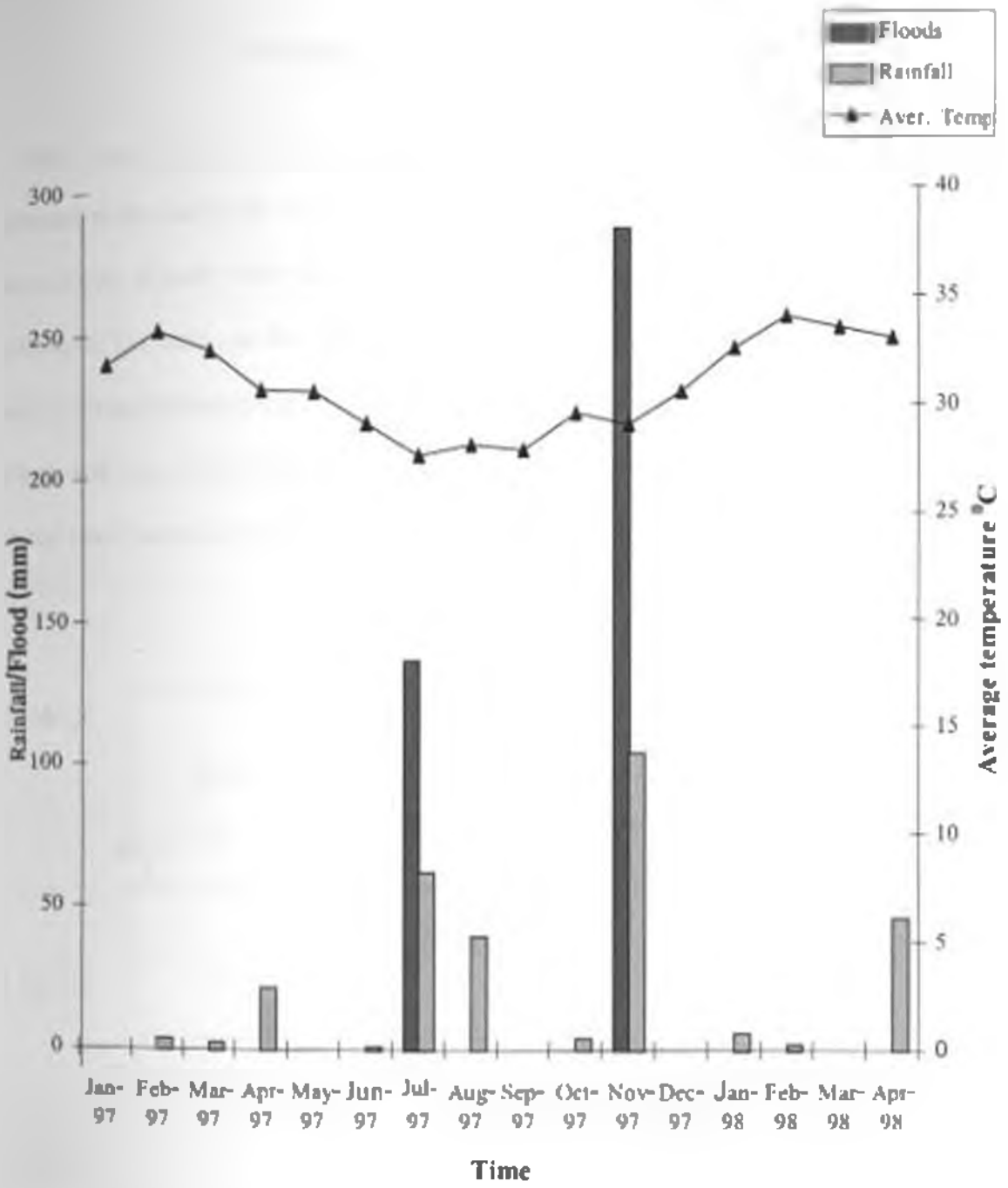
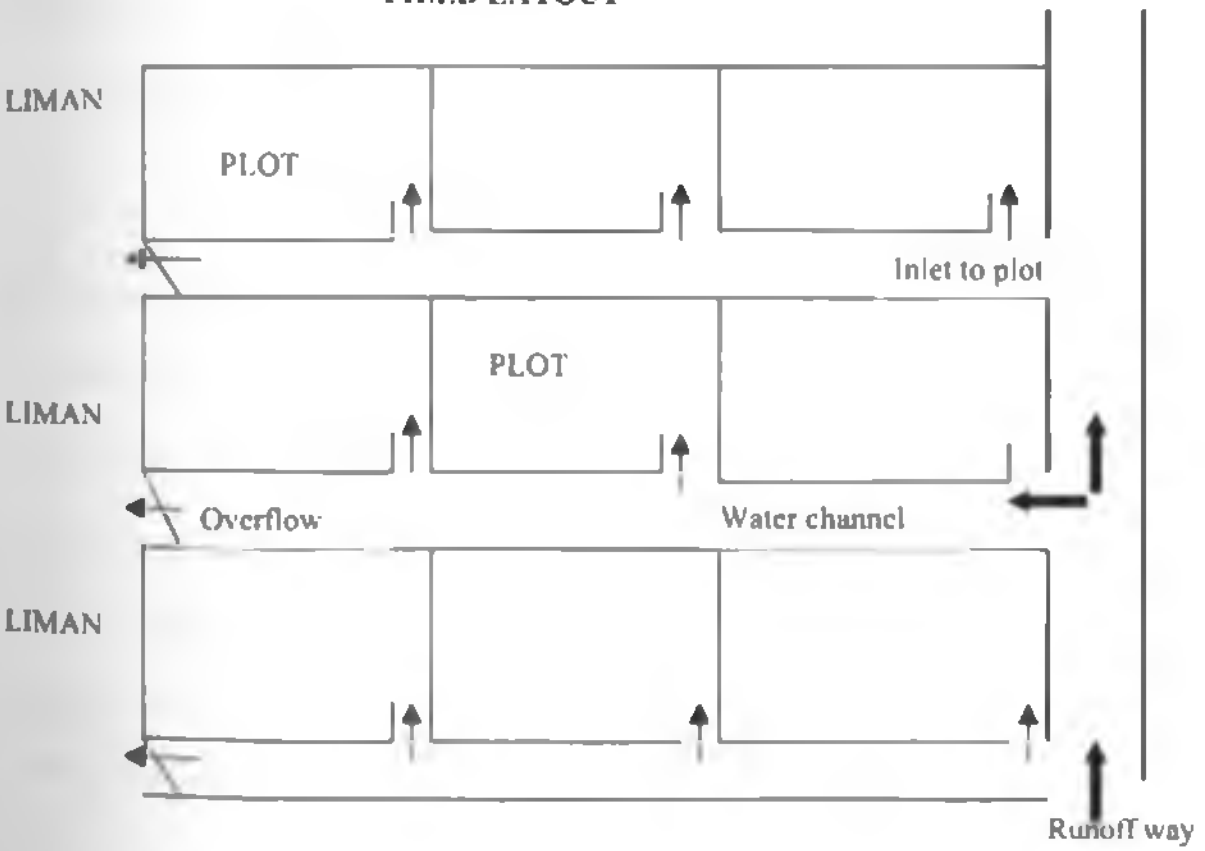


Fig.2 Weather conditions at the experimental site between Jan. 1997 and April 1998

3.1.2 Field layout

Runoff water harvested at the experimental site was generated at the Pelekech range (hills) situated to the east of the site. The field lay on a plain below the hills and was sited along a runoff way. Runoff water was diverted from the runoff way to the field by means of water channels. The field was divided into three limans. A liman is part of the field surrounded by soil walls and serves to trap the diverted runoff water. Each liman served as an experimental block and was divided into three plots. Each plot was surrounded by a soil wall and had a water inlet connecting it to a water channel.

FIELD LAYOUT



3.1.3 Treatments.

The experimental layout was a randomised complete block design with three replicates. The experiment had three treatments namely:

(i) Natural precipitation and harvested runoff (NIP)

(ii) (i) plus irrigation with fresh (low-salt) water (FWIP)

(iii) (i) plus irrigation with brackish water (BWIP).

Acacia saligna seedlings which had been raised in nursery for six months were transplanted onto the fields at a spacing of 4 m x 1m. The trees were further raised under harvested runoff for one year in the fields before the treatments were applied.

3.1.4 Water quality and irrigation:

The fresh and brackish irrigation waters were sampled during each irrigation. At the end of the experiment, all samples of each water type were bulked together and analysed for its quality (Table 3 Page 24).

The main ions present in the two irrigation waters were Na^+, K^+ Ca^{2+}, Mg^{2+} HCO_3^{2-}, and SO_4^{2-}. The brackish water had higher levels of these ions compared to the fresh water except for Ca^{2+}. The computed residual sodium carbonate (RSC), sodium adsorption ratio (SAR) and adjusted sodium adsorption ratio ($SAR_{adj.}$) were also higher in the brackish

water relative to the fresh one. The pH and electrical conductivity (ECw) were 7.30 and 3.15 dsm^{-1} and 6.50 and 0.30 dsm^{-1} for brackish and fresh waters respectively.

All plots received both natural precipitation and harvested runoff water. In addition irrigation water was applied to the two treatments involving irrigation. During each irrigation, the plots were flooded at 0.4 m of water. From previous work at our experimental site, Okumu (1998) observed that irrigating at 0.2 m of water, *Acacia saligna* maintained favourable stomatal conductance and transpiration rate for up to a fortnight. This worked out to 0.4 m of irrigation water per month. The first irrigation was undertaken on 5th September 1997. Thereafter the plots were irrigated every month. Following rainfall and or irrigation, soil dries up starting with the top layers. As the soil dries up, plant roots tend to grow deeper in pursuit of the receding waterfront. This monthly irrigation interval was expected to encourage deep rooting of the trees by allowing fields to dry up and have the roots grow deeper. Deep rooting enable trees to survive long dry spells as the trees continue accessing soil moisture until their whole rooting depth finally dries up. No irrigation was undertaken during November and December because of the heavy rainfall that spread throughout November. Irrigation resumed on 3rd January 1998 and continued to April 1998.

Table 3. Quality of the two water types used for irrigation

Parameter	pH	ECw dsm^{-1}	Na $meql.^{-1}$	K $meql.^{-1}$	Ca $meql.^{-1}$	Mg $meql.^{-1}$	ΣCations $meql.^{-1}$	HCO_3 $meql.^{-1}$	Cl $meql.^{-1}$	SO_4^{2-} $meql.^{-1}$	Σanions $meql.^{-1}$	RSC	SAR	SAR_{adj}	PI	ψπ kPa
Brackish water	7.30	3.15	18.70	1.53	0.23	0.86	21.32	11.80	18.65	3.62	34.07	10.71	25.33	44.33	27.91	-113
Fresh water	6.50	0.30	1.13	0.92	0.42	0.42	2.89	3.40	0.50	0.24	4.14	2.56	1.74	4.53	108.04	-10.80

3.2 Measurement of parameters

3.2.1 Growth and biomass accumulation *Acacia saligna*

Healthy and vigorous trees were monitored for their growth and biomass accumulation throughout the experiment. The stem girth at 0.2 m height above ground level was measured using a forester's tape. Both the growth and biomass accumulation of trees were determined from increments in stem diameter according to the method of Lövenstein and Berliner (1993). For multi-stemmed trees, the girth/circumference was obtained by summing up the circumferences of all the different stems. The circumference were first measured on 2nd July 1997 and thereafter measured on a monthly interval. The last measurement was taken on 2nd May 1998. The accumulated biomass was calculated as follows:

$$\text{Dry matter (kg/tree)} = 0.168\,(DB)^2 \qquad (6)$$

where DB is basal diameter at 0.2 m height.

3.2.2 Soil chemical properties

Soil was sampled at five depths based on the changes in texture. Proportion of sand increased down the profile (Fig.1 Page 19). The sampling depths were:

Depth I 0-15 cm

Depth II 15-30 cm

Depth III 30-60 cm

Depth IV 60-90 cm

Depth V 90-120 cm

The samples were used to obtain data on the following soil properties.

(i) pH and Electrical conductivity (EC)

Soil samples were extracted using distilled water in the 1 2.5 ratio (weight of soil: volume of water). pH(H_2O) was determined from soil suspensions made using the same (soil : distilled water) ratio. For the pH($CaCl_2$), 0.01M $CaCl_2$ was used in making the soil suspension instead of the distilled water. A pH meter was first calibrated and checked for sensitivity using buffer solutions of known pH values. The calibrated sensitive pH meter was then used to obtain the pH values from the soil suspensions. A conductivity meter and a conductivity flow cell having automatic temperature compensation were used to determine the EC at 25^0C from the soil extract.

(ii) Exchangeable cations and cation exchange capacity (CEC):

The soil samples were extracted by leaching with 1N ammonium acetate (NH_4Ac) of pH 7.0 to provide the first leachate. Excess NH_4Ac was washed out of the samples using methylated spirit. The adsorbed NH_4^+ ions were extracted by leaching the soil with 1M potassium chloride (KCl) to provide the second leachate according to the method of Rhoades (1982). The first leachate was used to determine exchangeable K^+ and Na^+ using flame photometer and Ca^{2+} and Mg^{2+} using atomic absorption spectrophotometer at 422.7 and 285.2 nm respectively.

The second leachate was steam distilled to yield ammonium nitrogen. This was then titrated with hydrochloric acid (HCl) using methyl red/bromocressol green indicator to determine the CEC of the soil.

From the levels of the exchangeable cations and CEC the exchangeable sodium percentage (ESP) was calculated using the formula:

$$ESP = \frac{Na^{+} 100}{CEC} \quad (7)$$

Sodium adsorption ratio (SAR) was calculated as follows:

$$SAR = \frac{Na^{+}}{\{1/2(Ca^{2+} + Mg^{2+})\}^{0.5}} \quad (8)$$

Where: Na, Ca and Mg are the concentration of the ions in cmol kg^{-1}.

(iii) Soluble anions:

The levels of OH , CO_3^{2-} and HCO_3^{-} were determined by titrating the extracts from the soil samples with sulphuric acid (H_2SO_4). Phenophthelein indicator was used in the first titration to determine CO_3^{2-} levels. At the end point of this first titration, methyl orange indicator was added to the soil sample extracts (previously titrated using Phenophthelein indicator). Titration with H_2SO_4 was continued to determine the levels of HCO_3^{-}. Table 3 (Page 28, US Salinity laboratory Staff, 1954) was used to calculate the levels of OH , CO_3^{2-} and HCO_3^{-}.

Meql.$^{-1}$ of OH^{-}, CO_3^{2-}, HCO_3^{-} =

$$\frac{1000 * \text{Normality of } H_2SO_4 * \text{titration volume (mL)}}{\text{Volume of aliquot taken}} \quad (9)$$

The soil samples were titrated with silver nitrate ($AgNO_3$) using potassium chromate as indicator to determine the levels of chloride (Cl^{-}).

Meql.$^{-1}$ of Cl^{-} =

$$\frac{1000 * \text{Normality of } AgNO_3 * (\text{ml } AgNO_3 - \text{Blank})}{\text{Volume of aliquot}} \quad (10)$$

Table 4: Titration of OH^-, $C0_3^{2-}$ and $HC0_3^-$ ions in the presence of phenolphthalein and methyl orange indicators.

Results of Titration	Titration value related to each ion		
	Hydroxide (OH^-)	**carbonate ($C0_3^{2-}$)**	**bicarbonate ($HC0_3^-$)**
P=0	0	0	T
P<½T	0	2P	T-2P
P=½T	0	2P	0
P>½T	2P-T	2(T-P)	0
P= T	T	0	0

Source US Salinity laboratory staff, 1954

Where P= Titre in the titration to the phenolphthalein end point

T= Titre for the complete titration to the methyl orange endpoint.

The barium sulphate procedure was used to determine the level of sulphates in the soil extracts. To 5 ml of samples, standard series, and a blank (distilled water) were added 1mL of arabic gum followed by a pinch of barium chloride. The solution was then thoroughly mixed and left to stand for 1-2 hours. The concentration of precipitated sulphate was then read from a colorimeter at 340 nm using a blue filter. The concentration of SO_4^{2-} in the sample was calculated as:

SO_4^{2-} ($meqL^{-1}$) = (A-B) * D (11)

A – sample concentration obtained from colorimetric readings

B – blank concentration obtained from colorimetric readings

D – dilution factor

(iv) Infiltration rate:

The double cylinder infiltrometer with a falling head method was used. The cylinders were carefully and slowly driven into the soil to a depth of about 10 cm. A floating ruler was placed into the inner cylinder and from it (ruler), the fall in water level (cm) was measured. The infiltration rate (IR) was calculated as follows:

IR = h/t (cm/hr) (12)

Where h – change in level of water in the inner cylinder (cm),

t – time interval in hours

3.2.3 Ionic content of phyllodes

At the beginning of the experiment, the nodes with the latest fully expanded phyllodes (leaves) were marked. At the end of the experiment, the phyllodes from the next four nodes above the marked ones were harvested for tissue analysis.

Plant samples were prepared and analysed for major cations according to the method outlined by Okalebo *et al.* (1993). The tree phyllodes were harvested and weighed to

obtain fresh weight then dried at 70^{0}C for 24 hours. The dried phyllodes were then ground and sieved through 1.0 mm sieves.

The dried phyllodes material was digested using a digestion mixture made from Selenium powder, Lithium sulphate, hydrogen peroxide and concentrated sulphuric acid (Okalebo *et al.*, 1993). Dried material (3g) was mixed with the digestion mixture (44 mL)and digested for 2 hours at 360^{0}C before being cooled. 25mL of distilled water was added to the digested and cooled material to dissolve the soluble sediments. The solution was then allowed to settle and the resultant clean solution used for analysis. Na^+, K^+, Ca^{2+}, Mg^{2+} were determined using atomic absorption spectrophotometer Cl was determined using a chloridometer (Haake and Butcher titrator).

3.3 Data Analysis.

Analysis of variance was performed to determine the differences among treatment means. The significantly different means were separated using LSD at 0.05 (Steel and Torrie, 1980).

CHAPTER FOUR

RESULTS

4.1 Growth and Biomass Accumulation of *Acacia saligna*:

The monthly tree growth as measured by increments in stem diameter did not significantly differ among the treatments throughout the experimental period (Table 5 Page 32). However the trees subjected to irrigation with brackish water had consistently, even though not significantly, higher growth and biomass accumulation throughout the irrigation treatments. Monthly biomass accumulation increased from July reaching a peak in January 1998 (Fig. 3 Page 33). A sharp drop in the monthly tree growth and biomass accumulation occurred in February 1998 despite the continuation of the irrigation treatments.

4.2 Soil chemical properties:

The fields were generally alkaline with pH averages of 8.6 and 8.05 for pH (H_2O) and pH ($CaCl_2$) respectively. The cation exchange capacity (CEC) of the site was low being less than 35cmolkg^{-1} soil. Electrical conductivity (EC), Na^+, K^+, Ca^{++}, Cl^-, HCO_3^- and sodium adsorption ratio (SAR) did not differ significantly among the treatments (Table 6 Page 35). The OH^- and CO_3^{--} ions occurred in trace amounts. Soils from plots irrigated with brackish water had significantly higher Mg^{++} and exchangeable sodium percentage (ESP) compared to those irrigated with fresh water.

Table 5. Means of monthly diameter increments (cm)

Treatment	Jul-97	Aug-97	Sep-97	Oct-97	Nov-97	Dec-97	Jan-98	Feb-98	Mar-97	Apr-98
Non-irrigated	0.16a*	0.38a	0.35a	0.38a	0.46a	0.47a	0.49a	0.26a	0.18a	0.06a
Fresh water irrigated	0.19a	0.41a	0.38a	0.45a	0.45a	0.53a	0.41a	0.20a	0.17a	0.12a
Brackish water irrigated	0.26a	0.45a	0.44a	0.48a	0.50a	0.61a	0.57a	0.21a	0.11a	0.02a
Grand mean	0.20	0.41	0.39	0.43	0.47	0.54	0.49	0.22	0.15	0.07

*: Any means within the same column, followed by different letters are significantly different at p=0.05.

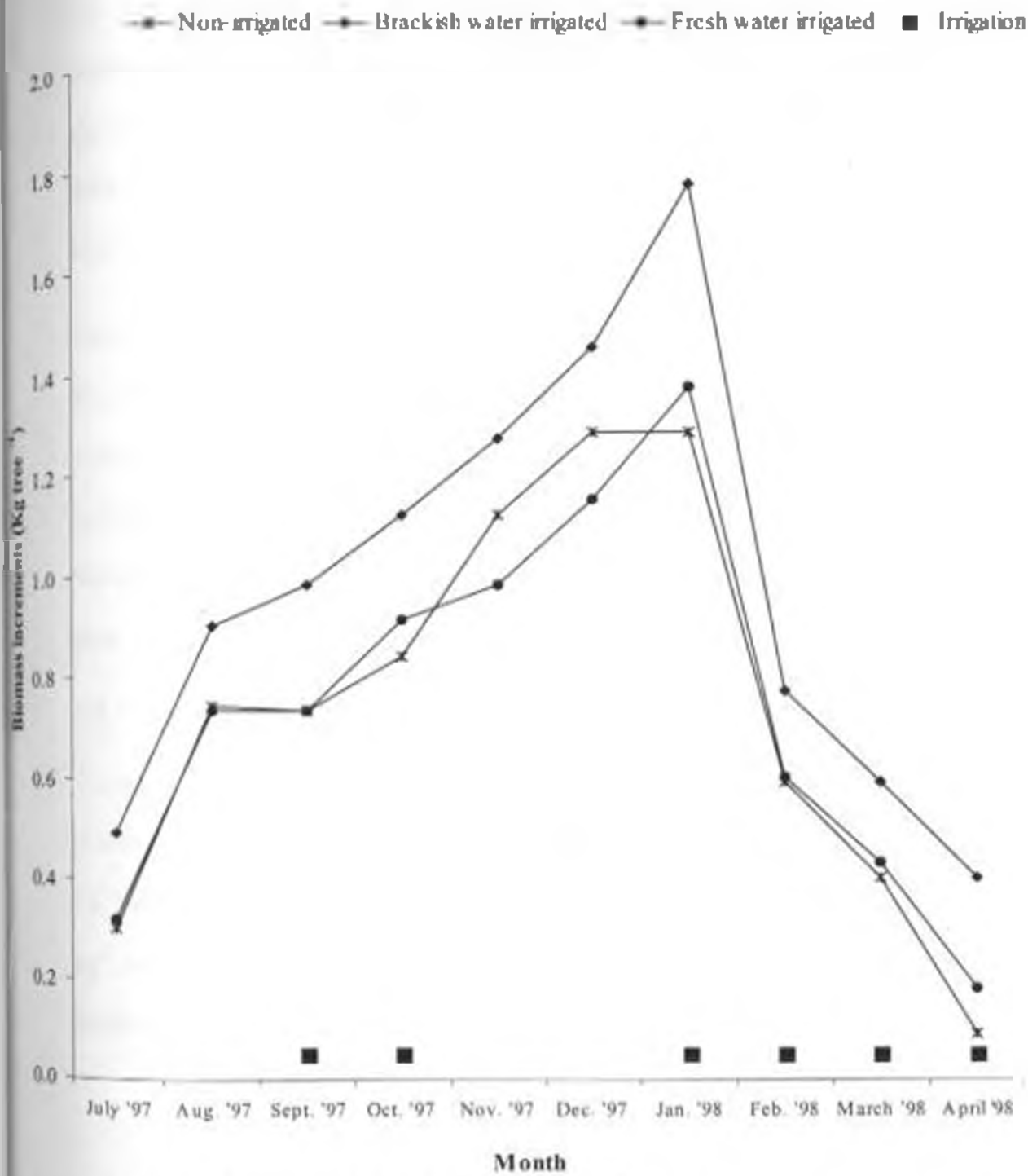


Fig.3 Monthly increments in tree biomass (kg tree^{-1})

The levels of all the measured cations, EC, ESP, SAR and CEC generally decreased down the soil profile (Table7 Page 36 and Fig.4 Page 37). Soil depth I (0-15 cm) had significantly higher levels of K^+, Ca^{2+}, Mg^{2+} and CEC compared to the lower depths. For the first two soil depths (0-30 cm), SAR of the soils from the plots irrigated with brackish water were significantly higher than that of the other treatments (Table 8 Page 38). In the other depths SAR values though not significantly different, were higher in the soils from plots irrigated with brackish water.

The infiltration rates had an asymptotic curve when plotted against time (Fig 5 Page 39). The infiltration rate dropped sharply within the first four minutes to more or less constant values. The plots irrigated with fresh water had significantly higher average and final infiltration rates compared to the other two treatments (Table 9 Page 40). Non-irrigated plots did not have significantly different infiltration rates compared to brackish water irrigated ones

4.3 Ionic content of phyllodes:

The major ions determined in the phyllodes of the tree were Na^+, K^+, Ca^{2+}, Mg^{2+} and Cl^- (Table 10 Page 41). The dominant cations taken up and accumulated by the tree were Ca^{2+} and Mg^{2+} and averaged 4.50 g kg^{-1} and 1.13 g kg^{-1} respectively. K^+ averaged 0.34 g kg^{-1} and Na^+, 0.078 g kg^{-1}. Cl^- generally only occurred in trace levels in the pyllodes. The levels of these ions in the phyllodes did not differ significantly among the treatments.

Table 6. Means of soil chemical properties at the end of the experiment.

Treatment	Parameters												
	pH (H_2O)	pH ($CaCl_2$)	Mg^{2+} cmolkg^{-1}	Ca^{2+} cmolkg^{-1}	Na^{+} cmolkg^{-1}	K^{+} cmolkg^{-1}	Cl^{-} meqL^{-1}	SO_4^{2-} meqL^{-1}	HCO_3 meqL^{-1}	CO_3^{2-} meqL^{-1}	EC dsm^{-1}	SAR	ESP
Non-irrigated	8.54a	7.99a	5.23ab	12.27a	3.83a	5.97a	1.09a	Trace	0.79a	Trace	0.20a	1.29a	15.80ab
Fresh water irrigated	8.51a	7.95a	4.93a	13.53a	3.22a	5.23a	0.94a	Trace	0.65a	Trace	0.18a	1.08a	13.10a
Brackish water irrigated	8.76a	8.21a	6.73b	13.40a	11.38a	5.53a	1.10a	0.06	0.74a	Trace	0.24a	3.47a	37.60b
Grand mean	8.60	8.05	5.63	13.06	6.15	5.58	1.05	0.01	0.73	Trace	0.21	1.95	22.10
LSD (0.05)			1.55*										20.20

* Shown LSD values are only the protected significant ones.

Table 7. Means of soil chemical properties according to depth at the end of the experiment.

Depth	Na cmol kg^{-1}	K cmol kg^{-1}	Ca cmol kg^{-1}	Mg cmol kg^{-1}	CEC cmol kg^{-1}	ECdsm^{-1}
I (0-15cm)	7.16a	10.06a	15.67a	8.01a	32.37a	0.25a
II (15-30cm)	7.28a	5.61b	13.76b	5.13b	26.04b	0.21ab
III (30-60cm)	8.00a	5.00bc	12.24bc	4.69b	23.11b	0.20ab
IV (60-90cm)	4.64b	4.00c	12.31bc	4.90b	22.09b	0.19ab
V (90-120cm)	3.66b	3.22c	11.33c	5.42b	21.81b	0.18b
Grand mean	6.15	5.58	13.06	5.63	25.08	0.21
LSD(0.05)	1.87	1.04	1.75	2.28	4.54	0.07

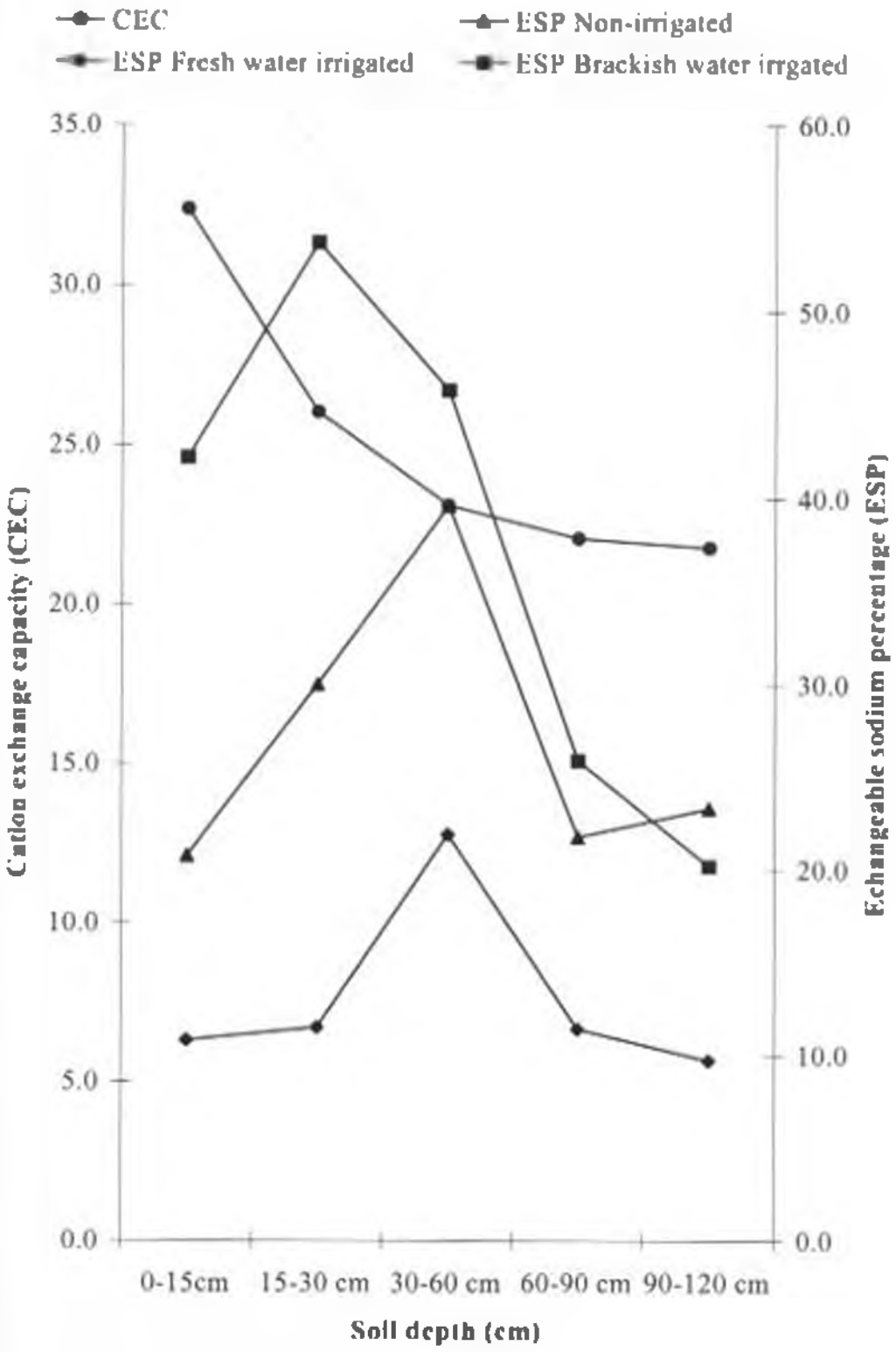


Fig.4 Variation of soil ESP and average CEC with depth at the end of the experiment.

Table 8. Means of soil EC, ESP and SAR according to depth at the end of the experiment.

Treatment	Depth I (0-15 cm)			Depth II (15-30 cm)			Depth III (30-60 cm)			Depth IV (60-90 cm)			Depth V (90-120 cm)		
	EC dsm^{-1}	ESP	SAR	EC dsm^{-1}	ESP	SAR	EC dsm^{-1}	ESP	SAR	EC dsm^{-1}	ESP	SAR	EC dsm^{-1}	ESP	SAR
Non-irrigated	0.22a	12.10a	1.13ab	0.19a	17.50a	1.50a	0.18a	23.10a	1.56a	0.16ab	12.70a	1.13a	0.23a	13.60a	1.13a
Fresh water irrigated	0.29a	10.80a	1.00a	0.18a	11.50a	1.07a	0.17a	21.90a	1.74a	0.12a	11.40a	0.85a	0.15a	9.70a	0.73a
Brackish water irrigated	0.24a	42.20b	4.23b	0.25a	53.70b	4.48b	0.24a	45.60b	4.37a	0.30b	25.90a	2.54a	0.17a	20.20a	1.92a
Grand mean	0.25	21.7	2.06	0.21	27.6	2.35	0.2	30.2	2.56	0.19	16.7	1.51	0.18	14.5	1.26
LSD (0.05)		20.47	3.16		20.47	3.16		20.47		0.14					

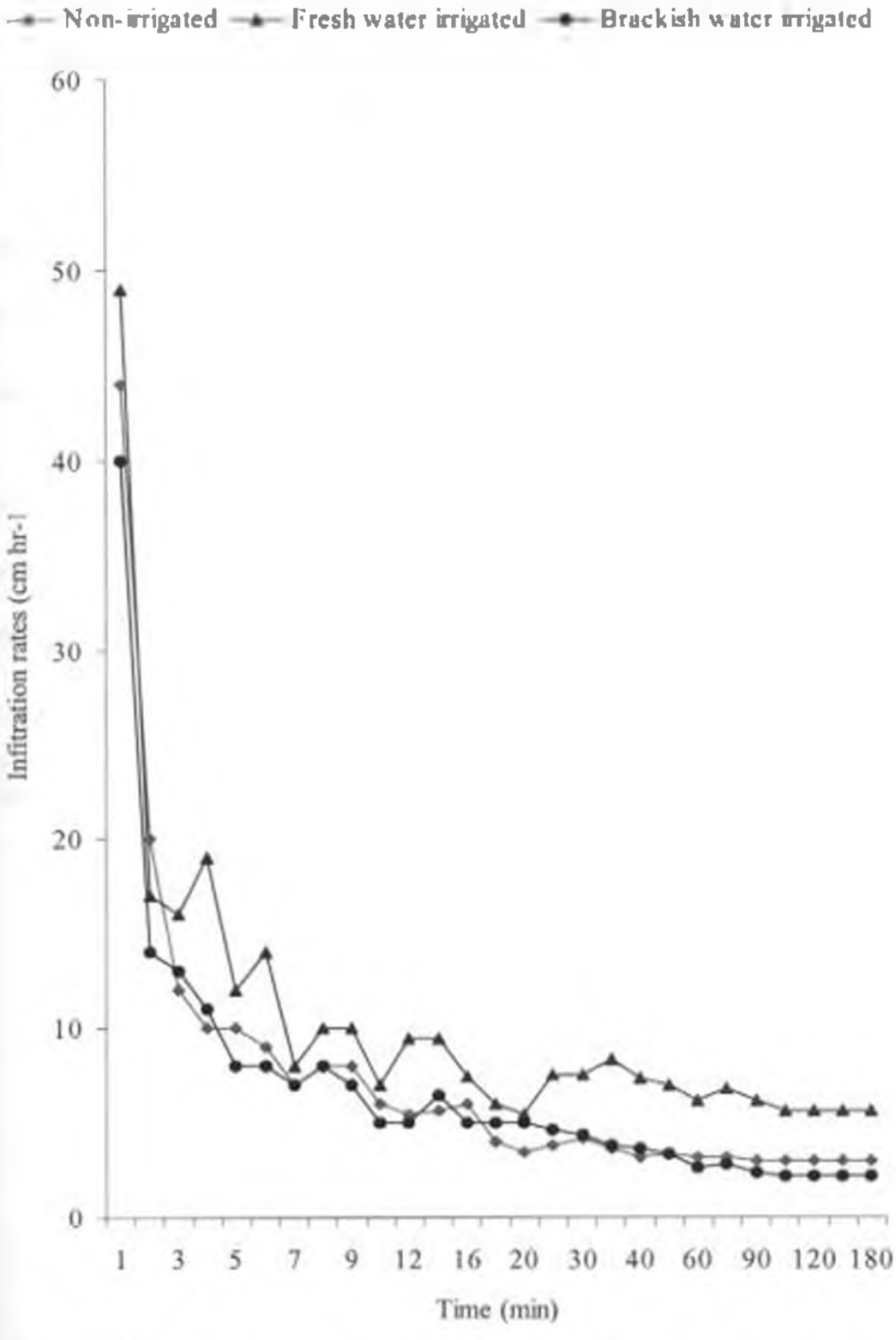


Fig. 5 Rates of water infiltration into the soil at the end of the irrigation experiment

Table 9. Means of average and final water infiltration rates into the soil at the end of the experiment

Treatment	Average infiltration rates (cm/hr)	Final infiltration rates (cm/hr)
Non-irrigated	3.68a	3.00a
Fresh water irrigated	6.73b	5.60b
Brackish water irrigated	3.30a	2.20a
Grand mean	4.57	3.60
LSD(0.05)	2.77	1.76

Table 10. Means of concentrations of ions in the phyllodes at the end of the experiment.

Treatment	Na (g kg^{-1})	K (g kg^{-1})	Ca (g kg^{-1})	Mg (g kg^{-1})	Cl (g kg^{-1})
Non-irrigated	0.06a	0.26a	5.17a	1.43a	0.00a
Fresh water irrigated	0.12a	0.43a	4.17a	0.90a	0.01a
Brackish water irrigated	0.05a	0.33a	4.17a	1.07a	0.00a
Grand mean	0.08	0.34	4.50	1.13	0.00

CHAPTER FIVE

DISCUSSION

The brackish water had higher levels of all ions measured except Ca^{2+} compared to the fresh water (Table 3 Page 24). However the level of all ions measured except Mg^{2+} in the water extracted soil samples did not significantly differ among the treatments (Table 6 Page 35). The salts in irrigation water interact with those (salts) in the soil finally attaining equilibrium. This is particularly so under natural field conditions in which the soil over a large area behaves as a continuous unit. Besides ion exchange between the incoming irrigation waters and the soil solution-soil exchange site, other processes including precipitation and solubilisation (Mott, 1988) do occur. The insignificant difference in the soil ionic levels among the treatments could be attributed to such irrigation water - soil solution interactions.

The soil Na^+ though not significantly different among treatments, was relatively higher in the plots irrigated with brackish water. Furthermore, chemical effects of irrigation water salts on soils are accumulative in nature. Therefore, the fact that plots irrigated with brackish water had higher albeit insignificant levels of soil Na^+ indicated a possibility of long term accumulation. The relatively higher levels of soil Na^+ would limit the use of the brackish water in irrigating most tree crops and woody ornamentals which, are generally sensitive to Na^+ (Ayers, 1985).

Soil ESP from plots irrigated with brackish water was significantly higher than that of fresh water irrigated plots (Table 6 Page 35) as well as non-irrigated plots in the top 60cm of soil

(Table 8 Page 38). The soil ESP of non-irrigated plots (though not significantly different from) was higher than that of fresh water irrigated plots (Fig .4 Page 37).

The high levels of Na^+ in the brackish compared to fresh water (Table 3 Page 24) possibly displaced other cations from the soil exchange site-solution complex (Shainberg *et al.*, 1975). This could have caused the high soil ESP in the plots irrigated with brackish water. This is consistent with the results of Costa *et al.* (1991) who reported increased proportion of soil Na^+ with increasing sodicity of irrigation water. In addition, the fresh water had higher Ca^{2+} compared to the brackish water. Adsorption of the Ca^{2+} from the fresh water could have resulted into further lowering of the exchangeable Na^+ ions in the plots irrigated with fresh water relative to the other treatments.

Besides soil organic matter (which is usually low in the ASAL), the other main contributor to the soil CEC is clay fraction. Clay was basically restricted to the top 60 cm of the soil (Fig. 1 Page 19). This high proportion of clay and hence CEC (Table 7 Page 36) at these soil depths was favourable for the exchange of Na^+ between the brackish water of irrigation and the soil exchange site. This could have resulted in the observed significantly higher ESP in the plots irrigated with brackish water compared to the non-irrigated plots at these depths.

The lower (though not significant) soil ESP of fresh water irrigated plots compared to non-irrigated plots is attributed to the leaching effects of fresh water and solubilisation of precipitated Ca^{2+}. The soils at the experimental sites were calcareous and had precipitated Ca-salts. The precipitated Ca^{2+} showed up in a soil analysis undertaken without first washing off excess soil salts, in which, levels of Ca^{2+} higher than the CEC were noted

(Appendix 3 Page 69). Alperovitch *et al.* (1986) also reported a sum of extractable cations higher than CEC. Waters with low electrolyte concentrations have been shown to solubilise non-exchangeable Ca^{2+} in calcareous soils (Shainberg *et al.*, 1981; Carter *et al.*, 1986). The fresh water with low salt concentration could have solubilised some of the precipitated Ca^{2+} bringing it into the soil solution. The solubilised Ca^{2+} then exchanged with cations at the soil exchange site thus lowering the soil ESP in the plots irrigated with fresh water compared to those subjected to the other treatments.

Soil permeability to water is key to the success of any irrigation system including runoff water harvesting. The plots irrigated with fresh water had significantly higher average and final rates of water infiltration into the soil compared to those plots subjected to the other two treatments (Fig. 5 Page 39 and Table 9 Page 40). Permeability of soils to water is positively correlated to the soil mean pore radius. Under sodic conditions the main limitations to soil hydraulic conductivity results from clay swelling and dispersion which reduces the soil mean pore radius.

ESP reflects potential for degradation of soils structure and hence reduction in soil permeability to water. The soil ESP of the brackish water irrigated and non-irrigated plots were significantly higher than that of fresh water irrigated (Table 6 Page 35). For soils having 2:1 clay (smectite vermiculite, and illite) as at the experimental site (Ute, 1996), high levels of exchangeable Na^{+} (ESP) relative to the divalent cations lead to clay swelling (McNeal 1968; McNeal *et al.*, 1966) and dispersion (Yousaf *et al.*, 1987; Ali *et al.*, 1987),. The high soil ESP of plots irrigated with brackish water relative to those irrigated with fresh water could have resulted in swelling and dispersion and hence reduction in the proportion of soil macro-pores. This would have led to the observed

lower rates of water infiltration into the brackish water irrigated plots compared to the fresh water irrigated ones. Moreover, plots irrigated with brackish water had significantly higher Mg^{2+} than those irrigated with fresh water. This higher level of soil Mg^{2+} may have further contributed to the lower water infiltration rates in the plots irrigated with brackish water. Yousaf *et al.* (1987) reported enhanced clay dispersion and thus reduced soil hydraulic conductivity for equal soil ESP's when Mg^{2+} was the complementary ion in soil compared to Ca^{2+}.

The non-irrigated plots had significantly lower rates of water infiltration into the soil compared to those irrigated with fresh water (Table 9 Page 40) even though their soil ESP values did not differ significantly (Table 6 Page 35). The soil ESP of the non-irrigated was however higher than that of fresh water irrigated plots (Fig. 4 Page 37) and above 15% (Table 6 Page 35) cut of value into sodic soils (US Salinity laboratory staff, 1954). Soils with ESP of 15% and above (Table 2 Page 15) are regarded to be prone to degradation of structure and thus reduction in permeability to water. Non-irrigated plots unlike fresh water irrigated ones, therefore possibly had clay swelling and dispersion leading to lower rates of water infiltration.

High electrolyte concentration in soil solutions ameliorates the effects of high ESP on the degradation of soil structure by preventing clay dispersion and swelling (Shainberg *et al.*, 1981, Alperovitch *et al.*, 1986; McNeal *et al.*, 1966). Shainberg *et al.* (1981) concluded that sodic soils containing minerals such as precipitated Ca-salt that readily release soluble electrolytes would not easily disperse when leached with low electrolyte solution. The leaching solution through solubilisation of the soil salts leading to release of soluble electrolytes ensures maintenance of high enough salt concentration to prevent clay

dispersion. The fresh water of irrigation had low salt concentration (Table 3 Page 24). The soils at the experimental site being calcareous could have easily been solubilised by the fresh water to yield high salt concentration in the soil solution. This could then reduce clay swelling and dispersion. The solubilisation of the calcareous soils at the experimental site was prone to yield Ca^{2+}. Kamphorst (1990) reported that adding a solution of Ca-salts to sodic soils resulted in stabilisation of aggregates and improved their water transmissions. The combination of high concentration of soil solution, stabilising effects of released Ca^{2+} resulting from solubilisation of the calcareous soils and low soil ESP led to the higher rates of water infiltration into the plots irrigated with fresh water compared to those subjected to the other treatments.

Phyllodes of *Acacia saligna* were analysed for the main ions (K^+, Na^+, Ca^{2+}, Mg^{2+} and Cl^-) observed in the soil solution. Even though brackish water irrigated plots had significantly higher soil Mg^{2+} and ESP (Table 6 Page 35), the levels of the ions measured from the phyllodes did not differ significantly among the treatments (Table 10 Page 41). This is contrary to the results of, Shaybany and Kashirad (1978) who reported increased Na^+ and Cl^- and decreased Ca^{2+}, Mg^{2+} and K^+ levels in the phyllodes of *Acacia saligna* following irrigation with salty water of 5.5 dsm^{-1}.

Salts from irrigation waters interact with those inherent in the soil before equilibrium is finally attained. Such interactions entail ion exchange, precipitation, and solubilisation of salts. The ionic composition of the resultant soil solution following irrigation water - soil solution interaction is thus not only dependent on the salt from irrigation water but also those on the soil solution - soil exchange site complex. Plants take up ions from the soil solution and then translocate them to the shoots. Furthermore, plants are known to

selectively take up and translocate ions to their shoots (Gregory, 1988). Shaybany and Kashirad (1978) used pure sodium chloride (NaCl) as the source of salts in a sand culture. The use of pure NaCl was prone to have an overwhelmingly high proportion of Na^+ and Cl^- ions in the medium. Furthermore the use of sand culture which generally has very limited CEC restricted the possible interaction of the various ions present in irrigation water and soil solution-exchange site complex as do occur under natural field conditions. In addition, Shaybany and Kashirad (1978) used relatively younger trees (two months old) compared to one and a half years-old trees to which irrigation treatments were applied in this study. The age difference could have affected the uptake and selectivity of ions by *Acacia saligna* trees. The combination of pure NaCl and sandy medium limited any possible interaction between salts in irrigation water and those in the soil solution as usually occur under natural field conditions.

The salt concentration in the brackish water used in our experiment was at 3.15 dsm^{-1}. This was lower than 5.5 dsm^{-1} (Shaybany and Kashirad 1978) and 8 dsm^{-1} (Miyamoto *et al.*, 1996) observed to produce significantly higher levels of Na^+ and Cl^- in phyllodes of *Acacia saligna* and leaves of four halophytes respectively. Morris *et al* (1994) reporting on fieldwork which, covered ten-years, noted that *Acacia saligna* satisfactorily tolerated salinity of up to 20 dsm^{-1} in the root zone. Furthermore, all experimental trees received natural precipitation and harvested runoff. The percolating harvested runoff water could have leached down some of the soil salts. This would have further lowered the resultant level of salts in the soil.

It is therefore arguable that the salt level in the brackish water used in the present experiment was not high enough to cause an enhanced uptake and accumulation of Na^+ and Cl^- in the

phyllodes of *Acacia saligna*. This relatively low salinity was further ameliorated by the interaction between salts in irrigation water and those in the soil under the natural field soil conditions and occasional leaching down by harvested runoff water.

Acacia saligna almost completely excluded Cl^- from its phyllodes (Table 10 Page 41). Mass (1993) and Hoffman *et al.* (1989) suggested that Cl^- was the most injurious ion to the leaves of trees. *Acacia saligna* by limiting the levels of Cl^- in its phyllodes to nearly zero was therefore expected to register minimal effects of salinity especially with regard to specific ion toxicity.

Monthly tree growth and biomass accumulation did not differ among the treatments throughout the experiment (Table 5 Page 32 and Fig. 3 Page 33). The trees not subjected to supplementary irrigation registered growth and biomass accumulation comparable to those irrigated during the dry spells.

All the treatments received natural precipitation and harvested runoff water. Under runoff farming, water is trapped and let to percolate into the fields becoming stored in the soil (Lovenstein *et al.*, 1991; Evenari *et al.*, 1982). The water stored in the soil is depleted by evapotranspiration during subsequent dry spells. The depletion of soil water progresses down the soil profile restricting the access of the water to deeply rooted plants. Deeply rooted plants can therefore maintain a good supply of soil moisture throughout the year provided precipitation and/or harvested runoff recharges the stored soil water before it begins to limit plant growth.

Acacia saligna has been reported to perform well under runoff irrigation. Sauerhaft (1997) reported biomass yield of up to 9.8 tonnes ha^{-1} $year^{-1}$ of lopped material under a

runoff system in the Negev desert, Israel. The region has a long term single season annual rainfall averaging only 115 mm and a precipitation to potential evapotranspiration (P/ETP) ratio of less than 0.03 (Evenari *et al.*, 1982). This region is prone to a faster depletion of stored soil water compared to our experimental site with a bimodal rainfall pattern averaging 220-300 annually and P/ETP above 0.07 (FAO, 1993).

Acacia saligna develops an elaborate and deep root system (Berliner *et al.*, 1998; Witkowski, 1991; El-Lakany and Mohamed, 1993). In a study involving four desert species, El-Lakany and Mohamed, (1993) reported the greatest root size and extension from *Acacia saligna*. Witkowski (1991) explained out-competing of *Protea repens* (L.) L. by *Acacia saligna* on the latter's ability to allocate a greater proportion of its total dry mass to root growth. At the present site, *Acacia saligna* has been observed to send its roots as deep as three metres below the ground.

Such an elaborate and deep root system coupled with runoff harvesting would ensure that even the non-irrigated trees would have obtained sufficient soil moisture and maintained growth during the dry spells. Acquisition of soil moisture by *Acacia saligna* would have been further augmented by the bimodal rainfall pattern which enables recharge, from rainfall and harvested runoff, of the stored soil water before it is depleted to growth limiting levels. It is therefore possible that availability of soil moisture was not the most limiting factor to growth and biomass accumulation of *Acacia saligna* during the experiment.

Trees irrigated with brackish water consistently had higher even though insignificant monthly growth and biomass accumulation compared to the other two treatments (Table

5 Page 32 and Fig. 3 Page 33). Berliner *et al.*, (1998) reported significantly higher accumulated biomass for brackish water irrigated *Acacia saligna* trees compared to those subjected to fresh water and runoff irrigation. This was attributed to the adaptation of *Acacia saligna* to saline conditions. Greenway (1968) reported increased leaf area per plant and stimulation of overall growth of *Atriplex nurmmularia* an halophyte.

Tree growth and biomass accumulation dropped sharply in February 1998 and continued to drop thereafter though gradually (Fig.3 Page 33). This was observed despite the irrigations undertaken in the irrigated treatments.

The plant water status is governed by two main factors namely soil moisture level and atmospheric vapour pressure deficit (VPD) (Batten *et al.*, 1994, Ferreira and Katerji, 1992). Whereas the soil water potential (ψ_{soil}) sets the limit to the plant water potential (ψ_{pl}), the VPD determines the level of transpirational water loss. Plants therefore respond to both the levels of soil moisture and the atmospheric VPD. Dry air above the shoots of plants have been shown to cause the closure of stomata in an attempt to reduce water loss (Hsiao, 1973) and to reduce photosynthetic rates both directly and through loss of cell turgor (Schulze, 1986). Mansfield and Davies (1981) considered rapid closure of stomata in response to a decrease in atmospheric humidity as 'a first line of defence' protecting the leaf from tissue desiccation even before low leaf water potentials have occurred. Such regulation of stomatal aperture though important in maintaining a favourable plant water status, do reduce photosynthesis and hence growth. Trees like all plants are dependent on photosynthesis for the supply of food needed for growth. Mooney (1980) reported a near negligible dry matter production during a hot season for the evergreen perennial *Atriplex*

hymenelytra. This was despite the adaptation of the photosynthetic apparatus to high temperatures.

The reduction in growth and biomass accumulation having occurred even in the trees subjected to irrigation at 0.4m of water a month is thus not necessarily caused by low soil moisture. The period after November 1997 had relatively higher average temperatures (Fig. 2 Page 20) with peaks of about 33^{0}C in February and March. High temperatures cause steeper vapour pressure gradients between the plants and the atmosphere (Kozlowski *et al.*, 1991). Even though, the temperatures were already high in December and January, the relatively moist soils ensured that absorption of water could still keep pace with the evaporative demand of the atmosphere. The moist soils could have also provided evaporational water and this enabled the maintenance of relatively high humidity and hence low VPD. As evaporation continued through the months, water available for evaporation decreased and VPD increased. VPD increases with increasing temperatures. At our experimental site, daily average temperatures between 28^{0}C and 30^{0}C have been shown to result in VPD values of 0.5 kPa and above and this in turn caused declines in the stomatal conductance (gs) (Okumu, 1998). Okumu (1998) in particular reported that VPD values above 0.6 kPa resulted in gs values below 0.1 cms ^{1}.

Besides the reduction in stomatal conductance, photosynthetic rate has been shown to respond directly to air humidity and hence VPD. In a review of the effects of atmospheric drought on plants, Schulze (1986) reported that the rate of photosynthesis at CO_2 saturation decreased at low air humidity. In addition, there is an after-effect of dry air that continues to depress the rate of photosynthesis. The present experimental site registers sharp drops in atmospheric VPD as early as 10.00 hrs and the values remain at low levels

throughout the day up to 17.00hrs on hot days (Okumu, 1998). Thus prolonged daily atmospheric drought and its after-effects would therefore limit plant photosynthesis to near negligible levels for a greater part of the day even under favourable soil water status.

The decreasing growth and biomass accumulation rates after February 1998 are therefore attributed to high temperature mediated increments in VPD and not necessarily soil moisture. Whereas the adaptability of *Acacia saligna* to drylands has been well documented for the Mediterranean climates (Tiedman and Johnson, 1992; Degen *et al.*, 1995) the mechanism of this adaptability has not been extensively investigated. Furthermore, the performance of *Acacia saligna* in the tropics with all-year-round high evaporative demand has not been evaluated. *Acacia saligna* is thus suggested to have responded to the high VPD conditions at our experimental site through low photosynthesis. This resulted in limited photosynthates and hence the observed lower monthly growth and biomass accumulation after January 1998 regardless of moisture supplied via irrigation

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 CONCLUSION

The soils at the experimental site already have low permeability to water. This low permeability to water was further reduced by irrigation with brackish water. Irrigation using brackish water significantly increased the soil exchangeable sodium percentage (ESP). The increased soil ESP could have caused swelling and dispersion of clay particles leading to reduced mean pore radius and permeability of the soil to water. Irrigation with fresh water lowered soil ESP level possibly through leaching and significantly improved infiltration of water into the soil.

The low permeability to water of the site presents a problem with irrigation including runoff water harvesting. The low permeability is particularly important at the site where atmospheric evaporative demand and hence evaporational water loses is high. This low permeability is thus a bottleneck to the practice of runoff farming where the water is trapped on the fields and left to percolate into the soil with time. The ability of irrigation with fresh water to improve water infiltration rate points to a possibility of enhancing soil permeability of the site to water by leaching using relatively fresh water.

Both the trees relying only on runoff water and those subjected to supplemental irrigation did not differ in their growth and biomass accumulation. An elaborate root system ensured that non-irrigated *Acacia saligna* trees continued to access soil moisture from deeper soil layers during the dry spells. With the bimodal rainfall pattern ensuring

relatively frequent recharge of soil water, runoff harvesting seemed sufficient to grow *Acacia saligna* at the present site without supplemental irrigation.

Acacia saligna tolerated the resultant soil salinity following irrigation with brackish water. In addition, the tree nearly totally excluded Cl^- from its phyllodes. The brackish water of 3.15 dsm^{-1} can therefore be used in supplemental irrigation of *Acacia saligna* at the present site.

Tree growth and biomass accumulation declined in response to high ambient temperature and atmospheric VPD. It is therefore arguable that under the present tropical conditions with high evaporative demand, growth and biomass accumulation of *Acacia saligna* was largely limited by atmospheric drought rather than actual soil water status.

6.2 RECOMMENDATIONS:

The effect of supplemental irrigation during dry spells should be monitored for a long enough period. This will help establish whether it lacks the presupposed advantage on the growth and biomass accumulation of *Acacia saligna*. Physiological parameters including water potentials and photosynthesis of the tree, VPD and changes in soil water status should be monitored concurrently to ascertain the importance of atmospheric drought relative to soil moisture level on the growth and biomass accumulation of *Acacia saligna*.

Effect of runoff water harvesting on soil ESP and hydraulic conductivity for a prolonged period should be studied. Runoff water would be important in providing the much needed soil moisture while at the same time leaching salts and particularly exchangeable sodium

out of the root zone thus lowering soil sodicity and improving the permeability of the soil to water.

The levels of various ions should be monitored along the soil-root-shoot continuum. This would explain the cause of the observed low levels of the ions and in particular Cl^- in the phyllodes. *Acacia saligna* could have excluded Cl^- in the soil solution or taken it up and restricted its translocation to the shoots or both.

CHAPTER SEVEN

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Appendix 1 Quality of the water types used for irrigation

Parameter	pH	ECw dsm^{-1} 25^0C	Na $meqL^{-1}$	K $meqL^{-1}$	Ca $meqL^{-1}$	Mg $meqL^{-1}$	HCO_3 $meqL^{-1}$	Cl $meqL^{-1}$	SO_4 $meqL^{-1}$	∑Cations $meqL^{-1}$	∑anions $meqL^{-1}$	RSC	SAR
Brackish water	7.30	3.15	18.7	1.53	0.23	0.86	11.8	18.65	3.62	21.32	34.07	10.71	25.33
Fresh water	6.50	0.30	1.13	0.92	0.42	0.42	3.40	0.50	0.24	2.89	4.14	2.56	1.74

Appendix 1. continued.

Parameter	$SAR_{adj.}$	Cu (ppm)	Fe (ppm)	Zn (ppm)	Mn (ppm)	ψ, kPa	PI	OH $meqL^{-1}$	CO_3 $meqL^{-1}$
Brackish water	44.33	trace	trace	trace	trace	-113	27.91	trace	trace
Fresh water	4.53	trace	trace	trace	trace	-10.8	108.04	trace	trace

Appendix 2 Monthly growth and biomass accumulation of *Acacia saligna* trees.

Monthly increments in tree biomass, stem circumference and diameter												
Treatment	**July '97**			**August '97**			**September '97**			**October '97**		
	Circ. (cm)	Diam. (cm)	Biomass (kg/tree)	Circ. (cm)	Diam. (cm)	Biomass (kg/tree)	Circ. (cm)	Diam. (cm)	Biomass (kg/tree)	Circ. (cm)	Diam. (cm)	Biomass (kg/tree)
Non-irrigated plots	0.500	0.160	0.300	1.200	0.380	0.740	1.10	0.35	0.730	1.200	0.383	0.840
Brackish water irrigated Plots	0.800	0.256	0.490	1.400	0.447	0.900	1.400	0.443	0.980	1.500	0.48	1.120
Fresh water irrigated plots	0.600	0.193	0.320	1.300	0.41	0.730	1.200	0.383	0.730	1.400	0.447	0.910

Appendix 2 continued

Monthly increments in tree biomass, stem circumference and diameter												
Treatment	**November '97**			**December '97**			**January '98**			**February '98**		
	Circ. (cm)	Diam. (cm)	Biomass (kg/tree)	Circ. (cm)	Diam. (cm)	Biomass (kg/tree)	Circ. (cm)	Diam. (cm)	Biomass (kg/tree)	Circ. (cm)	Diam. (cm)	Biomass (kg/tree)
Non-irrigated plots	1.500	0.462	1.120	1.600	0.493	1.280	1.500	0.468	1.280	0.600	0.197	0.590
Brackish water irrigated plots	1.600	0.500	1.270	1.800	0.567	1.770	1.900	0.614	1.770	0.800	0.258	0.770
Fresh water irrigated plots	1.400	0.446	0.980	1.600	0.407	1.370	1.700	0.532	1.370	0.700	0.207	0.600

Appendix 2 continued.

Monthly increments in tree biomass, stem circumference and diameter						
Treatment	**March '98**			**April '98**		
	Circ. (cm)	Diam. (cm)	Biomass (kg/tree)	Circ.(cm)	Diam.(cm)	Biomass (kg/tree)
Non-Irrigated plots	0.300	0.111	0.400	0.100	0.021	0.090
Brackish water irrigated plots	0.600	0.175	0.590	0.400	0.117	0.400
Fresh water irrigated plots	0.500	0.165	0.430	0.200	0.058	0.180

Appendix 3 Soil ionic concentration according to depth at the end of the experiment.

Soil Depth	pH (H_2O)	pH ($CaCl_2$)	Na $cmolkg^{-1}$	K $cmolkg^{-1}$	Ca $cmolkg^{-1}$	Mg $cmolkg^{-1}$	CEC $cmolkg^{-1}$	EC dsm^{-1}	HCO_3 $meqL^{-1}$	Cl $meqL^{-1}$	Ca^{*1} $cmolkg^{-1}$
0-15cm	8.4	7.7	7.16	10.06	15.67	8.01	32.37	0.25	0.81	0.99	39.3
15-30cm	8.5	7.9	7.28	5.61	13.76	5.13	26.04	0.21	0.65	1.04	32.05
30-60cm	8.6	8.0	8.00	5.00c	12.24	4.69	23.11	0.20	0.68	1.04	26.86
60-90cm	8.6	8.1	4.64	4.00	12.31	4.90	22.09	0.19	0.71	1.04	21.68
90-120cm	8.9	8.4	3.66	3.22	11.33	5.42	21.81	0.18	0.75	1.11	20.59

*1 Ca levels determined without first washing off excess salts

Appendix 4 Average rates of water infiltration into the soil (cm/hr) at the end of the experiment

Time(min)	Non-irrigated	Fresh water irrigated	Brackish water irrigated
1	44.00	49.00	40.00
2	20.00	17.00	14.00
3	12.00	16.00	13.00
4	10.00	19.00	11.00
5	10.00	12.00	8.00
6	9.00	14.00	8.00
7	7.00	8.00	7.00
8	8.00	10.00	8.00
9	8.00	10.00	7.00
10	6.00	7.00	5.00
12	5.50	9.50	5.00
14	5.60	9.50	6.50
16	6.00	7.50	5.00
18	4.00	6.00	5.00
20	3.50	5.50	5.00
25	3.80	7.60	4.60
30	4.20	7.60	4.40
35	3.60	8.40	3.80
40	3.20	7.40	3.60
45	3.40	7.00	3.40
60	3.20	6.20	2.60
75	3.20	6.80	2.80
90	3.00	6.20	2.40
105	3.00	5.60	2.20
120	3.00	5.60	2.20
150	3.00	5.60	2.20
180	3.00	5.60	2.20

Appendix 5 Results of the Analysis of Variance for measured parameters

Soil pH(w)

Source of variation	d.f.	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	1.395	0.698	7.200	
Block Treat Stratum					
Treat.	2.00	0.556	0.278	2.870	6.940
Residual	4.00	0.388	0.097		
Block.Treat Depth Stratum					
Depth	4.00	1.579	0.395	4.990*	2 780
Treat Depth	8.00	0 904	0 113	1.430	2.36
Residual	24.00	1 897	0 079		
Total	44 00	6.719			
MEANS					
Grand mean	8.604				
Treatments	BWIP	FWIP	NIP		
	8.76	8.507	8.547		
Depth	DI	DII	DIII	DIV	DV
	8.356	8 544	8.567	8.622	8.933
Treatments Depths					
BWIP	8 667	8.833	8 733	8.633	8.933
FWIP	8 167	8 267	8.567	8.433	9.100
NIP	8.233	8.533	8.400	8.800	8.767
		Depths			
l.s.d.(0.05)		0.274			

Soil pH($CaCl_2$)

Source of variation	d.f.	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	1.832	0.916	7.840	
Block Treat Stratum					
Treat	2 00	0.576	0 288	2.470	6.940
Residual	4.00	0.468	0.117		
Block Treat.Depth Stratum					
Depth	4.00	2.13	0.533	5.020*	2.780
Treat.Depth	8.00	0.679	0 085	0.800	2 360
Residual	24.00	2.547	0.106		
Total	44.00	8.232			
MEANS					
Grand mean	8 049				
Treatments	BWIP	FWIP	NIP		
	8.207	7.947	7.993		
Depth	DI	DII	DIII	DIV	DV
	7.744	7.933	8.033	8.133	8 400
Treatments Depths					
BWIP	8.067	8 167	8.233	8.133	8.433
FWIP	7.567	7.700	8.000	7.967	8 500
NIP	7 600	7.933	7.867	8.300	8 267
		Depths			
l s d.(0.05)		0.317			

Soil EC

Source of variation	d.f.	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	0.024	0 012	0 820	
Block Treat. Stratum					
Treat.	2.00	0 029	0.014	1.000	6 940
Residual	4.00	0.057	0.014		
Block.Treat.Depth Stratum					
Depth	4.00	0.24	0.006	1.360	2.780
Treat Depth	8 00	0.061	0.007	2.680*	2.360
Residual	24.00	0.109	0 004		
Total	44 00	0 305			
MEANS					
Grand mean	0 205				
Treatments	BWIP	FWIP	NIP		
	0.239	0.180	0.195		
Depth	DI	DII	DIII	DIV	DV
	0.249	0.206	0.196	0.192	0.181
Treatments Depths					
BWIP	0.240	0.247	0.243	0 300	0.167
FWIP	0.287	0.180	0.167	0.117	0.150
NIP	0.220	0 190	0.177	0.160	0.227
Lsd			Treat Depth		
			0.139		

Soil CEC

Source of variation	d.f.	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum		41.420	20.710	0 230	
Block. Treat. Stratum					
Treat.	2.00	36.220	18.110	0.210	6.940
Residual	4 00	353.270	88.320	4.080	
Block.Treat Depth Stratum					
Depth	4 00	698.140	174.530	8.070*	2.780
Treat Depth	8 00	132.850	16 610	0.770	2 360
Residual	24 00	497 460	21 630		
Total	44.00	1756.170			
MEANS					
Grand mean	25.080				
Treatments	BWIP	FWIP	NIP		
	26.000	25.380	23.87		
Depth	DI	DII	DIII	DIV	DV
	32.370	26 040	23.110	22 090	21 810
Treatments Depths					
BWIP	32.000	25.330	27 670	23.930	21.080
FWIP	34.430	26 470	23.000	21.670	21.330
NIP	30.670	26.330	18.670	20.670	23.000
		Depths			
l s d (0 05)		4.535			

Soil Na

Source of variation	d.f.	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	119.319	59.660	0.510	
Block. Treat. Stratum					
Treat	2.00	619.313	309.697	2.660	6.940
Residual	4.00	465.181	116.295	31.800	
Block.Treat.Depth Stratum					
Depth	4.00	128.128	32.032	8.760*	2.780
Treat.Depth	8.00	93.515	11.689	3.200*	2.360
Residual	24.00	80.447	3.657		
Total	44.00	1382.820			
MEANS					
Grand mean	6.150				
Treatments	BWIP	FWIP	NIP		
	11.380	3.220	3.830		
Depth	DI	DII	DIII	DIV	DV
	7.160	7.280	8.000	4.640	3.660
Treatments Depths					
BWIP	14.200	14.170	14.500	8.240	5.800
FWIP	3.620	3.000	5.000	2.500	2.000
NIP	3.670	4.670	4.500	3.170	3.170
		Depths	Treatments Depths		
L.s.d.(0.05)		1.869	10.705		

Soil K

Source of variation	d.f.	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	23.011	11.506	1.770	
Block. Treat. Stratum					
Treat	2.00	4.078	2.039	0.310	6.940
Residual	4.00	25.989	6.497		
Block.Treat.Depth Stratum					
Depth	4.00	255.811	63.953	13.250*	2.780
Treat.Depth	8.00	31.256	3.907	0.810	2.360
Residual	24.00	115.833	4.826		
Total	44.00	455.978			
MEANS					
Grand mean	5.580				
Treatments	BWIP	FWIP	NIP		
	5.530	5.230	5.970		
Depth	DI	DII	DIII	DIV	DV
	10.060	5.610	5.000	4.000	3.220
Treatments Depths					
BWIP	9.330	4.000	5.170	5.330	3.830
FWIP	9.670	5.830	5.330	3.330	2.000
NIP	11.170	7.000	4.500	3.330	3.830
		Depths			
l.s.d (0.05)		2.137			

Soil Ca

Source of variation	d.f.	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	3.103	1.551	0.220	
Block Treat. Stratum					
Treat	2.00	14.394	7.197	1.010	6.940
Residual	4.00	28.574	7.143	2.200	
Block.Treat.Depth Stratum					
Depth	4.00	103.327	25.832	7.970*	2.780
Treat.Depth	8.00	24.317	3.040	0.940	2.360
Residual	24.00	77.778	3.241		
Total	44.00	251.493			

MEANS

Grand mean	13.060				
Treatments	BWIP	FWIP	NIP		
	13.400	13.530	12.270		
Depth	DI	DII	DIII	DIV	DV
	15.670	13.760	12.240	12.310	11.330
Treatments Depths					
BWIP	14.970	13.970	12.100	13.280	12.670
FWIP	17.400	13.530	12.870	11.830	12.000
NIP	14.630	13.770	11.770	11.830	9.330
		Depths			
l.s.d.(0.05)		1.751			

Soil Mg

Source of variation	d.f.	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	1.396	0.698	0.300	
Block. Treat. Stratum					
Treat.	2.00	28.026	14.013	7.030*	6.940
Residual	4.00	9.298	2.325	0.420	
Block.Treat.Depth Stratum					
Depth	4.00	66.393	16.598	3.030*	2.780
Treat.Depth	8.00	24.779	3.097	0.570	2.360
Residual	24.00	131.292	5.470		
Total	44.00	261.184			

MEANS

Grand mean	5.630				
Treatments	BWIP	FWIP	NIP		
	6.730	4.930	5.230		
Depth	DI	DII	DIII	DIV	DV
	8.010	5.130	4.690	4.900	5.420
Treatments Depths					
BWIP	9.800	6.130	5.700	5.570	6.470
FWIP	7.970	3.400	4.030	5.300	3.930
NIP	6.270	5.870	4.330	3.830	5.870
	Treatments	Depths			
l.s.d.(0.05)	1.546	2.276			

Soil ESP

Source of variation	d.f.	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	234.480	117.240	0.300	
Block. Treat. Stratum					
Treat.	2.00	5409.250	2704.630	7.810*	6.94
Residual	4.00	1587.600	396.900	7.190	
Block.Treat.Depth Stratum					
Depth	4.00	1651.180	412.790	7.480*	2.780
Treat.Depth	8.00	1258.030	157.250	2.850*	2.360
Residual	24.00	1213.890	55.180		
Total	44.00	1087.060			
MEANS					
Grand mean	22.100				
Treatments	BWIP	FWIP	NIP		
	37.600	13.100	15.800		
Depth	DI	DII	DIII	DIV	DV
	21.700	27.600	30.200	16.700	14.500
Treatments.Depths					
BWIP	42.200	53.700	45.800	25.900	20.200
FWIP	10.800	11.500	21.900	11.400	9.700
NIP	12.100	17.500	23.100	12.700	13.600
	Treatments	Depths	Treatments.Depths		
l.s.d.(0.05)	20.200	7.26	20.470		

Soil SAR

Source of variation	d.f.	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	9.173	4.586	0.450	
Block. Treat. Stratum					
Treat.	2.000	52.515	26.258	2.560	6.940
Residual	4.00	41.032	10.258		
Block.Treat.Depth Stratum					
Depth	4.00	10.937	2.734	8.980*	2.780
Treat.Depth	8.00	7.745	0.968	3.180*	2.360
Residual	24.00	6.697	0.304		
Total	44.00	117.398			
MEANS					
Grand mean	1.946				
Treatments	BWIP	FWIP	NIP		
	3.469	1.078	1.291		
Depth	DI	DII	DIII	DIV	DV
	2.055	2.351	2.559	1.505	1.261
Treatments.Depths					
BWIP	4.027	4.483	4.373	2.538	1.923
FWIP	1.004	1.070	1.740	0.850	0.727
NIP	1.133	1.500	1.563	1.127	1.133
		Depths	Treatments Depths		
l.s.d (0.05)		0.539	3.181		

Soil Cl

Source of variation	d.f.	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	12.478	6.239	6.950	
Block. Treat. Stratum					
Treat.	2.000	3.811	1.906	2.120	6.940
Residual	4.00	3.589	0.897	1.760	
Block.Treat Depth Stratum					
Depth	4.00	1.133	0.283	0.550	2.780
Treat.Depth	8.00	0.800	0.100	0.200	2.360
Residual	24.00	12.267	0.511		
Total	44.00	34.078			
MEANS					
Grand mean	4.180				
Treatments	BWIP	FWIP	NIP		
	4.400	3.770	4.370		
Depth	DI	DII	DIII	DIV	DV
	3.940	4.170	4.170	4.170	4.440
Treatments.Depths					
BWIP	4.330	4.500	4.500	4.170	4.500
FWIP	3.330	3.670	3.670	4.000	4.170
NIP	4.170	4.330	4.330	4.330	4.670

Soil HCO_3

Source of variation	d.f.	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	1.394	0.697	0.640	
Block. Treat. Stratum					
Treat.	2.000	2.440	1.220	1.110	6.940
Residual	4.00	4.388	1.097	1.090	
Block Treat.Depth Stratum					
Depth	4.00	2.454	0.614	0.610	2.780
Treat Depth	8.00	2.428	0.304	0.300	2.360
Residual	24.00	24.225	1.009		
Total	44.00	37.330			
MEANS					
Grand mean	2.900				
Treatments	BWIP	FWIP	NIP		
	2.940	2.600	3.170		
Depth	DI	DII	DIII	DIV	DV
	3.220	2.610	2.720	2.830	3.120
Treatments Depths					
BWIP	3.500	2.830	2.670	2.670	3.030
FWIP	3.000	2.500	2.500	2.500	2.500
NIP	3.170	2.500	3.000	3.330	3.830

Average infiltration rates (cm/hr)

Source	df	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	6 443	3.222	2 161	
Block units stratum					
Treat	2.000	21.23	10.615	7.120*	6.940
Residual	4.000	5.965	1.491		
Total	8.000	33 638			
MEANS					
Grand mean	4.570				
Treatments	BWIP	FWIP	NIP		
	3 300	6.730	3 680		
LSD	2.768				

Final Infiltration Rates (cm/hr)

Source	df	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	4.560	2.265		
Block units stratum					
Treat	2.000	18 960	9.480	15.800*	6.940
Residual	4 000	2.4	0 600		
Total	8 000	25 920			
MEANS					
Grand mean	3 600				
Treatments	BWIP	FWIP	NIP		
	2.200	5.600	3.000		
LSD	1.756				

Plant tissue K

Source	df	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	0 0006	0 0003		
Block units stratum					
Treat	2 000	0 01076	0 0054	0.3190	6 9400
Residual	4 000	0.0675	0.0169		
Total	8.000	0.0789			
MEANS					
Grand mean	0.3090				
Treatments	BWIP	FWIP	NIP		
	0.3333	0.3333	0 2600		

Increments in stem diameter July 1997

Source	df	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	0.009	0.005		
Block units stratum					
Treat	2.000	0.014	0.007	0.841	6.940
Residual	4.000	0.034	0.009		
Total	8.000	0.058			
MEANS					
Grand mean	0.203				
Treatments	BWIP	FWIP	NIP		
	0.256	0.193	0.160		

Increments in stem diameter Aug 1997

Source	df	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	0.077	0.039		
Block units stratum					
Treat	2.000	0.007	0.003	0.289	6.94
Residual	4.000	0.046	0.012		
Total	8.000	0.13			
MEANS					
Grand mean	0.203				
Treatments	BWIP	FWIP	NIP		
	0.447	0.410	0.380		

Increments in stem diameter Sept 1997

Source	df	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	0.033	0.017		
Block units stratum					
Treat	2.000	0.013	0.007	1.010	6.940
Residual	4.000	0.027	0.006		
Total	8.000	0.073			
MEANS					
Grand mean	0.392				
Treatments	BWIP	FWIP	NIP		
	0.443	0.383	0.350		

Increments in stem diameter Oct. 1997

Source	df	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	0.019	0.010		
Block units stratum					
Treat	2.000	0.014	0.007	0.696	6.940
Residual	4.000	0.042	0.010		
Total	8.000	0.075			

MEANS

Grand mean	0.392		
Treatments	BWIP	FWIP	NIP
	0.480	0.447	0.383

Increments in stem diameter Nov. 1997

Source	df	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	0.032	0.016		
Block units stratum					
Treat	2.000	0.015	0.008	0.775	6.940
Residual	4.000	0.04	0.010		
Total	8.000	0.087			

MEANS

Grand mean	0.531		
Treatments	BWIP	FWIP	NIP
	0.540	0.447	0.577

Increments in stem diameter Dec. 1997

Source	df	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	0.058	0.029		
Block units stratum					
Treat	2.000	0.033	0.016	3.922	6.940
Residual	4.000	0.029	0.007		
Total	8.000	0.120			

MEANS

Grand mean	0.536		
Treatments	BWIP	FWIP	NIP
	0.614	0.527	0.468

Increments in stem diameter Jan. 1998

Source	df	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	0.064	0.032		
Block units stratum					
Treat	2.000	0.038	0.019	2.913	6.940
Residual	4.000	0.026	0.007		
Total	8.000	0.129			

MEANS

Grand mean	0.489		
Treatments	BWIP	FWIP	NIP
	0.567	0.494	0.407

Increments in stem diameter Feb. 1998

Source	df	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	0.064	0.032		
Block units stratum					
Treat	2.000	0.006	0.003	5.206	6.940
Residual	4.000	0.003	0.001		
Total	8.000	0.072			

Means

Grand mean	0.221		
Treatments	BWIP	FWIP	NIP
	0.258	0.207	0.197

Increments in stem diameter March 1998

Source	df	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	0.041	0.020		
Block units stratum					
Treat	2.000	0.008	0.004	5.557	6.940
Residual	4.000	0.003	0.001		
Total	8.000	0.052			

MEANS

Grand mean	0.152		
Treatments	BWIP	FWIP	NIP
	0.180	0.165	0.111

Increments in stem diameter April 1998

Source	df	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	0.013	0.006		
Block units stratum					
Treat	2.000	0.014	0.007	3.890	6.940
Residual	4.000	0.007	0.002		
Total	8.000	0.034			

MEANS

Grand mean	0.065		
Treatments	BWIP	FWIP	NIP
	0.118	0.057	0.021

Plant tissue Na

Source	df	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	0.01076	0.0054		
Block units stratum					
Treat	2.000	0.0094	0.0047	4.8670	6.9400
Residual	4.000	0.0038	0.0010		
Total	8.000	0.0240			

MEANS

Grand mean	0.0780		
Treatments	BWIP	FWIP	NIP
	0.0530	0.1230	0.0570

Plant tissue Cl^-

Source	df	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	2.087	1.043		
Block units stratum					
Treat	2.000	2.000	1.000	3.5290	6.9400
Residual	4.000	1.133	0.2830		
Total	8.000	5.220			

MEANS

Grand mean	4.5000		
Treatments	BWIP	FWIP	NIP
	4.1670	4.1670	5.1670

Plant tissue Mg^{++}

Source	df	s.s.	m.s.	F_{cal}	F_{tab}
Block stratum	2.000	6.740	3.87		
Block units stratum					
Treat	2.000	8.607	4.303	0.5850	6.940
Residual	4.000	29.413	7.3530		
Total	8.000	44.760			

MEANS

Grand mean	1.933		
Treatments	BWIP	FWIP	NIP
	1.067	3.300	1.433

Plant tissue Cl

Source	df	s.s.	m.s.	F_{ob}	F_{tab}
Block stratum	2 000	0 00007	0 00003		
Block units stratum					
Treat	2 000	0.00007	0.00003	1.9980	6 940
Residual	4.000	0 00007	0.00002		
Total	8.000	0.0002			
MEANS					
Grand mean	0.0030				
Treatments	BWIP	FWIP	NIP		
	0.0067	0.0067	0.000		