THE RESPONSE OF CITRUS SEEDLINGS TO SOIL COMPACTION AND VARIATIONS IN SOIL WATER POTENTIAL IN THE UPPER RANGE OF PLANT-AVAILABLE-WATER

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Report to the Water Research Commission

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REPORT

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Compaction and Variations in Soil Water Potential
in the Upper Range of Plant-Available Water

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EXECUTIVE SUMMARY

Introduction

Irrigation technologies have changed dramatically over the past few decades. In intensive, high-value irrigated agriculture drip and micro-sprinkler irrigation systems have become popular. With these systems relatively high soil water potentials are maintained continuously (i.e. the soil is kept wet continuously) by means of high frequency water applications. Under such system there is always the danger that soils may be kept too wet. This would lead to oxygen deficiencies in the root zone and cause degeneration of trees and aggravate the incidence of root diseases. It would also waste scarce irrigation water. Excessive wetness has been observed by project team members in citrus orchards under drip or micro-sprinkler irrigation in South Africa and Swaziland, especially in marginal soils.

What is "too wet" and what soil water potential is "too high" both vary greatly between soils. It depends upon the physical characteristics of the soil, especially texture, structure and bulk density. A thorough understanding of soil-water-air-plant (SWAP) relationships in the wet range of plant-available water, therefore, becomes very important under high frequency drip or micro-sprinkler irrigation.

Objectives

The objectives of this study were to identify appropriate upper limits of plant-available water for different soil bulk density/soil water potential combinations and to identify the effects of soil compaction on citrus rootstock performance in the upper range of plant-available water. The aim was to improve irrigation management under high frequency drip or micro-sprinkler irrigation systems.

Soil Experiments

Soils were selected on the basis of (i) differences in physical characteristics, (ii) difficulties that have been experienced under irrigation on them and/or (iii) the demand for establishing citrus on such soils.

Rough lemon (RL) and Troyer citrange (TC) seedlings were grown in pots in a greenhouse in compacted and non-compacted soils at specific soil water potential levels. Soil water potentials were maintained using the "Pero" facility (an electronic system that monitors and regulates the soil water potential in pot experiments).

In the first study, consisting of two experiments, the effects of soil compaction and soil water potential on growth and development of TC (Experiment 1) and the effects of soil compaction on RL and TC rootstocks (Experiment 2) were investigated. In Experiment 1, TC performed best in the compacted soil at both soil water potentials (-6 and -30 kPa), indicating the tolerance of TC rootstocks to compacted soils. In the compacted soil, the seedlings grew better at the lower soil water potential while in the non-compacted soil those at the higher soil water potential performed better. In the second experiment, a soil water potential of -6 kPa was maintained both in compacted and non-compacted soil (Oakleaf form). The RL seedlings in compacted soil showed symptoms of stress later in the growing season. The bottom leaves became yellow and the growth rate declined. Total mass, top dry mass, root dry mass, leaf area, projected root surface area, water consumption and water use efficiency (WUE) were all significantly reduced in the compacted soil. The air-filled porosity of the compacted soil at a soil water potential of -6 kPa was 10.5%, very near to the minimum threshold value for citrus. For TC on the other hand, soil compaction resulted in better seedling growth. This was probably due to better contact between soil and roots in compacted soil early in the season.

In the second study, RL was grown in compacted and non-compacted soil of the Hutton form at three different soil water potentials (-10, -20 and -40 kPa). Both soil compaction and soil water potential affected seedling growth. Their growth patterns in the compacted soil were irregular and fluctuated throughout the growing season. A consistent growth rate was found in seedlings grown in non-compacted soil. Soil compaction had a greater negative effect on seedlings at a soil water potentials of -10 and -40 kPa than at -20 kPa. In the non-compacted soil, a reduction of the soil water potential from -10 kPa to -20 kPa resulted in a significant negative effect on all plant parameters.

There were significant differences in the status of certain nutrient elements in plants as a result of different compaction/soil water potential treatments. At high soil water potential levels (wet conditions), N and K concentrations (% or $mg.kg^{-1}$) were higher in seedlings grown in compacted soil while the Ca:Mg ratio was significantly higher in those grown in non-compacted soil. However, nutrient contents (mg per pot) were generally higher in seedlings grown in the non-compacted soil. The lower concentrations of nutrients in non-compacted soil were partly due to the larger size of these seedlings, resulting in a "dilution" of the nutrients in the plants.

During a third study, comprised of three experiments, the upper limit of plant-available soil water was identified. In the first two experiments, different soil water potentials were maintained in compacted topsoil of the Sterkspruit form. These were -5, -10, -20, -40 and -50 kPa in the first experiment. In the second experiment the number of treatments was reduced to three (-10, -20, and -30 kPa) and the replications were doubled. In a third experiment these three soil water potential levels were maintained in both compacted and non-compacted treatments of the same soil.

In the first experiment, the seedlings at -50 kPa died in the first two weeks, probably due to drought stress. The seedlings at -5 and -40 kPa died three to four weeks later, due to excessively high and very inadequate soil water availability at -5 and -40 kPa, respectively. For some unknown reasons, the seedlings at -20 kPa did not perform well compared to those at -10 and -30 kPa.

In the second experiment, the seedlings at -20 kPa had a significantly higher total mass, WUE, leaf area and projected root surface area compared to those at -10 and -30 kPa. In the third experiment, soil compaction at -10 and -30 kPa resulted in a significant reduction in total mass, water consumption, leaf area and projected root surface area, compared with non-compacted soil. At -20 kPa only water consumption and leaf area were significantly lower as a result of soil compaction. In fact, most of the plant parameters measured at -20 kPa were relatively better for seedlings in compacted soil than in non-compacted soil, but these differences were not statistically significant.

Water Culture Experiments

Another series of experiments was conducted using water culture. The purpose of these experiments was to supplement the information from soil experiments and to make it possible to alter and/or maintain certain factors, such as the aeration and pH of the rhizosphere, which would be difficult if soil was used as a growing medium.

In the first study the main aim was to identify the effects of aeration and non-aeration of the rhizosphere on the performance of RL and TC rootstocks. In the second study the aim was to determine the effects of the rhizospherical pH (pH 4 and pH 7), aeration/non-aeration and their interaction on growth and development of seedlings. The third study was conducted in order to identify the effects of aeration and non-aeration on the nutrient status of TC seedlings and the possibility of this as a cause of differences in performance of this rootstock under different conditions.

The experiments highlighted the greater sensitivity of RL rootstock to anaerobic (e.g. poorly drained) rhizospherical conditions compared to TC rootstock. The data illustrate that the root system of both RL and TC is more sensitive to the effects of poor aeration than the top growth. These data also indicate that non-aeration affected both RL and TC more at pH 4 than at pH 7.

The effects of low pH on nutrient uptake from aerated and non-aerated nutrient solutions were inconsistent for both RL and TC. For most nutrient elements there was no significant difference in nutrient concentration (% or $mg.kg^{-1}$) as a result of aeration/non-aeration in TC. However, for most nutrient elements the nutrient content (mg per pot) was significantly higher in aerated than in non-aerated seedlings.

Conclusions

Soil compaction had negative effects on RL seedlings, especially at soil water potentials above -20 kPa. For most soils when compacted, the seedlings could not grow at soil water potentials above -10 kPa.

The root system and the root hydraulic conductivity were the most affected plant parameters in RL seedlings grown in compacted soil. The WUE was also negatively affected by both soil compaction and high soil water potentials. The leaf area and top dry mass were affected by soil compaction at both high and very low soil water potentials. The optimum soil water potential for rootstock development in most compacted soils was -20 kPa.

In non-compacted soil, an increase in soil water potential resulted in better seedling growth. However, a point was reached at which an excessively high soil water potential resulted in low WUE. Lower soil water potentials in non-compacted soil resulted in a poor hydraulic conductivity and thus poorly developed seedlings.

Rhizospherical stress conditions resulting from both soil compaction and very high soil water potential as well as non-aeration of the nutrient solution had some effects on the nutrient status of seedlings. The stressed seedlings had a higher concentration (% or $mg.kg^{-1}$) of most nutrient elements compared to the non-stressed seedlings, but non-stressed seedlings had higher nutrient contents (mg per pot).

The anaerobic rhizospherical conditions in water culture experiments resulted in poor seedling growth. Both the top growth and the root system were affected as a result of anaerobic conditions. The RL seedlings formed a thick and short fibrous root system when grown in non-aerated nutrient solution. Defoliation was excessive in both non-aerated RL and TC seedlings.

The pH of the solution had some effects on growth and development of both RL and TC rootstocks in aerated and non-aerated nutrient solutions. At pH 4, the effects of anaerobic conditions were not significant in TC while there was a significant decline in total mass of non-aerated seedlings at pH 7. A low pH of the aerated nutrient solution also resulted in reduced plant parameters. However, there were no differences between seedlings at pH 7 and pH 4 in non-aerated nutrient solution as they were negatively affected at both pH levels.

The effects of soil compaction were very similar to those of anaerobic rhizospherical conditions for both RL and TC. In both cases the root system was more negatively affected. On the other hand, the negative effects of soil water potential were more pronounced on the top growth than on the root system.

This project was concluded by an irrigation scheduling trial at the Moosrivier citrus estate. The recommendations made by the research team have been implemented since 1993 by the management at the estate and considerable savings in irrigation water and pumping costs, an increase in yield as well as a higher quality yield were obtained since the implementation of the programme.

This project concluded the PAWC research by Laker, Hensley, De Jager, Boedt and Vanassche in determining the upper and lower limits of plant-available water.

Recommendations

The results of this study indicate the necessity that each soil should be characterized carefully and dealt with separately for irrigation scheduling purposes. The irrigation scheduling experiment at the Moosrivier citrus estate illustrates the benefits that can be obtained when an efficient irrigation scheduling is implemented. The findings of this project can, therefore, be transferred by extension officers to other farmers. It is clear that if further research could be done on other crops such as avocado, mango, tea, etc. more farmers and indirectly the whole community would benefit, especially as water is becoming a scarcer commodity.

The results of all plant-available water related research should be incorporated in a database in order to make them accessible to researchers, extension officers and farmers.

There is still a need for (i) research on the influence of soil bulk density on hydraulic conductivity, (ii) root distribution patterns in different soils under various irrigation systems, (iii) real crop water requirements, especially under very hot and dry conditions, (iv) field studies, as well as the establishment of expert support systems, for practical in-field irrigation scheduling in order to improve the economics of water use and WUE in irrigated agriculture.

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CHAPTER 1

INTRODUCTION

1.1 General

The history of civilization is accompanied by examples of how irrigation has, in many places, become self-destructive. All too often, the short-term gain in production resulting from irrigation leads to resource exploitation. This, in turn, is followed by long-term or permanent loss due to pollution and soil degradation. Continuing poor water and soil management practices result in a wasteful use of these resources and ultimately the loss of their productivity.

Irrigation practices have gradually evolved in the direction of increasing the growers' control over soil, water, crop, and even weather variables. Although the degree of control possible even today is only partial, as the open field remains subjected to unpredictable extreme conditions, modern irrigation is a highly sophisticated operation, involving the simultaneous manipulation of numerous factors of production.

Despite the modern sophistication, irrigated farming in many areas still fails to achieve its potential and also leads to serious soil degradation. According to Greenwood (1993), it may, for example, lead to cropping having to be abandoned in some of the most productive areas of California. The problems do not arise from irrigation principles and technologies per se, but from inappropriate application of these principles and technologies in practice. It generally results in excessive application of water, with little regard for the wastage of scarce water or for the degradation that is caused. Provision for adequate drainage or salinity or erosion control is also often neglected.

A well managed irrigation system is one that optimizes the spatial and temporal distribution of water so as to promote optimum crop growth and yield, and to enhance the economic efficiency of crop production. In irrigated agriculture, provision of just enough water is best. This means application of a controlled quantity of water sufficient to meet the daily needs of the crop so as to avoid yield losses due to drought stress. On the other hand, waterlogging of the soil may even be more harmful, as it may impede aeration, leach nutrients or induce high evaporation and salinization.

The poor soil aeration that accompanies waterlogging induces various physiological changes in plants that influence their growth (Kozlowski, 1984). Poor soil aeration is not limited to waterlogged soil, but is also a problem in fine-textured soils which tend to be compacted. Plant responses to poor aeration may vary widely, with differences according to genetic constitution of plant species, age, duration of waterlogging and external factors, such as temperature.

Most soil and plant researchers are now aware of the importance of maintaining the soil water content within a given range for optimal crop production. However, with the refinements that have been made in irrigation technology over the past few decades, such as the use of low pressure sprinkler, drip and micro-spray systems, the need for knowledge about the relationships between soil, soil-water potential, plant growth and yield are even more pressing (Wierenga & Saddiq, 1985). There is, therefore, a need for more information on the tailoring of irrigation techniques to specific combinations of soils, crops, water and climate. This will overcome most of the problems which are encountered if one or more of these production components are overlooked.

Since the mid-1970's a large amount of research has been done in South Africa on the definition and determination of the lower limit of the plant available water capacities (PAWC) of different soils for a number of agronomic crops for irrigated situations, i.e. where crop loss due to drought stress is not permitted. The results of this research have been reported by Hensley & De Jager (1982), Boedt & Laker (1985) and Vanassche & Laker (1989), as well as in several reports by Bennie and his co-workers at the University of Orange Free State. It formed the basis for the very successful BEWAB irrigation scheduling programme developed by Bennie and his co-workers.

With the availability of irrigation systems such as drip and micro-spray there is a tendency to keep the soil water content within a narrow range close to the upper limit of plant-available soil water. This is aided by scheduling according to monitoring of soil water content with tensiometers and is especially used for high value fruit and vegetable crops. The emphasis on "how much" and "when" to irrigate, which has been the focus in the past, can now be shifted to "specific soil-plant-water-air relationships" in irrigated agriculture. In the latter approach the most critical issue is to identify an appropriate upper limit for soil water content for each soil-plant combination.

Citrus is one of the major agricultural crops produced for both export and local marketing in South Africa. The majority of both newly-planted and old citrus orchards are presently under micro or drip irrigation. Du Plessis & Terblanche (1986) state that microjet irrigation is the most versatile for controlling irrigation volumes. It is used for short cycle irrigation scheduling to maintain the soil water content in the wet range of plant-available water. It is believed that such a short cycle irrigation schedule gives a more rapid and uniform rate of plant and fruit growth than a long cycle irrigation schedule.

Many citrus orchards in South Africa and neighbouring countries, such as Swaziland, have been established on soils that are far from ideal for citrus. These soils are too fine-textured and/or prone to severe crusting and compaction. Field observations in citrus orchards under microjet or drip irrigation on compacted medium- and fine-textured soils in South Africa and Swaziland yielded the impression that the soil water potential ranges that were used for irrigation scheduling on these soils were too high and that the soils were, in fact, kept too wet. A case in point was a specific citrus orchard in the Sundays River valley where the recommendation was that the farmer had to keep the tensiometer readings between -10 and -30 kPa (irrigating each time it reached -30 kPa) on such compacted soil. It was, however, not clear what was "too wet" for citrus on such sub-optimal and marginal soils. The study of Nel (1981) only included relatively good citrus soils and not such marginal soils.

Furthermore, because water is becoming very scarce and pumping costs more expensive, citrus growers are faced with challenging times ahead with regard to water management decisions. Growers, therefore, require information on young tree response to irrigation so that they can optimize irrigation scheduling and thus save water and minimize costs without jeopardizing yields and income.

Horticultural characteristics of citrus rootstocks are important, especially in regard to disease resistance and drought tolerance. Rough lemon (RL) rootstock has been extensively used in the past because of its drought tolerance (Wutscher, 1979). With changes in production aspects, such as the introduction of citrus into marginal soils, and improvement in irrigation technologies, this rootstock has been gradually replaced. Troyer citrange (TC), for example, has been widely introduced to overcome the problems of fine-textured soils. However, the drawback is that TC rootstock is very sensitive to saline soils.

However, it must not be assumed that the solution to all crop production problems should be sought through plant breeding (Reuss & Danielson, 1974). Soil modification or management adaptation rather than plant manipulation might be the more realistic direction for research in a great majority of the soil structure problem cases. In the broadest interpretation, soil structure and bulk density are perhaps the most significant of the soil physical properties because they have such an important influence on other physical properties and, thus, on chemical and biological relationships (Larson & Gupta, 1980). Soil structure and compaction exert their influence through effects on soil water, aeration and temperature.

In this study the overall objective was to examine the relative effects of certain soil physical properties, high soil water potential and the availability of air to the roots on the development of young citrus rootstock. An understanding of the relationships between these production components could help to determine the most suitable and appropriate practices to be followed.

1.2 Literature Review

1.2.1 Upper Limit of Plant Available Water

The status of water in the soil is one of the most important parameters determining plant growth and yield (Wierenga & Saddiq, 1985). Most studies have shown that crop yield is strongly related to the energy status of water in the soil and thus to the soil water potential (Sommer, 1981; Wierenga & Saddiq, 1985). As the soil dries out, its water potential decreases, resulting in less available water for plant uptake and reduced plant growth and yield.

The most commonly accepted upper limit of the plant available water in the soil is the field capacity, which is the amount of water held in the soil after all gravitational water has drained from the soil and downward movement of water in the soil profile has ceased. Depending on the soil physical properties, drainage may continue for a long time after a soil profile has been wetted in fine textured soils and probably never stops (Hillel, 1980). It is therefore meaningless to consider field capacity as a soil constant in such soils.

A major problem confronting attempts to use a standard set of soil water potential values for irrigation scheduling in the wet range of plant available soil water is the fact that field capacity does not represent a standard soil water potential value, as was for a long time believed. Ratliff, Ritchie & Cassel (1983), for example, compared in situ determined field capacity and soil moisture content at -33 kPa (the soil water potential originally believed to represent field capacity) for different soils. The soil water content at -33 kPa for sand, sandy loam, and sandy clay loams was significantly less than the in situ determined field capacity. On the other hand, the laboratory measured field capacity at -33 kPa for silt loams, silty clay loams and silty clays was higher than the in situ determined field capacity. It has been found that soil water potential values at soil water contents representing field capacity can range from as high as -5 kPa for sandy soils to as low as -50 kPa for clayey soils. For three soils from South African citrus orchards Nel (1981) found that field determined field capacity represented the water contents at soil water potentials of -8, -12, and -22 kPa for the three respective soils. Authors such as Marshall & Holmes (1979) have recommended that soil water contents at soil water potentials of -10 kPa should be used as field capacity values. This would represent a vast over-estimation of the field capacities of medium- and fine-textured soils.

The above illustrates a fundamental weakness in any attempt to use a single soil water potential value as baseline for irrigation scheduling with the aid of tensiometers. For this reason authors such as Hillel (1980), Hensley & De Jager (1982), Boedt & Laker (1985) and Vanassche & Laker (1989) have stressed that in situ determined field capacity should always be used as indicator of the upper limit of plant-available soil water. Moreover, different soil-plant-water-air relationships exist even at fixed soil water potentials between field capacity and permanent wilting point (Gardner, 1960).

According to Boedt & Laker (1985) and Vanassche & Laker (1989), it is obvious that a crop stress index is required to indicate the limits of plant-available water because plant performance is the ultimate reflection of the plant-available soil water status. Although these researchers were focusing on the lower limit of plant-available water, the same approach should also be used to define the so-called "optimum level" at the upper limit of the plant-available water in a specific soil. Stolzy, Moore, Klotz & DeWolfe (1959) found that at a soil water potential of -9 kPa a significantly higher mass of top growth in citrus was produced compared to -60 kPa, even if the citrus seedlings were inoculated with Phytophthora. Smajstrla, Parson, Aribi & Velledis (1985), using a fine sandy loam, found that irrigation scheduling when the soil water potential reached -20 kPa gave better growth of citrus compared to a -40 kPa schedule.

As a result of the dynamic nature and the inconsistency of the upper limit of plant-available water in the soil, it is rather difficult to define and maintain an optimum soil water potential through irrigation practices (Bresler, 1977). Moreover, variation in soils, plant species and cultivars, rootstocks, climatic factors, and irrigation systems impose some limitation to the effective use of existing irrigation models.

Irrigation methods such as drip and micro-sprinklers make it possible to have a restricted soil zone of very high water potential, with the water application rate being determined by the evaporative demand (Bresler, 1977). Consequently drip irrigation has experienced an enormous increase in commercial significance and research interest (Elfving, 1982).

Maintenance of appropriate soil oxygen levels while maintaining a high soil water potential within narrow bounds appears to be an important factor affecting optimum irrigation frequency (Silberbush, Gornat & Goldberg, 1979). In sandy soils, this factor is not a problem since the limited soil water holding capacity dictates very frequent irrigation. With more clayey and marginal soils under citrus, frequent irrigation may create a localized oxygen deficiency within the wetted volume. Oxygen deficiency as a result of drip irrigation limits root development to a specific soil volume (Elfving, 1982; Silberbush et al., 1979). This may have significant implications for plant growth and development, especially in fruit trees. Confinement of roots to a smaller soil volume may result in more rapid fluctuations in soil water and nutrient levels, increasing plant dependence on a stable fertigation schedule and increasing risk of oxygen stress if water application is in excess or exposing the plants to drought stress if the water supply is interrupted.

1.2.2 Soil Factors that Influence the Rhizosphere

The need to acquire information on the factors and processes controlling the movement, storage, and plant availability of soil water is one of the most important reasons for detailed investigations in irrigation studies (Boedt & Laker, 1985). It is therefore necessary to focus on the role of soil structure because both water, air and plant roots move between structural units. Soil structure is also one of the intrinsic physical properties, which are easily, frequently and widely altered, particularly by cultivation.

According to Sommer (1981), numerous soil parameters can be controlled, but maintaining a constant soil water potential remains one of the most difficult technical problems. Recently, a technique has been developed to control soil water potential in pot experiments. The main advantage of this facility is that it overcomes excessive fluctuation in soil water potential in the pot (Durr, Vanassche, Schwarz, Laker & Sommer, 1992). This facilitates studies of soil physical properties and their influence on plant growth and development while maintaining a constant soil water potential. Carter & Johnston (1989) found that when all other factors are uniform, a decrease in macropores results in an increase in relative water saturation of the soil which may cause excess water and sub-optimal oxygen levels, leading to oxygen stress and increased severity of root rot in spring cereals (Figure 1.1). Durr et al. (1992), using the Sommer facility, found that spring barley had both higher cumulative and daily water consumption when grown in loose soil than in compacted soil.

Since the soil water potential is the material property which most completely describes the status of the soil water, there is a need to know how a change in soil structure manifests itself in the soil water potential function (Bradford & Gupta, 1986; Hamblin, 1985). Water movement through soil is predominantly by bulk flow driven by a pressure gradient, although diffusion also accounts for some water movement (Taiz & Zeiger, 1991). The rate of water flow depends on the size of the pressure gradient through the soil and on the hydraulic conductivity of the soil. According to McNeal, Layfield, Norvell & Rhoades (1968), the hydraulic conductivity can be used to quantify changes in the physical properties of the soil. Darcy's law can be employed to explain the water flow in the soil as:

$$q = V/At = k\,(H'' - H')/L$$

where q = flux (mmh^{-1}); V = volume of water passing through a soil column (mm^3); A = cross sectional area of the soil column (mm^2); t = time elapsed (h); H''-H' = hydraulic head difference (mm); L = length of soil column (mm); k = hydraulic conductivity (mmh^{-1}).

The hydraulic conductivity of the soil is correlated with the structure and texture of the soil, mainly clay content (Danielson & Sutherland, 1986). Any factor influencing the size and the configuration of soil pores will influence its hydraulic conductivity. Fine textured soil with high clay and silt content can clog the connecting channels of even the larger pores, thereby reducing the water movement to a minimum.

According to Gupta, Sharma & Franchi (1989) and Hill & Sumner (1967), it has been found that increasing the bulk density of the soil modifies the pore size distribution such that there results:

- a decrease in the amount of water held at high water potentials.
- a decrease in the water potential at which air first enters the soil.
- an increase in the amount of water held at low potentials.

Besides the soil type, the water content also affects the hydraulic conductivity of soil (Blackwell, Ringrose-voase, Jayawardane, Olsson, McKenzie & Mason, 1990). As the soil water potential declines, the hydraulic conductivity decreases drastically (Brady, 1974).

The aeration of soil is characterized by the air-filled porosity at a specific soil water content (Frank, Verhaegh & Bakker, 1991). A more compacted soil has a higher dry bulk density and consequently lower air-filled porosity at a specific soil moisture content (Gupta & Allmaras, 1987). A formula that is widely used in determining the air-filled porosity is:

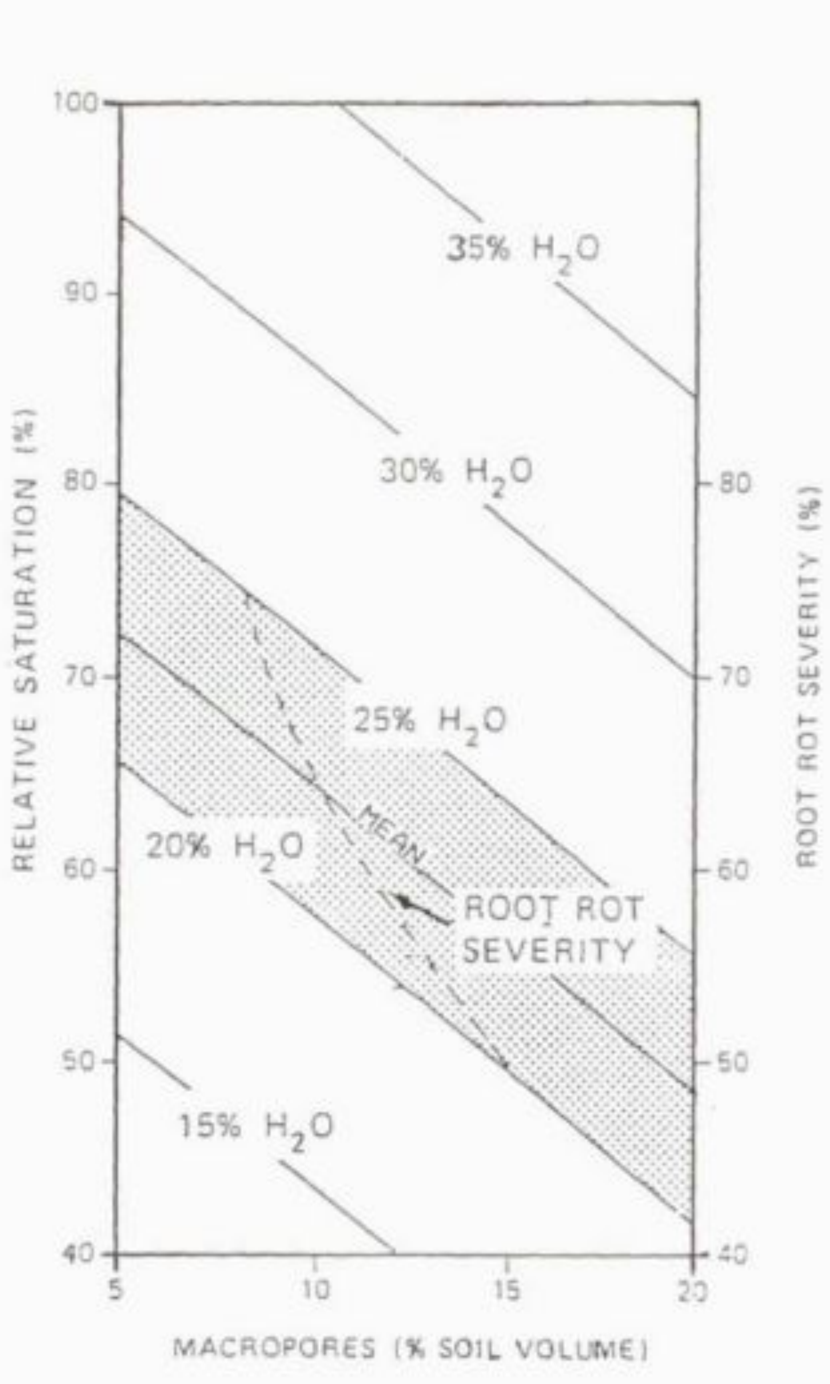


Fig. 1.1. Relative water saturation of a Charlottetown fine sandy loam as a function of macropores and water content. The shaded area shows the standard error for soil moisture content. Super imposed is the root rot severity as a function of macropores (Adapted from Carter & Johnston, 1989)

Air-filled porosity = [1 - DBD/2656] - Q
where DBD = dry bulk density of the soil ($kg.m^{-3}$)
Q = water content of the soil (percent volume)

Within any given soil, plants are able to extract water over a range of soil water content. Waterlogging occurs when water fills air spaces for a long period, and restricts the diffusive gas interchange of the soil and the above-ground atmosphere such that the normal chemical, biological, and oxidative processes in a soil are inhibited. According to Rowe & Beardsell (1973), waterlogging is a problem in heavy clay soils with a low hydraulic conductivity or where a water-impermeable horizon exists. Stolzy, Letey, Klotz & DeWolfe (1965a) also state that rotting of citrus feeder roots occurs in soils that are often saturated and poorly aerated and may result in the invasion of roots by fungi.

1.2.3 Water Status and its Influence in the Rhizosphere

Waterlogging can produce stressful conditions quite opposite to the extremely low soil water potentials of dry soils. Damage in this case results from the exclusion of oxygen. In waterlogged soil not only is air displaced by water, but the water is a barrier for both oxygen and carbon dioxide diffusion. When a soil is waterlogged, the oxygen trapped is rapidly taken-up by plant roots and aerobic micro-organisms at a rate dependent on soil temperature (Drew, 1992). According to Rowe & Beardsell (1973), oxygen in waterlogged soil disappears within a few hours. In several studies it has been shown that carbon dioxide concentration in waterlogged soil can reach up to 98% of soil air (Rowe & Beardsell, 1973; Stolzy & Sojka, 1984). Rowe & Beardsell (1973) also showed that carbon dioxide excess and oxygen deficiency have different inhibitory effects on water uptake, the inhibition caused by excess carbon dioxide being more rapid.

Roots usually obtain sufficient oxygen for their aerobic respiration directly from the soil (Salisbury & Ross, 1985). Air-filled pores in well drained and well structured soil readily permit the diffusion of gaseous oxygen to depths of several meters (Ishii & Kadoya, 1991; Taiz & Zeiger, 1991). Consequently, the oxygen concentration deep in the soil is similar to that in humid air. Excessive water in the soil fills the macro-pores and blocks the diffusion of oxygen in the gaseous phase. Oxygen dissolves in water and diffuses very slowly, with the result that only a few centimeters of topsoil remain oxygenated.

It has been presumed that high carbon dioxide in soil has no direct toxic effect on root growth but possibly reduces translocation of both nutrients and metabolites in the plant. According to Labanauskas, Stolzy, Klotz, & DeWolfe (1971), there is a decrease in N, P, K, Ca, Mg, and Mn concentration in top growth of citrus seedlings due to high carbon dioxide levels in the soil.

Active uptake of nutrients is also reduced as a result of low energy conversion in roots under waterlogged conditions (Drew, 1992). The energy requirements of citrus roots become so high that the top alone cannot satisfy the demand. As a result, less resistant cellular constituents are metabolized, resulting in the development of lysigenous zones of intercellular voids in root tissue (Drew, 1992; Stolzy & Sojka, 1984). In this way a certain level of normal plant functioning resumes as a result of energy supply from the breakdown of cell components which ultimately results in breakdown of plant roots.

When the waterlogging episode is over, the root system becomes less adaptable and the respiratory demand too high to be met by shifts in the respiratory pathway (Stolzy & Sojka, 1984). The root system then becomes necrotic. This provides entry for pathogens and also impairs physiological recovery of plants by limiting the root volume. As a result, the reduced root:top ratio impairs soil nutrient and soil water extraction in the recovering plant, slowing its growth.

1.2.3.1 Plant Response and Tolerance to Waterlogging

In general, plants require a well drained soil for maximum growth and productivity (Carter & Johnston, 1989). Perennial crops are particularly vulnerable since poor drainage, even for a short period, can have long term effects on growth and productivity (Rowe & Beardsell, 1973). Considering the complexity of changes in the rhizosphere as a result of waterlogging, it is not surprising that plant growth in such a situation is adversely affected. Some confusion which exists in literature results from observations that not all plant species or the same species in different localities are affected to the same degree by what, superficially at least, looks like excess water in the soil (Drew, 1992; Ford, 1964; Rowe & Beardsell, 1973). Although environmental changes in the soil due to excess water have been documented, there is much less information about the causes of the differential sensitivity of citrus rootstocks to these conditions.

The growth of existing roots, formation of new ones, and root viability are very sensitive to the availability of oxygen. Roots need at least 8-10% oxygen for fast growth but can make some growth with 2% or less (Rowe & Beardsell, 1973; Stolzy, Letey, Szuszkiewicz & Lunt, 1961). Ayres, Button & De Jong (1972) showed that 10-12% air per soil volume is the lowest limit for optimum growth for various crops. Patt, Carmeli & Zafrir (1966) found that 10 % air capacity at field capacity is the critical threshold for adequate soil aeration for citrus. In a South African study Nel (1981) found that citrus tree volumes increased from 20 m^3 at an air capacity of 15% to 40 m^3 at an air capacity of 26%. He concluded that 15% and 30% air capacity can be considered as threshold values below or above which tree growth will be seriously retarded.

It was shown that the oxygen diffusion rate (O.D.R) of about 0.2 $\mu g\ cm^{-2}min^{-1}$ is the minimum threshold, below which roots of most crop plants do not grow well (Silberbush et al., 1979). In poorly aerated soil, root growth is restricted to the soil surface (Drew, 1992; Taiz & Zeiger, 1991). This results in poorly anchored trees that are also subject to drought injury because their roots are too shallow and occupy too small a volume of soil to supply water and nutrients to the shoots during a drought.

The effects of excess water are more severe when trees are actively growing than when they are dormant (Drew, 1992; Kozlowski, 1984; Ponnamperuma, 1984; Sena Gomes & Kozlowski, 1980). Older trees generally tolerate waterlogging much better than seedlings of the same species even though they also suffer when actively growing (Kozlowski, 1984). Responses include inhibition of shoot and root growth, arrested reproductive growth, morphological changes, and often, death of trees. The dry mass of leaves of waterlogged plants is highly reduced compared to well-aerated plants in certain species. The leaf numbers also vary greatly. However, according to Newsome, Kozlowski & Tany (1982), the most dramatic effect of waterlogging is a drastic reduction in dry mass increment of roots, even though new adventitious roots comprise a third to a half of the dry mass of the root system of waterlogged plants. Reduction in both fresh and dry mass of citrus roots as a result of waterlogging was also observed in several studies (Klotz, DeWolfe & Wong, 1958; Stolzy, Moore, Klotz & DeWolfe, 1959; Stolzy, Letey, Klotz & Labanauskas, 1965b).

There is some controversy as to the mechanisms that enable some plant species or cultivars to withstand waterlogging better than others. Rowe & Beardsell (1973) suggest that different tolerances of citrus rootstocks to waterlogging are due to their differential tolerance to poisoning by hydrogen sulphide. Syvertsen (1981) and Syvertsen, Zablotowicz & Smith (1983) further stated that although different rootstocks in pots produce root systems that differ from those in the field, some of the growth and resistance characteristics that have been associated with rootstocks may be partially explained by the hydraulic conductivity of roots. De Villiers (1939) found that there are other factors beyond the number of xylem vessels that determine the differences in water conductivity between citrus species. Luxmoore, Stolzy, Joseph & DeWolfe (1971) found that the roots of citrus species do not only differ in air porosity but also change the porosity in order to overcome drastic conditions in the rhizosphere. They further stated that characterization of root porosity is an important factor in assessing the significance of internal plant aeration. Although there are differences in root hydraulic conductivity between citrus species, Syvertsen (1981) and Syvertsen & Smith (1983) found that there was no apparent change in root hydraulic conductivity of the remaining citrus feeder roots from blight affected trees.

The root length (<2 mm diameter) has been used to express root hydraulic conductivity (Graham & Syvertsen, 1985; Levy, Syvertsen & Nemec, 1983; Zekri & Parsons, 1989). However, other researchers have used dry root mass (Anderson, Lombard & Westwood, 1984) while others have used a projected and estimated root area (Syvertsen, 1981; Syvertsen et al., 1983; Syvertsen & Graham, 1985). The latter, unlike the root length and dry root mass, brings into effect the size and distribution of the root system as well as its water transport efficiency. According to Fiscus (1977), Fiscus, Klute & Kaufmann (1983), MacFall, Johnson & Kramer (1991) and Michel (1977), the root surface area is the most reliable component to be employed in computing the root hydraulic conductivity.

In wetland species, stems and roots develop longitudinally interconnected, air filled channels that provide a low resistance pathway for diffusion of oxygen and other gases (Drew, 1992; Kozlowski, 1984). The air enters through stomata on woody stems. In many of these plants, tissues are composed of cells separated by prominent, air-filled spaces called aerenchyma. In extensive root systems such as citrus, however, internal oxygen transport through the roots is less important compared to oxygen supply from the rhizosphere (Sojka, 1992; Rowe & Beardsell, 1973).

Plant roots play a role in the hormonal balance of plants, so that injury of the root system due to waterlogging may lead to changes in plant hormonal reactions (Sojka, 1992; Wilkins, 1984). Shoot growth is, to a certain degree, under the control of gibberellins (Wilkins, 1984). Cytokinins are involved in the maintenance of chlorophyll and protein in plant tissue. Some of the symptoms of waterlogging are thus similar to hormonal imbalances. There is, however, a lack of adequate information relating the effects of waterlogging to hormonal imbalance in horticultural species and how this may influence productivity (Rowe & Beardsell, 1973).

Many plant species intolerant to low oxygen lose part of the original root system by decay and do not regenerate new roots on the original root system or the submerged part of the stem, or on both (Kozlowski, 1984). A decrease in root:top ratio by waterlogging, reflecting greater reduction in growth of roots than of shoots, often predisposes trees to drought injury when the excess water recedes (Marler & Davies, 1990). Soil waterlogging in citrus orchards often results in decay of roots, primarily as a result of invasion by Fusarium and Phytophthora fungi. According to Stolzy et al. (1965b), the amount of decay increases as the duration of soil saturation is increased. However, when non-infested soil is saturated, root predisposition to decay results from lack of oxygen and not from fungi.

1.2.3.2 Disease Incidence and Occurrence

The invasion of fruit trees by fungi is often associated with excessively wet soils (Gisi, Zentmeyer & Klure, 1980). The importance of soil physical conditions in controlling the activities of soil fungi has been documented (Ford, 1964; Stolzy et al., 1965b; Zentmeyer & Richards, 1952). It is difficult to determine whether pathogen invasion is a prime factor in the decline of waterlogged trees or simply a secondary invasion of root tissue already dead or dying. High water content and low soil aeration, two factors associated with saturated soils, influence root decay of citrus by Phytophthora species (Stolzy et al., 1965b).

Stolzy et al. (1965b) found that the duration of waterlogging is more important than the number of water saturation episodes in causing Phytophthora root rot in citrus. It is therefore probable that prolonged saturation of soil zones under drip irrigation can also lead to Phytophthora root rot of citrus in infested orchard soils. Citrus trees in poor environmental conditions generally have few functioning feeder roots. The Fusarium and Phytophthora fungi can develop with great rapidity as saprophyte on roots damaged by waterlogging, by-products of fermentation, or by other factors (Klotz, Stolzy, DeWolfe & Szuszkiewicz, 1965; Stolzy et al., 1965b). The build-up of fungi population may be promoted by certain adverse soil conditions, especially if the soil moisture conditions are unfavourable to the host.

1.3 Objectives of the Present Study

The overall objective of this study was to identify the appropriate upper limit of plant-available water for certain soil-plant combinations and the effects of soil compaction on an acceptable upper limit. The interaction of soil compaction and high soil water potential, and their influence on plant growth and development was studied mainly for sub-optimal and marginal citrus soils. The study tried to identify adaptation and tolerance of Rough lemon and Troyer citrange rootstocks to unfavourable rhizospherical conditions.

The specific objectives of the research project were threefold, viz.

(a) Development of techniques for effective research on physical, chemical and biological processes in the upper range of plant-available water. A modernized computer controlled version of the technique of Sommer (1981) was used as basis for this (Refer to Chapter 2).

(b) Collection of basic data regarding physical, chemical and biological processes in different soils in the upper range of plant-available soil water.

(c) The development of models which could be used for better planning and management of irrigation in the upper range of plant-available water.

1.4 Research Programme

The study attempted to look at realistic situations in the rhizosphere under intensively irrigated young citrus as follows:

(a) Identify appropriate upper limit of plant-available water:
This was done by imposing high levels of soil water potential on citrus seedlings. Sub-optimal soil types that are currently under citrus and those that have a potential for citrus growth were considered. In contrast to the study of Nel (1981), which concentrated on relatively favourable soils, this study included some of the most problematic marginal citrus soils. Seedling performance at different levels of soil water potential in these soils was studied.

(b) Effects of certain soil physical properties:
Various soils with known physical characteristics were

compacted to dry bulk densities that are usually found in citrus groves in South Africa. The performance of citrus seedlings was monitored and several plant parameters, such as plant growth, root system, and leaf area were measured.

(c) The interaction of dry bulk density and high soil water potential in different soils:
Soils with known physical characteristics were compacted to different levels of dry bulk density. Various levels of soil water potential (considered to be wet) were super-imposed on the levels of dry bulk density. The performance of citrus seedlings in such conditions was monitored and certain plant parameters that are sensitive to waterlogged conditions were measured.

(d) Study about response and tolerance possessed by RL and TC when grown under waterlogged conditions:
Both RL and TC were grown in aerated and non-aerated nutrient solution. These two types of citrus were considered because of their different tolerance to waterlogging. Several plant parameters, especially the root system and the root hydraulic conductivity, were measured. Plant performance under different rhizospherical conditions was observed.

(e) Effects of the interaction between waterlogging and the pH of the rhizosphere:
Both RL and TC were grown as in (d). However, half of the pots had a pH 4 and another half a pH 7. Plant growth and development was monitored and several plant parameters were measured.

(f) Application of the results of the previous experiments in (i) a field study and (ii) practical irrigation scheduling.

CHAPTER 2

DEVELOPMENT AND EVALUATION OF RESEARCH METHODOLOGIES FOR THE REGULATION OF SOIL WATER IN POTS BY MEANS OF AN AUTOMATED ELECTRONIC SYSTEM

2.1 Introduction

Pot experiments are used under controlled agricultural research conditions. The factor to be studied can be changed while all other factors are kept as constant and uniform as possible. Pot experiments can in this way be used to explain results of field experiments or to conduct basic studies in order to improve planning of subsequent field experiments.

Pot experiments, for instance, facilitate studies of the influence of soil physical properties (e.g. bulk density, soil aeration and soil water content/potential) on plants. Most of these require well-controlled soil water regulation. Problems are, however, experienced regarding soil water regulation in pots (Durr et al., 1992).

Traditionally pots were wetted from the top or bottom and the soil water content was monitored gravimetrically (Durr et al., 1992). The inherent uneven water distribution of this type of wetting is unacceptable for experiments involving studies on the interactions between soil bulk density, soil water potential and water consumption by plants.

Watering was subsequently done by capillary wetting of the soil by means of a suction plate installed at the bottom of the pot. Some researchers used horizontally installed ceramic cells instead of suction plates. Lipiec, Kubota, Iwama & Hirose (1988) found that horizontally installed ceramic cells gave good results in relatively small pots (diameter = 7.5 cm, height = 5 cm).

Sommer and his co-workers at the Federal Agricultural Research Centre (FAL) in Braunschweig, Germany, found that vertically installed ceramic cells gave a more even water distribution than horizontally installed cells, especially in larger pots (diameter = 40 cm, height = 34 cm). Consequently, a water regulation method based on vertically installed ceramic cells and a simple regulation technique was developed and successfully used in a number of studies at the FAL, e.g. Sommer (1981).

The method developed by Sommer and his co-workers was a mechanically controlled system which was regulated by a regulating vacuum meter connected to a vacuum pump (Figure 2.1). This method maintains a constant underpressure in the ceramic cell. The underpressure results in a defined soil water potential, at least if the system is static or quasi-static (Durr et al., 1992). Although this system gave better results than the traditional systems it still could not quite maintain a constant soil water potential under a dynamic system where plants extract water, especially during high transpiration rates.

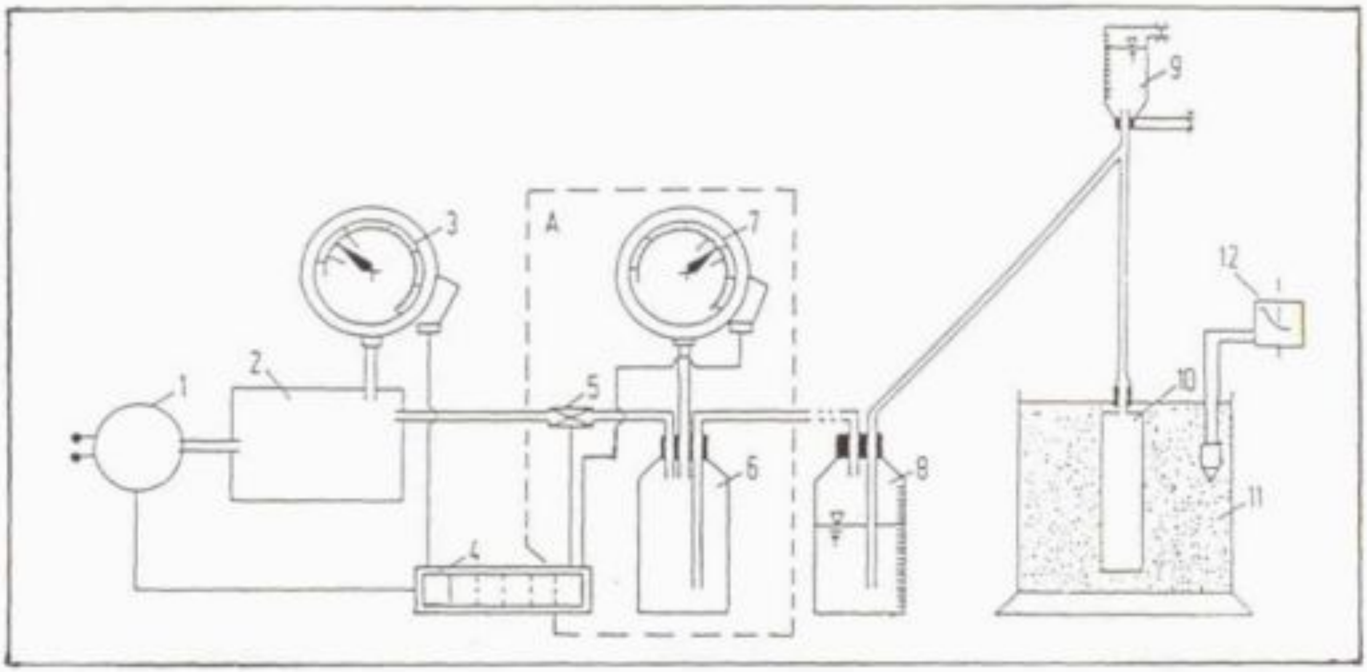


Fig. 2.1. A system for supplying pots with water based on soil water potential regulation (conventional system) (From Durr et al. 1992)

(1) vacuum pump
(2) vessel
(3) vacuum meter
(4) relay switches
(5) control device
(6) buffer vessel
(7) regulating gauge
(8) water-storage bottle
(9) air-collecting bottle
(10) diaphragm cell
(11) pot
(12) tensiometer

Differences between desired and actual soil water potentials at high transpiration rates can be corrected by manually controlled valves which will reduce the underpressure in the system (Durr et al., 1992). This requires a constant monitoring of the soil water potential and a constant adjustment of the underpressure in the water storage bottles. It is impossible to do this manually. Therefore, an electronically controlled system was designed in Braunschweig. Instead of a constant underpressure, this system uses the actual soil water potential value, measured by a tensiometer in the pot, as a control value.

The development of the electronic system in Braunschweig coincided with the start of the Water Research Commission (WRC) sponsored research project at the University of Pretoria (UP) which is reported here. The WRC project at UP was planned around the original mechanical "Sommer" system. With the development of the new electronic system, it was logical that its advantages would be investigated and methodologies developed and evaluated for use in the project at UP.

2.2 Description of the Electronic System for the Regulation of Soil Water in Pots

The comprehensive description of the system given by Durr et al. (1992) is repeated here, with minor amendments, because the journal in which their paper was published is not commonly available in South Africa.

The system (Figure 2.2) uses the same equipment (1-4) for generation of the underpressure as shown in Figure 2.1. A vacuum pump (1) maintains a certain underpressure in a vessel (2), regulated by a regulating vacuum meter (3). The setting of maximum and minimum values on the meter starts the pump whenever the minimum value is reached and stops it as soon as the maximum value is reached. The regulation of the system is controlled by relay switches (4).

The system also uses the same equipment (6 and 8-11) for supplying water to the pots as in Figure 2.1. The underpressure generated in the vacuum buffer vessel is also created in the water storage bottle by means of a Tygon tubing connection (OD = 10 mm; ID = 6 mm).

As illustrated in Figure 2.3 this bottle is connected with the vertically placed ceramic cell in the pot (11) by means of a closed water column and an air collecting bottle (9). An equilibrium between the underpressure in the storage bottle and the soil water potential in the pot (11) is thus created. Disturbance of this equilibrium, by evaporation from the soil surface and/or water uptake by plants, will be restored by the flow of water according to the unsaturated hydraulic conductivity of the soil. Because it is nearly impossible to prevent leaks in the system, especially when several pots are connected to it, it is important that air bubbles are collected in the air collecting bottles (9). It is, therefore, necessary to have two reading scales, one on the water storage bottle and one on the air collecting bottle, if water consumption has to be measured.

The regulating gauge (7) used in the conventional method (Figure 2.1) is replaced by a Pneumat (5), a datalogger (7) and a personal computer (13) in order to regulate the underpressure in a vacuum buffer vessel (6)(Figure 2.2).

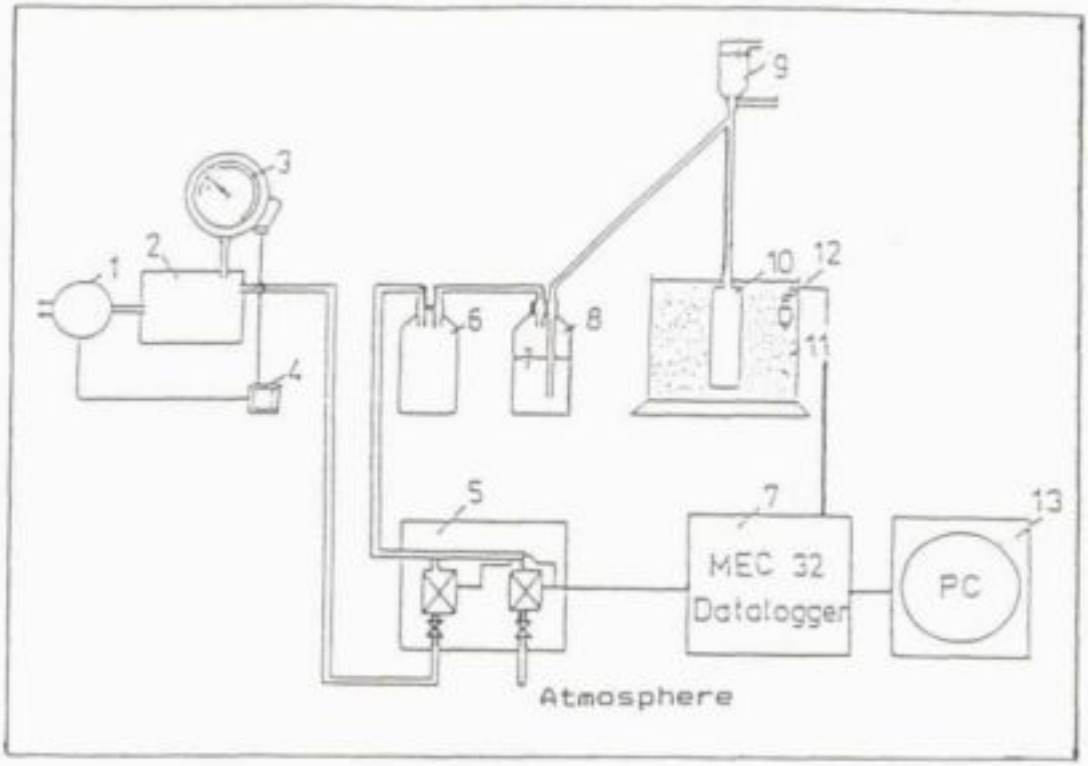


Fig. 2.2. A system for supplying pots with water based on soil water regulation by means of an electronic device (From Durr et al. 1992).

(1) vacuum pump
(2) vessel (bottle)
(3) vacuum meter
(4) electronic control
(5) electromagnetic pneumat
(6) buffer vessel
(7) datalogger
(8) water-storage bottle
(9) air-collecting bottle
(10) diaphragm cell (s)
(11) pot
(12) tensiometer
(13) computer

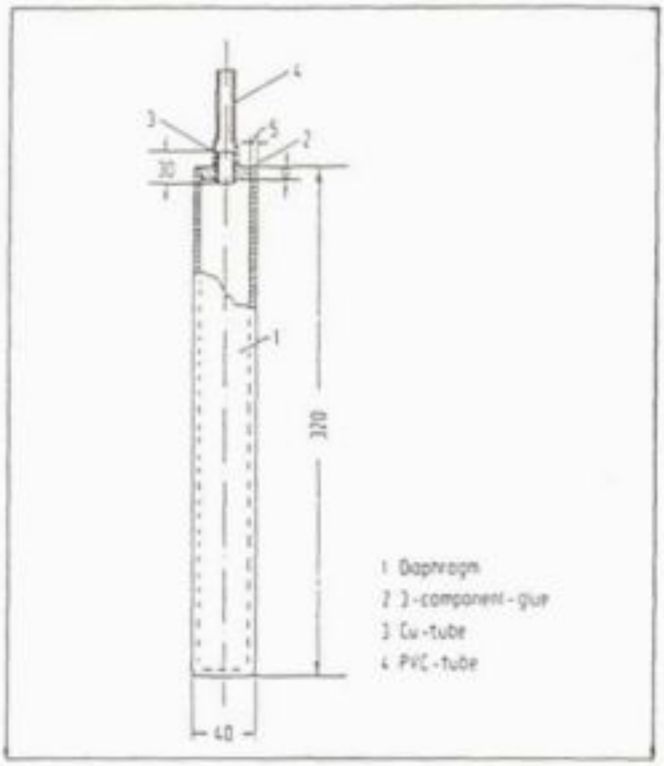


Fig. 2.3. Schematic illustration of a ceramic cell (From Durr et al., 1992).

The Pneumat (5) contains two solenoid valves which can increase or decrease the underpressure, by means of a connection with the atmosphere, according to the needs of the system. These solenoid valves function as a unit and are connected with the electronic measuring devices in the control unit and with the power supply. Opening and closing of the solenoid valves is regulated by the datalogger (7). The datalogger registers the value of the soil water potential by means of a pressure recording tensiometer (12), calculates the difference between measured and desired value and, based on this, determines the opening times of the solenoid valves. An underpressure buffering vessel (6) is inserted between the water storage bottle (8) and the control device (5). The personal computer (13) serves as a programming unit for the control device, a monitoring station, and a storage unit for the collected data. It also allows for producing hard copies of the data in the form of graphs.

The regulating functions according to the Pulsation Duration Modulation (i.e. opening times of the solenoid valves) are calculated according to the difference between measured and desired soil water potential values and executed at preset time intervals (Figure 2.4).

The soil water potential in the pots is adjusted by the regulation of the respective solenoid valves. The combination of the opening time of the valves and the change in soil water potential results in an integral regulation. Time interval between measurements, pulsation duration, valve setting and volume of the underpressure buffer vessel determine the proportion factor (the amplification of the regulator). The difference between measured and desired soil water potential value is in this case of static or quasi-static conditions equal to zero. In other words, the soil water potential measured by the tensiometers is equal to the preset value. In the case of a dynamic system, a difference will be measured which is mainly dependent on the time delay for reaching equilibrium between ceramic cell and soil. The amplification of the regulation can be controlled by the settings on the solenoid valves and by changing the time interval between measurements in order to prevent fluctuations in the soil water potential.

The system not only monitors the soil water potential and regulates water application accordingly, but also keeps a continuous record of the soil water potential. At the end of an experiment, a full record for the whole period is, therefore, available. The capacity of the system can be expanded by applying the monitoring and recording mode only to some pots and simply using a regulation mode on the others. This was done in some experiments of the research reported here.

2.3 Comparisons of the Mechanical "Sommer" and Electronically Controlled "Pero" System for the Regulation of Soil Water in Pots

2.3.1 General

A co-operative study, initiated and planned by the project leader of the research programme reported here (Laker) and dr. Sommer of FAL, was conducted at the FAL, Braunschweig, to compare the "conventional" mechanically regulated "Sommer" system with the then newly developed electronically regulated "Pero" system. One researcher from the project reported here

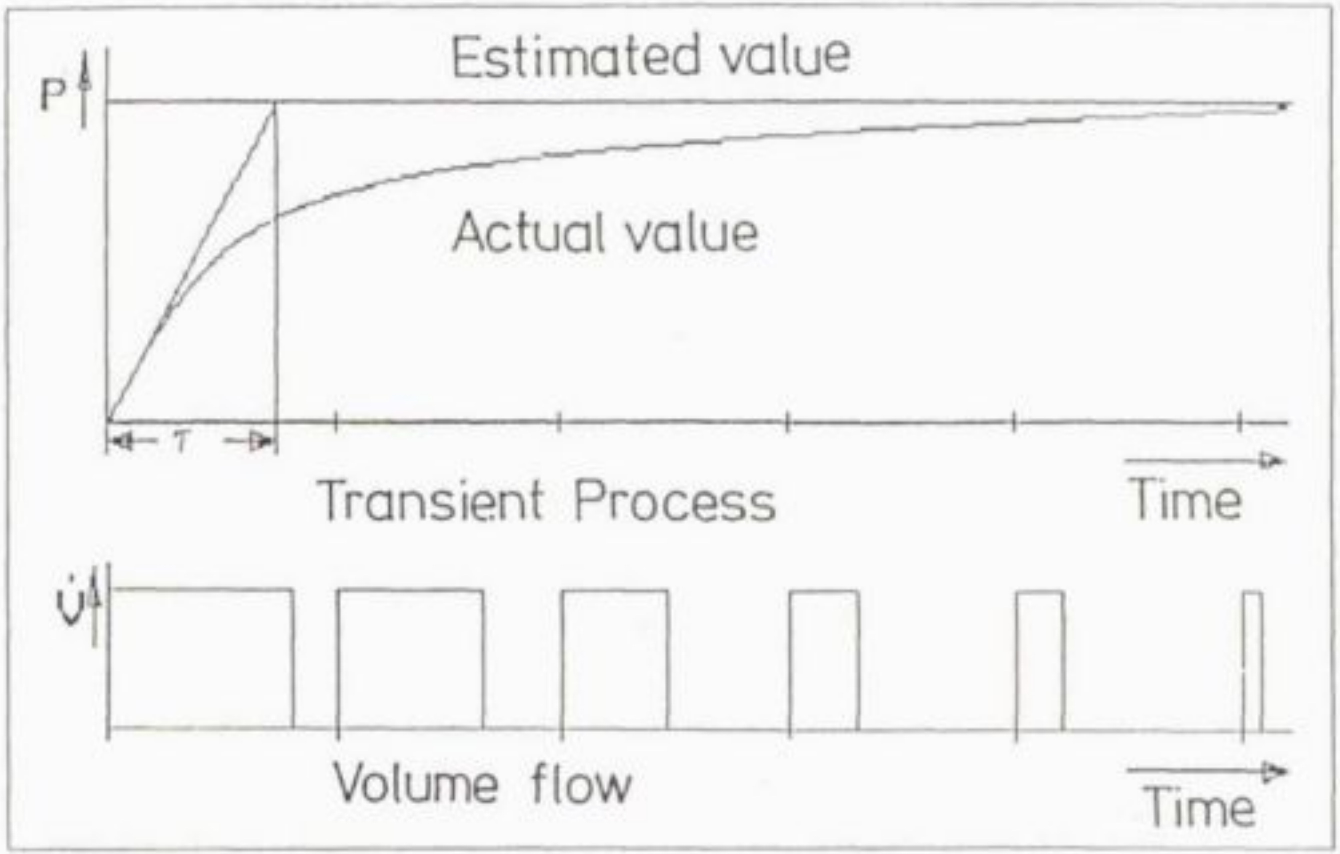


Fig. 2.4. Pulsation Duration Modulation for the regulation of soil water potential (From Durr et al., 1992).

(Vanassche) and two from the FAL (Durr and Schwarz) conducted the study.

The participation of members of the research team of the project reported in this study had three objectives:

(a) To determine whether the new electronic system was so much better than the mechanical system; that is, was it worthwhile to purchase the more expensive and technically more demanding and vulnerable (to power failures, etc) electronic system. No comparative study had yet been done at that stage.

(b) To gain first hand experience in the handling of this type of facility by physically working together with dr. Sommer, who had more than a decade of experience with the conventional "Sommer" system at that stage.

(c) To establish personal contacts with the researchers at FAL, as well as the developers and manufacturers of the electronic system (Pero of Braunschweig), with a view to solving of management and maintenance problems which might arise if we started using the system.

2.3.2 Experimental Evaluation

The conventional method (with constant underpressure) and the improved method (with electronic regulation) were compared in an experiment with spring barley, using three soil bulk densities and three soil water potential values (-6 kPa, -30 kPa and -60 kPa) with 8 replications. The pots had a diameter of 13 cm and a height of 18.5 cm and one ceramic cell each. Evaporation from the soil surface was reduced by covering the surface with styropor material.

The experiment was fully reported by Durr et al. (1992), but because of the unavailability of this publication in South Africa the main findings are summarized here.

Before planting, when there were no growing plants in the soil, the electronic system gave virtually perfect water regulation at all three pre-set soil water potentials (Figure 2.5). It was far superior to the mechanical system.

During the period of maximum rate of water consumption the electronic system still gave excellent water regulation at a pre-set soil water potential of -6 kPa and was much better than the mechanical system (Figure 2.6). Although the system was "merely satisfactory" (Durr et al., 1992) at pre-set soil water potentials of -30 and -60 kPa during this period, it was incomparably better than the mechanical system, which could not handle it at all. The critical period for water regulation in pots is the time during highest rate of water consumption by plants (Durr et al., 1992).

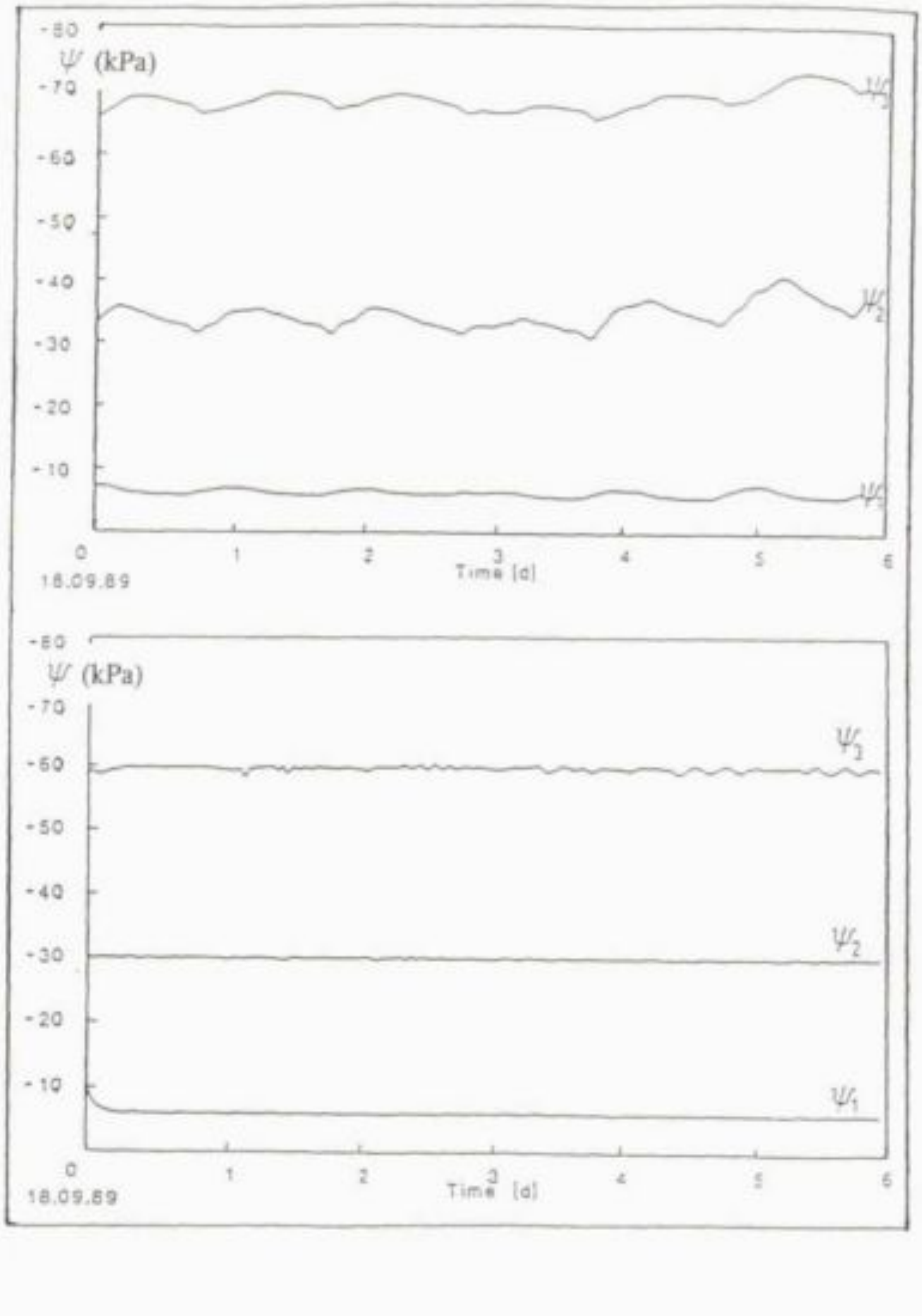


Fig. 2.5. Measured soil water potential (Ψ) values before planting. Regulation by the conventional method (top) and by means of the electronic device (bottom)(Adapted from Durr et al. 1992)

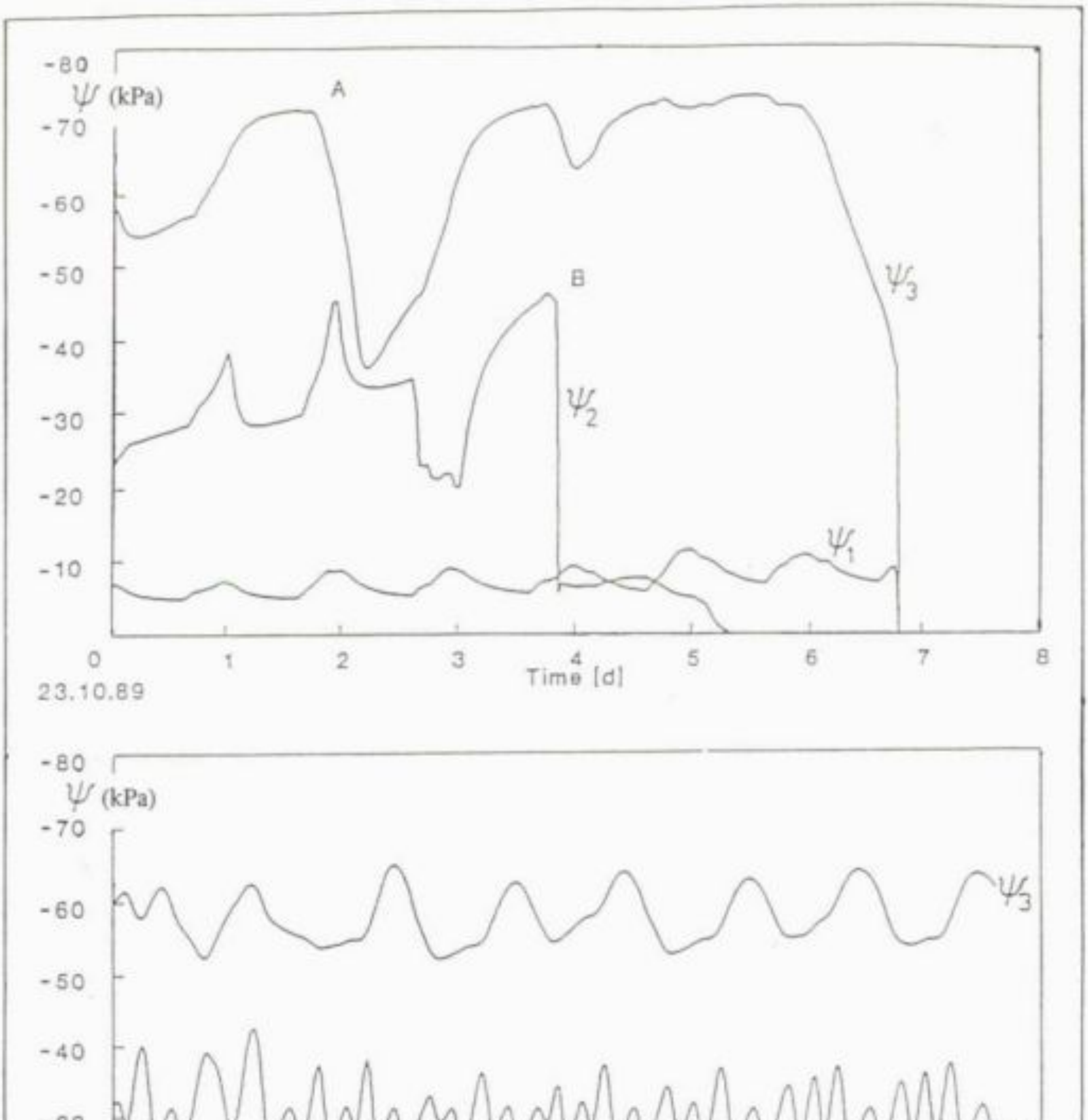


Fig. 2.6. Measured soil water potential (Ψ) values as a function of time during maximum water consumption. Regulation by the conventional method (top) and by means of the electronic device (bottom) (Adapted from Durr et al. 1992).

Water regulation at lower (e.g. -30 or -60 kPa) soil water potentials by the electronic system could be improved by increasing the ratio of cell:soil volume (Durr et al., 1992). This can be done by increasing the number of cells per pot.

According to Durr et al. (1992), the effectiveness of the system will depend upon the following factors:

* The unsaturated hydraulic conductivity of the soil. This is the best for loamy soils, which is why such soils were used in these experiments.

* The ratio of cell to soil volume: Depending on the size (diameter) of the pots one or more ceramic cells will have to be used.

* The porosity of the ceramic cells: The material (G8 Schumacher'sche Fabrik) allows for soil water potential values down to -80 kPa. In relation to water availability to plants these are still wet conditions (accepted permanent wilting point being -1500 kPa).

* The adjustable time interval for solenoid valve activation and the adjustable flow rate through these valves make it possible to correct regulation fluctuations. They must be adjusted as the water consumption increases during the vegetative growth period.

* There is still one problem: Water can only flow if there are potential gradients. Strictly speaking, this means that there cannot be one soil water potential value throughout the pot in the case of dynamic water consumption. On the other hand, there is no better method for continuous, automatic water regulation in pots at present.

* Only in a few cases were problems experienced with root growth around the ceramic cells. This can be avoided by correct installation of ceramic cells.

2.3.3 Achievement of Objectives

All three objectives were achieved highly successfully. In the first place the electronic system proved to be so far superior to the mechanical system that there was no doubt that the electronic system was the one to acquire for the WRC project at UP. Secondly, valuable practical experience was gained without which it would have been much more difficult and taken much longer to get the facility for this project operational. Thirdly, valuable personal contacts were made which were very useful to facilitate better management and maintenance of the facility at the University of Pretoria, when problems arose, by interaction with the persons at FAL and Pero. The biggest benefit was the fact that dr. Sommer not only assisted with purchasing of equipment for the UP facility, but in fact arranged for the donation of equipment by FAL to UP.

2.4 Primary Testing of the "Pero" System

2.4.1 General

Primary testing of the Pero facility assembled at the University of Pretoria was done before embarking on pot experiments with plants. The objectives of this testing were twofold, viz:

(a) To study the applicability of the Pero system to different soils that were available for pot experiments, especially a sandy soil.

(b) To study the importance of correct regulation time interval settings and to identify the optimum time interval setting.

2.4.2 Materials and Method

Four soils were included in this study. Three of these were red apedal soils of the Hutton form and one was an apedal soil of alluvial origin belonging to the Oakleaf form (Soil Classification Working Group, 1991). Two of the Hutton soils (Hutton 1 and Hutton 3) were from the M. Le Roux experiment farm of the University of Pretoria near Cullinan. The third one (Hutton 2) was from the Hatfield experimental farm of the University near the main campus in Pretoria. The Oakleaf soil was from a citrus grove on the farm Dunnbrody near Kirkwood in the Sundays River valley.

The particle size distribution for these soils are given in Table 2.1. Hutton 1 is a sandy soil. In addition the sand fraction is dominated by medium and coarse sand. The other three soils are medium-textured soils characterized by varying fairly high silt and very fine sand contents, which together with the fine sand, have important impact on pore-size distribution in these soils.

The soils were compacted to a bulk density of 1500 $kg.m^{3}$ in 10 dm^{3} metal pots. Each pot had one tensiometer to monitor the soil water potential and was independently regulated.

Table 2.1. Particle size distribution for four soils used in primary testing of the Pero system

Particle size distribution (%)	Soil			
	Hutton 1	Hutton 2	Hutton 3	Oakleaf
Very coarse + coarse sand	15	5	4	2
Medium sand	42	19	11	7
Fine sand	13	17	16	18
Very fine sand	6	14	23	36
Coarse silt +	2	4	3	
Fine silt	12	19	18	10
Clay	9	21	24	27

The soil water content in the pots was regulated by the Pero system until a soil water potential of -6 kPa was reached. The time interval for regulation was then set at 300 seconds for all pots. This time interval was then adjusted for each soil until straight or nearly straight soil water potential lines were obtained. The system was then reconfigurated for regulation of a soil water potential of -30 kPa. Due to several power failures, tests could not be done at a soil water potential of -60 kPa since time started becoming a limiting factor.

2.4.3 Results and Discussion

In the case of Hutton 1 (sandy soil) regulation was merely satisfactory for a time interval regulation setting of 300 seconds at a pre-set soil water potential of -6 kPa (Figure 2.7a). When the time interval setting was increased to 420 seconds the water regulation was much better (Figure 2.7b). This relatively long optimum time interval setting illustrates the poor unsaturated hydraulic conductivity of this sandy soil. Figure 2.7c illustrates the adverse effect on regulation when the time interval is too large (1200 seconds). Regulation of the soil water potential at a pre-set value of -30 kPa failed completely in this soil (Figure 2.8). The unsaturated hydraulic conductivity of this soil is too low and only for a pre-set value of -6 kPa the system was able to keep the soil water potential constant - and only at a relatively long time interval setting.

In the case of the Oakleaf soil almost perfect regulation was obtained with a time interval of 300

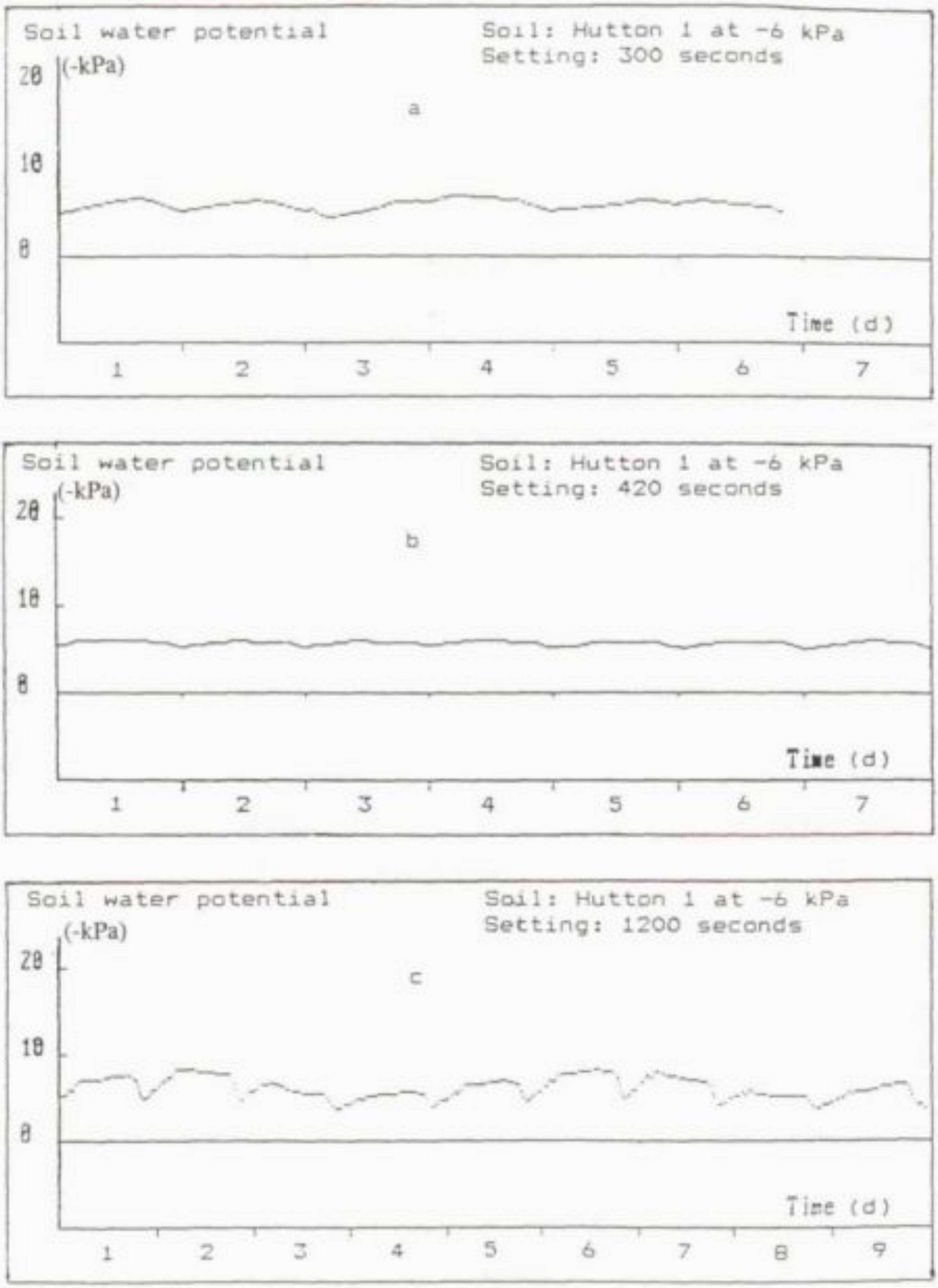


Fig. 2.7. Time interval regulation setting for Hutton 1 soil at -6 kPa at (a) 300 (b) 420 and (c) 1200 seconds.

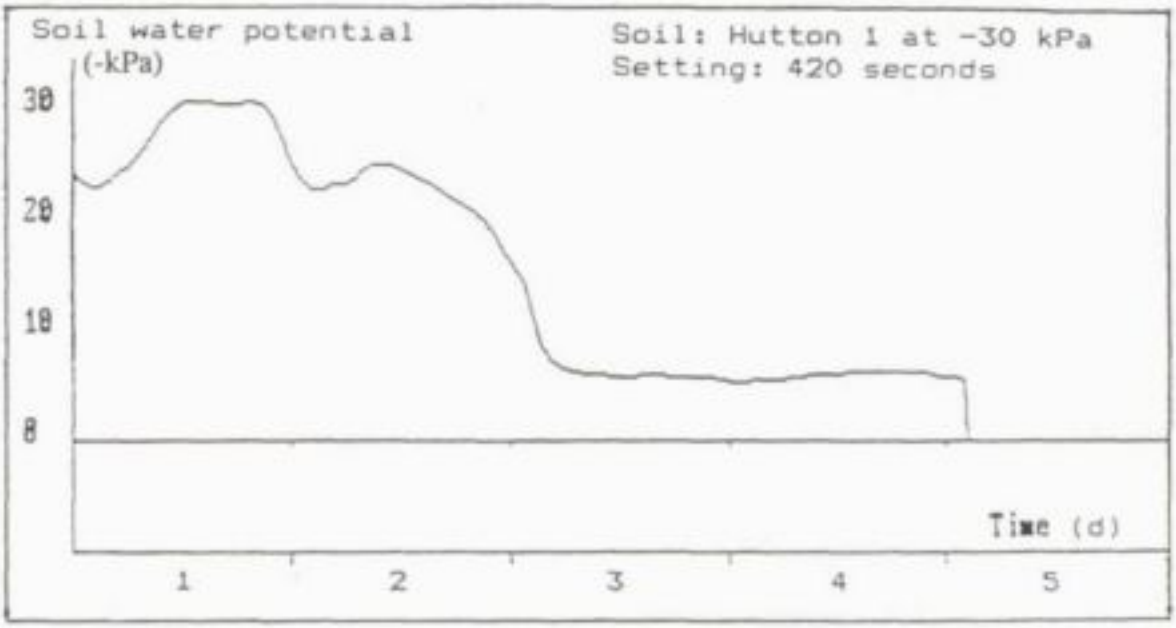


Fig. 2.8. Time interval regulation setting for Hutton 1 soil at -30 kPa at 420 seconds.

seconds at a pre-set soil water potential value of -6 kPa (Figure 2.9a). In this case a time interval of 420 seconds (the optimum for the sandy Hutton 1 soil) was too long and gave erratic results (Figure 2.9b). Regulation at -30 kPa soil water potential was not quite satisfactory, but acceptable (Figure 2.9c). Unfortunately better time interval selection studies could not be done at this soil water potential value due to the power failures. Results for the Hutton 2 soil were very similar to those for the Oakleaf soil.

In the case of the Hutton 3 soil almost perfect results were obtained at a pre-set soil water potential value of -6 kPa with a time interval setting of only 240 seconds. This reflects the good unsaturated hydraulic conductivity of this stable soil. Fair results were also obtained at -30 kPa with a time interval setting of 240 seconds in this soil.

2.4.4 Conclusions

From this study the following can be concluded:

- Soils with coarse sandy textures similar to the Hutton 1 soil are not suitable for experiments which require a constant soil water potential. Regulation of the soil water potential was only satisfactory for a pre-set value of -6 kPa at a relatively long time interval setting.

- Medium-textured soils similar to the Hutton 2, Hutton 3 and Oakleaf can be used in this type of experiment. However, one must take into consideration the amount of cells to be used. It will be necessary to use two or more cells for efficient regulation at soil water potentials of -30 kPa and lower.

- Finally, this experiment proved that the time interval between measurements is very important. In order to achieve a satisfactory regulation of the soil water potential, one has to choose the correct time interval for each case. This experiment was conducted in a soil without any plants. The only soil water loss was due to evaporation which was reduced as the soil surface was covered with styropor material. In other words this experiment was conducted in a quasi-static system where water extraction from the soil was more or less constant. When a plant is grown in the pot, water extraction will increase as the plant is growing. In this case we deal with a dynamic system. It is obvious that in a dynamic system this time interval will have to be adjusted as water extraction increases during the vegetative growth period.

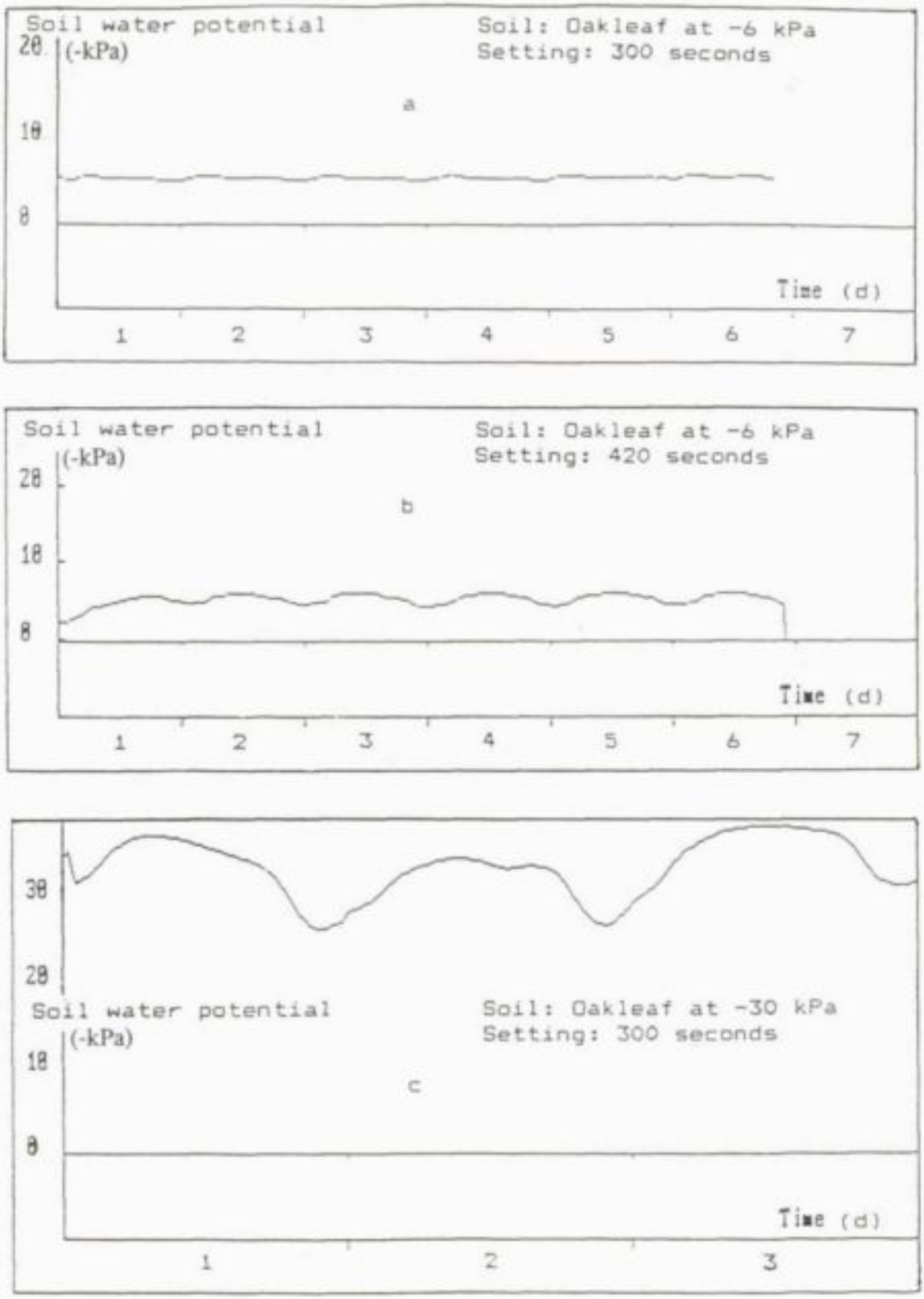


Fig. 2.9. Time interval regulation setting for Oakleaf soil at -6 kPa at (a) 300 and (b) 420 seconds, and at (c) -30 kPa at 300 seconds.

2.5 Comparative Evaluation of the Effectiveness of the Pero System at Low and High Bulk Densities in a Dynamic Situation

2.5.1 General

In the experiment with the four soils it was found that the regulation of soil water potential in the sandy soil was not very effective, especially at the lower soil water potentials, due to poor hydraulic conductivity. A similar situation could arise, for the same reason, at a low bulk density in a medium-textured soil.

In the evaluation study in Braunschweig, bulk densities of 1460 $kg.m^{-3}$, 1510 $kg.m^{-3}$ and 1650 $kg.m^{-3}$ were used. In our study with the four soils a bulk density of 1500 $kg.m^{-3}$ was used.

As indicated, the critical test for water regulation is in a dynamic situation when the water uptake rate by plants is at a peak. For this reason, citrus rootstocks were grown in pots where the soil water potential was regulated using a Pero system.

2.5.2 Materials and Method

The Oakleaf soil from Dunnbrody (Table 2.1) was used in this experiment. The soil was sterilized to eliminate soil-borne pathogens. All bottles and tubing were also sterilized.

Six pots with compacted soil (soil bulk density 1700 $kg.m^{-3}$) and six pots with non-compacted soil (bulk density 1400 $kg.m^{-3}$) were prepared. The soil water potential was regulated to a pre-set value of -6 kPa by means of the Pero system in three pots with compacted and non-compacted soil before the seedlings were transplanted. The same was done for a soil water potential of -30 kPa. Evaporation was greatly reduced by covering the soil with styropor material.

One Troyer citrange (Poncirus trifoliata L. Raf X Citrus. sinensis) seedling was transplanted into each pot on September 12, 1991. The experiment was then run for 144 days.

2.5.3 Results and Discussion

Only aspects related to soil water regulation will be discussed here. Aspects related to plant performance will be discussed in Section 4.3. The results given are the soil water potentials measured in the pots near the end of the experiment at maximum plant growth.

In compacted soil a very good soil water potential regulation was obtained at a pre-set soil water potential value of -6 kPa (Figure 2.10a). The regulation was slightly less stable than with the best time interval setting under static conditions (no plant grown in the pot) in the previous test (at a lower bulk density) for this soil (Figures 2.9a and 2.10a). In non-compacted soil at -6 kPa the regulation was slightly less stable than in the compacted soil, but still very good (Figure 2.10b).

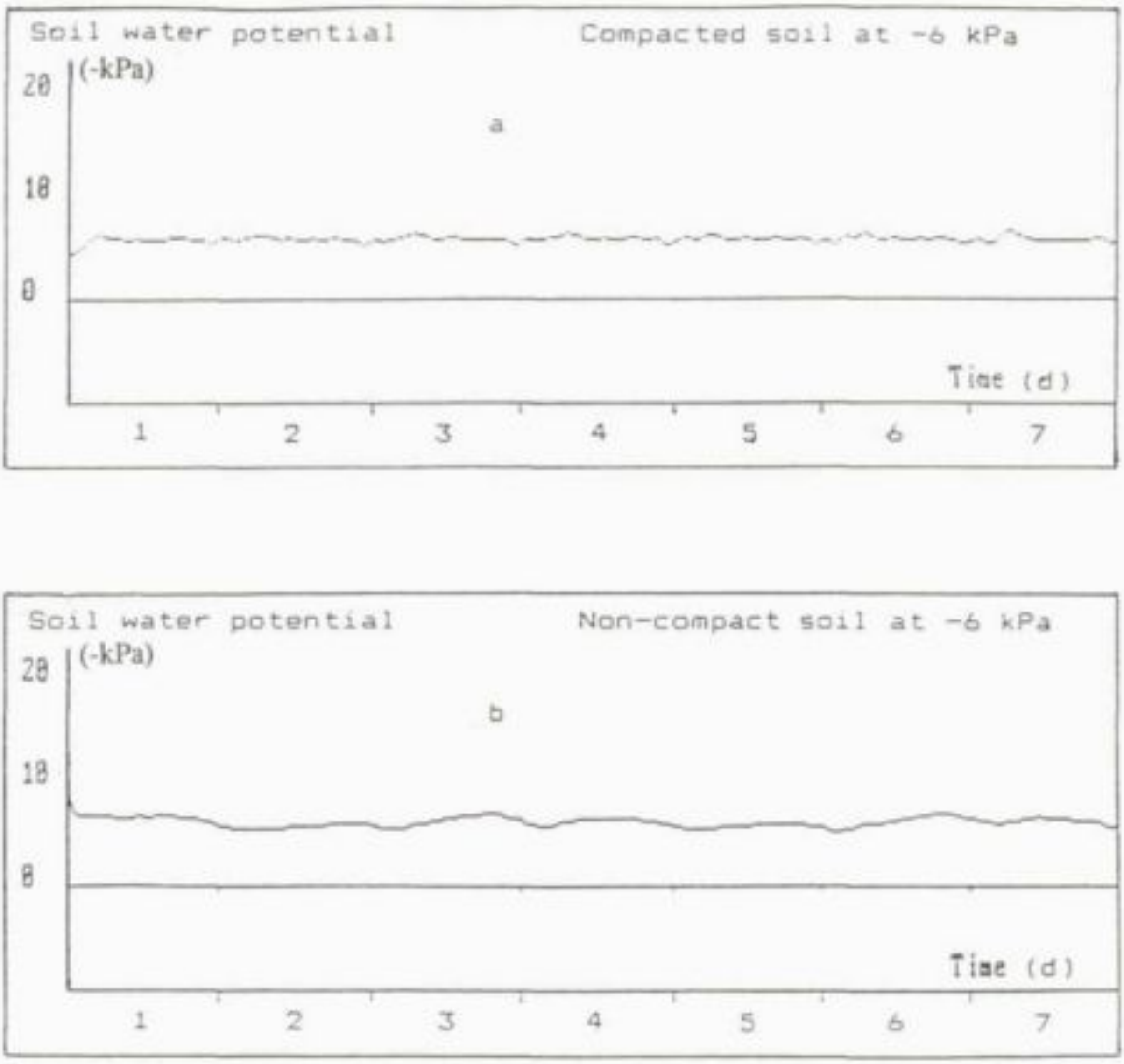


Fig. 2.10. Soil water potential regulation in (a) compacted and (b) non-compacted soil at -6 kPa.

It was much better than under a static condition with an incorrect time interval setting (Compare Figures 2.9b and 2.10b). An important aspect seen from Figures 2.10a and 2.10b is that the soil water potential did not drift, but maintained a constant average value. This indicates excellent soil water regulation by the Pero system at high soil water potential under a dynamic system (where water is extracted by plants) in both compacted and non-compacted soil.

Soil water regulation at -30 kPa showed clear diurnal fluctuations in both the compacted and non-compacted soils (Figures 2.11a, b). Although the amplitude of these fluctuations at first sight looks much larger than that for the same soil in the previous static study (Figures 2.9c), this is in fact not the case. The amplitudes of the fluctuations are very similar. It is only the difference in scale on the x-axis of the graphs that creates a false impression of larger deviations in a vertical direction.

The amplitudes of the fluctuations at -30 kPa in compacted and non-compacted soil were also very similar. There are two noteworthy aspects, however:

(a) In the compacted soil the average soil water potential was maintained almost perfectly at the pre-set -30 kPa over the whole period (Figure 2.11a). In non-compacted soil the soil water potential drifted up (i.e. to less negative values) during days 3 and 4 of the measuring period (Figure 2.11b) and then recovered slowly during days 5 and 6 until a correct average value was reached again on day 7.

(b) In the compacted soil virtually perfect plateaux were found on day 2 and days 4 and 5 at exactly the correct pre-set value (Figure 2.11a). The non-compacted soil also gave plateaux on day 2 and day 4, but the first one was too low (-35 kPa) and the second one too high (-25 kPa)(Figure 2.11b).

2.5.4 Conclusions

For both compacted and non-compacted soil the Pero system gave very good soil water regulation at a pre-set soil water potential of -6 kPa. From this point of view both these bulk densities are, therefore, suitable for soil water studies in medium-textured soils. Despite diurnal fluctuations in soil water potential values, the average value was maintained at the correct pre-set value of -30 kPa in the compacted soil. On some days the correct value was maintained perfectly. Studies can, therefore, be done at this soil water potential value in such compacted soil. In non-compacted soil at -30 kPa the diurnal fluctuations did not exceed those in the compacted soil, but the average drifted from the pre-set value at times. This drifting was towards the wet side. The system is not entirely satisfactory for studies at this lower soil water potential in soil with such relatively low bulk density. It is, however, still much better than any other system of soil water regulation.

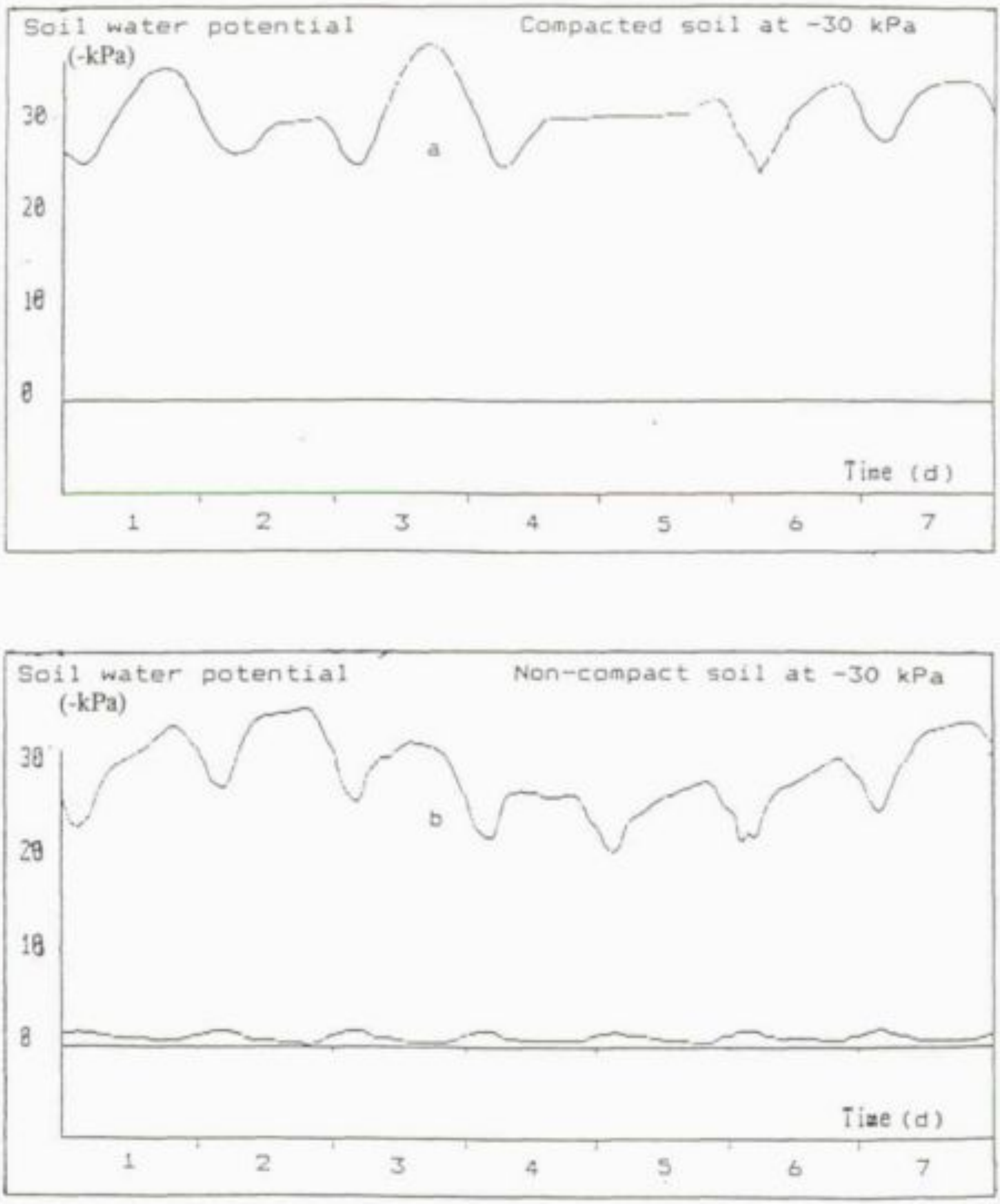


Fig. 2.11. Soil water potential regulation in (a) compacted and (b) non-compacted soil at -30 kPa. The bottom line indicates water potential of free water.

Plant performance was very bad at both soil water potentials in the non-compacted soil (bulk density 1550 kg.m^{-3}). Despite the fact that the Pero system performed well (at -6 kPa) to moderately well (at -30 kPa) with regard to soil water regulation in non-compacted soil (Oakleaf), studies of this nature can be difficult because of the problems with plant performance at such low bulk density.

2.6 Artificial Nature of the Diurnal Fluctuations in Soil Water Potentials in Pots Observed at the University of Pretoria's Pero Facility

From the results of the previous two studies it is clear that where fluctuations in soil water potential occurred in the pots they had a very specific similar recurring pattern (e.g. Figures 2.9c and 2.11). Once every day at a specific time the soil water potential rose sharply and then recovered again quickly. This gives a pattern of sharp downward bends in the graphs and broad upper curves. These patterns were found repeatedly in all subsequent studies with the facility.

The recurring "once a day" fluctuation found here is a sharp contrast to the fluctuations found under dynamic conditions in the study in Braunschweig. In the latter case there was a continuous series of sharp, short fluctuations throughout each day (See, for example, the -30 kPa curve in Figure 2.6b). In the case of the Braunschweig study it is clear that there was a problem with the assembly and/or the management of the system. Consequently, the system clearly had problems in regard to providing smooth water regulation. In the case of the Pretoria facility the fluctuations are of such a nature that there must be some artificial cause.

Tests with some of the pressure-transducer tensiometers in pure water revealed regularly recurring apparent "drops" in the potential of water, as evidenced by the small upward "bumps" in the line at the bottom of Figure 2.11b. These "drops" in the potential of pure water coincided with time of the day when the increase in soil water potentials in the pots are found (the downward curves in the graphs). Even the almost perfect line found with Oakleaf soil in a static system at a soil water potential of -6 kPa (Figure 2.9a) shows minute increases in soil water potential at this same time of the day each day, followed by a minute over-correction for a short period.

Any condition that will cause the system to perceive that there is a drop in soil water potential below the required level will trigger a signal that will cause it to release water to correct this perceived "deficiency". The apparent drop in water potential in the free water is a reflection of some condition that will also cause a tensiometer in a pot to perceive an apparent drop in soil water potential, to which it will then respond. It should be kept in mind that the pressure membrane/electronic transducer combination in the tensiometer is very sensitive to pressure changes. It registers a pressure change as small as 0.01 kPa.

It is physically impossible for the potential energy of free water to change. The apparent "drop" in the water potential at a specific time of the day each day, must therefore be associated with some atmospherically (e.g. temperature) induced pressure change which impacts on the pressure membrane of the tensiometer. Since this phenomenon always occurs from noon onwards, the following possible explanation can be given: when the temperature of water in the tensiometer

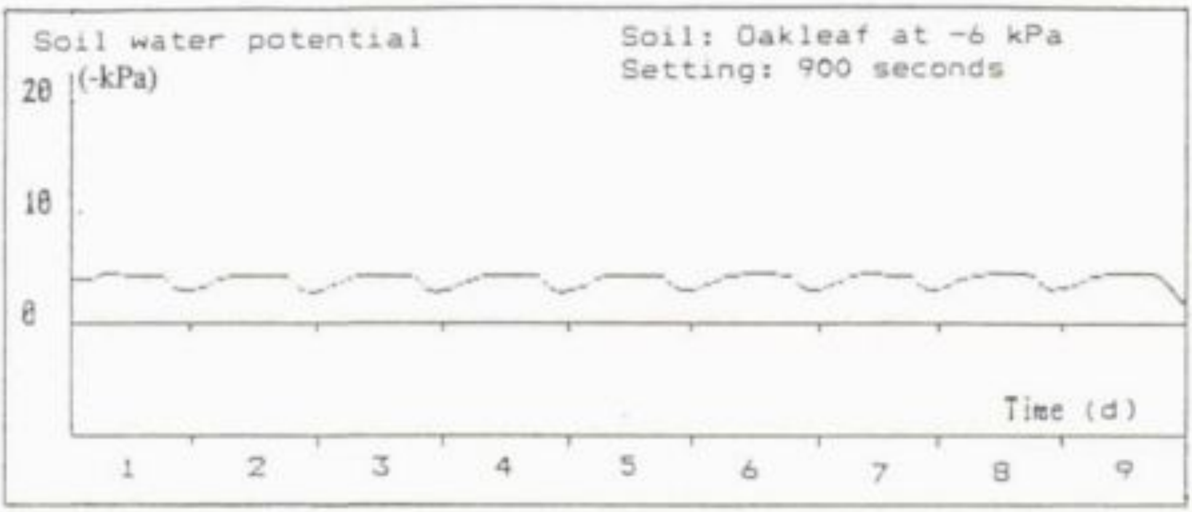


Fig. 2.12. Time interval regulation setting for Oakleaf soil at -6 kPa at 900 seconds.

increases, there is an increase in pressure which is then sensed by the pressure membrane/electronic transducer combination of the tensiometer. The pressure change is then interpreted by the Pero system as a change in soil water potential and triggers the regulation process of the system. This ultimately leads to these minute fluctuations in water potential.

The response of the Pero system to this condition will be affected by the hydraulic conductivity of the soil (which is a function of texture, bulk density and soil water potential) and the time interval setting of the system. The latter is clearly illustrated by comparing the 300 and 900 second time interval settings (Figures 2.9a and 2.12) for the Oakleaf soil at -6 kPa soil water potential in the static test described in Section 2.4. As pointed out earlier, at the 300 second setting there were minute, short dips in the graph followed by minute over-compensation (Figure 2.9a). At the 900 second setting, with its slower response, there were wider, deeper dips in the graphs (Figure 2.12). In between the artificial dips, this setting gave perfect regulation at the desired pre-set value (as indicated by the horizontal straight lines).

2.7 Conclusions

There is no doubt that the electronic Pero system, combined with vertically inserted ceramic diaphragm cells, is excellent for soil water regulation in pots. It is also clear that management of this system has been sorted out well by the research team on the WRC sponsored project at the University of Pretoria.

Research of this nature is also very strongly dependent on top-grade greenhouse/phytotron facilities and a good infrastructure, especially in regard to the provision of a reliable electrical power supply. Poor temperature and relative humidity control in the greenhouse and electricity power cuts, especially, may have a negative impact on this type of research.

CHAPTER 3

GENERAL RESEARCH PROCEDURES

3.1 Soil Water Regulation

In all experiments soil water regulation was done by means of the Pero system (Refer to Chapter 2). The system was managed in accordance with the results obtained during the evaluation studies.

In this study, the time interval setting was between 300 and 420 seconds. Two diaphragm cells were placed vertically in each pot in order to achieve a more even water distribution. The diaphragm cells were placed equidistant (10 cm) from both the seedling and the tensiometer in all pots. For each diaphragm cell, a hole of the same size as the cell was drilled and filled with a soil slurry and the diaphragm cell was pushed into the hole. This facilitates a good contact between diaphragm cell and the soil.

3.2 Plant Material

Two types of citrus rootstock, Rough lemon (Citrus jambhiri Lush.) and Troyer citrange (Poncirus trifoliata L. Raf X C. sinensis), were used. Plants were either ordered as seedlings from a nursery or seed was germinated. When the latter was used, the seed was germinated in vermiculite on speedling trays, covered with clear plastic to minimize drying-out of the growing medium. The seedlings were then transplanted into pots at the beginning of the experiments, and covered with shadecloth to minimize wilting and transplant shock. In most experiments, the seedlings were harvested after 120 - 150 days.

3.3 Soils

Different soil types (specified in each experiment) were used in this series of experiments. The soils were selected on the basis of differences in suitability for citrus growth, and their physical characteristics. In each case the soil was compacted into 10 dm^3 metal pots to dry bulk densities (DBD) of 1700 (compacted) and 1550 $kg.m^{-3}$ (non-compacted). Uniform compaction throughout a pot was achieved by not adding all soil at once, but by compacting it in small amounts. The soil was compacted in such a way that no transitional layers were formed as a result of compaction. This was achieved by loosening the surface of the compacted soil every time before more soil was added into the pot. Full details about the compaction procedure are given by Bennie (1972).

It should be kept in mind that the "non-compacted" soil, with a dry bulk density of 1550 $kg.m^{-3}$ is by no means "loose" soil. Its DBD is already higher than the 1500 $kg.m^{-3}$ which was found to be the limit above which the growth of sensitive deciduous fruit rootstocks was severely restricted (Terblanche, De Kock & van Zyl, 1974). The fact that the "non-compacted" soil is not "loose" soil should also be kept in mind when considering the unsaturated hydraulic conductivity effects in later chapters.

The use of a DBD of 1550 $kg.m^{-3}$ as "non-compacted" soil is realistic in terms of the real situation in South Africa where even virgin subsoils often have DBD's higher than 1600 $kg.m^{-3}$.

3.4 Measurements

The daily, weekly, and cumulative water uptake by each plant were calculated (Refer to Section 2.2). The plant height was measured using the Marler & Davies (1989) method. Briefly, the height was measured, using a ruler, from the soil surface to the branch of the topmost leaf. The temperature and relative humidity in the greenhouse were measured using a thermohygrograph. During harvest, several measurements were taken. The leaf area and projected root area were measured using a leaf area meter (Syvertsen, 1981). Leaves from seedlings were carefully cut from the stem and branches and run through the meter. Roots were cut from both the stem and main root, and air-dried in the shade for a few hours before projected area measurements were taken. This was done such that there was no or very minimal shrinking of the roots during the process. The projected root area was then multiplied by pi (3.14159) to correct it to estimated root surface area. The roots and leaves were then collected together with corresponding stems and main roots into paper bags for dry mass determination. The top:root ratio and water use efficiency were calculated.

The root volume was measured using the water displacement method (Marler & Davies, 1989). This was done by filling a flask with water and measuring the mass. The roots were then placed in a flask full of water such that some water from the flask overflows. They were then pulled out of the flask and allowed to drain into the flask. The flask was weighed again and the difference in water mass was calculated. Since the mass (g) of water is equivalent to the volume (cm^3) of water at room temperature, the displaced water was considered to be equivalent to the root volume.

3.5 Root Hydraulic Conductivity

The root hydraulic conductivity was determined using Syvertsen's (1981) method as follows: The soil was carefully removed from the roots and the plants were left in deionized water for 24 hours. The roots were thoroughly washed with deionized water and the stem was cut about two to three centimeters above the soil level. The root system was then placed in a modified Scholander pressure chamber (Vanassche & Laker, 1989) with 2 cm of the stem protruding above the chamber. The chamber was filled with water and a pressure of 1000 or 1500 kPa (specified in each experiment) was gradually applied and maintained. The time taken to exude 1 cm^3 water from the root system was recorded. The root hydraulic conductivity was calculated and expressed as volume (cm^3) of water exuded per root surface area (cm^2) per applied pressure (Pa) per time (s).

3.6 Aeration of Nutrient Solution

In the nutrient solution studies 10 dm^3 metal pots were filled with full-strength Hoagland's solution which was prepared with deionized water and replaced every two weeks. The plants were held onto the lid with sponge such that the roots were submerged into the nutrient solution while the top growth was exposed above the surface. The pH of the Hoagland's solution was measured with a pH meter (Astell model 3050) every week. When necessary, the pH was adjusted with dilute NaOH or HCl solution. Air was supplied into the nutrient solution through plastic tubing connected to a compressor. The air supply apertures on tubes were drilled such that uniform supply was achieved in all aerated pots. The pots were aerated for 7.5 hours every day, between 08H00 and 15H30.

3.7 Fertilization and Pest Control

The seedlings in soil experiments were fertigated with 100 cm^3 full-strength Hoagland's solution per pot per month. Dithane M-45 was used to control leaf rust, especially on TC seedlings. When necessary, Malasol and Metasystox were used alternatively to control red spider mite on both RL and TC seedlings.

3.8 Statistical Analysis of the Results

Analysis of variance was used to determine significant differences and Duncan's multiple range test was employed for mean comparison at $p<0.05$. Actual data and computed means are presented together with corresponding standard errors (S.E.) and least significant differences (LSD). Unless otherwise specified, the term statistically significant difference was used for $p<0.05$.

CHAPTER 4

EFFECTS OF SOIL COMPACTION ON YOUNG CITRUS PLANTS GROWING AT HIGH SOIL WATER POTENTIAL

4.1 Introduction

Soil compaction produces many adverse changes in the rhizosphere and the nature of these changes depends on the physical and chemical characteristics of a particular soil. Most of the changes that occur in compacted and waterlogged soil can be basically attributed to oxygen deficiency (Drew, 1992; Rowe & Beardsell, 1973). The negative effects of oxygen deficiency in plant roots may be compounded either by the formation of toxic hydrogen sulphide in waterlogged soil or by the auto-toxic production of hydrogen cyanide by the roots of certain plant species. Moreover, the formation of ethylene and the accumulation of carbon dioxide in waterlogged soil can add to the effects of oxygen deficiency.

Other factors tend to complicate the effects of soil compaction and waterlogging on different plant species. These factors make it extremely difficult to isolate any one change in soil conditions as being the cause of poor plant performance. For example, certain stress factors can be tolerated by certain cultivars of the same species, but not by other cultivars.

Sommer & Schwarz (unpublished), using the Sommer facility, found that some wheat cultivars had an ability to increase water use efficiency as water supply decreased. Durr et al. (1992) found that spring barley used less water when grown on a compacted soil than on a non-compacted soil. The plant growth was also reduced by soil compaction. It means that, to a large degree, consideration of soil barriers to plant development involves consideration of the root system and its activities, efficiency of water use by crops, the final yield, and more importantly the economic yield (Reuss & Danielson, 1974).

There is no information available on the effects of soil compaction on citrus seedling development at constant and high soil water potential as would be expected under drip or micro-sprinkler irrigation. Two experiments were conducted using Troyer citrange (in the first experiment) and Troyer citrange and Rough lemon (in the second experiment).

4.2 Materials and Treatments

Soil of alluvial origin (Oakleaf form) from a citrus orchard at the farm Dunnbrody near Kirkwood in the Sundays River valley in the Eastern Cape was used in this study. This is a problem orchard in which citrus does not perform well. The soil has a clay content of 27%. The most striking characteristic of the soil is its high content of silt + very fine sand + fine sand (64%), composed of 10% silt, 36% very fine sand, and 18% fine sand. Medium sand (7%) and coarse and very coarse sand (2%) comprise only a very small fraction of the total soil mass. Such soils with more than 50 % (silt + very fine sand + fine sand) and less than 35% clay, represent typical "hard-setting" soils of the Eastern Cape which are extremely vulnerable to compaction and crusting. The pH of the soil (2:5 water) is 7.9.

4.3 Experiment 1

The specific research procedures for this experiment have been discussed in Section 2.5.2. Briefly, TC seedlings were planted in compacted (DBD = 1700 $kg.m^{-3}$) and non-compacted (DBD = 1400 $kg.m^{-3}$) Oakleaf soil. Soil water potential was regulated at -6 kPa in half of the pots with non-compacted soil and half of those with compacted soil. In half of the pots, the soil water potential was regulated at -30 kPa. A total number of 12 pots were used. The plants were grown for 144 days.

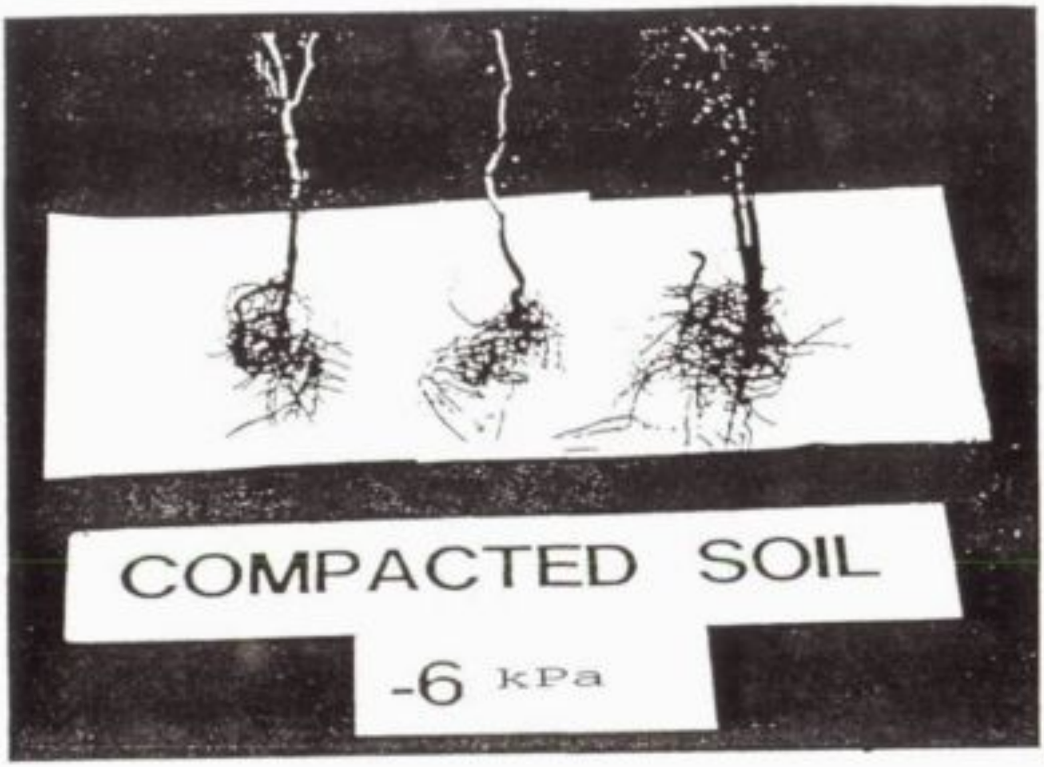
In addition, the general research procedures described in Chapter 3 were followed.

4.3.1 Results and Discussion

Results regarding soil water regulation in the first experiment have been discussed in Section 2.5.3. Only results pertaining to plant responses will be discussed here.

At both soil water potentials plant growth in non-compacted soil (DBD = 1400 $kg.m^{-3}$) was extremely poor, compared to plant growth in the compacted soil (Table 4.1). This was probably the result of poor root-soil contact during the initial growth stages and/or poor hydraulic conductivity of the soil at this low bulk density. The latter would mean that the poor hydraulic conductivity had a severe limiting effect on water supply to the roots although it did not have a serious negative effect on water regulation (Refer for the latter to Section 2.5.3). Total consumptive water use over the duration of the experiment was low in non-compacted soil (Table 4.1). The fact that both consumptive water use and plant mass were lower at -30 kPa than at -6 kPa in non-compacted soil supports the perception that low hydraulic conductivity was a serious limiting factor in this soil. Hydraulic conductivity would have been lower in the drier soil water regime of the two (i.e. at -30 kPa).

The biggest plants, together with the best developed root systems, were obtained in the compacted soil at a soil water potential of -30 kPa (Table 4.1 and Plate 4.1). This is due to a relatively high hydraulic conductivity of the soil resulting in an adequate water flow to the roots, which was maintained for the duration of the experiment. The seedlings in compacted soil at -6 kPa were poor compared to those at -30 kPa probably because of the waterlogging at this high soil water potential.



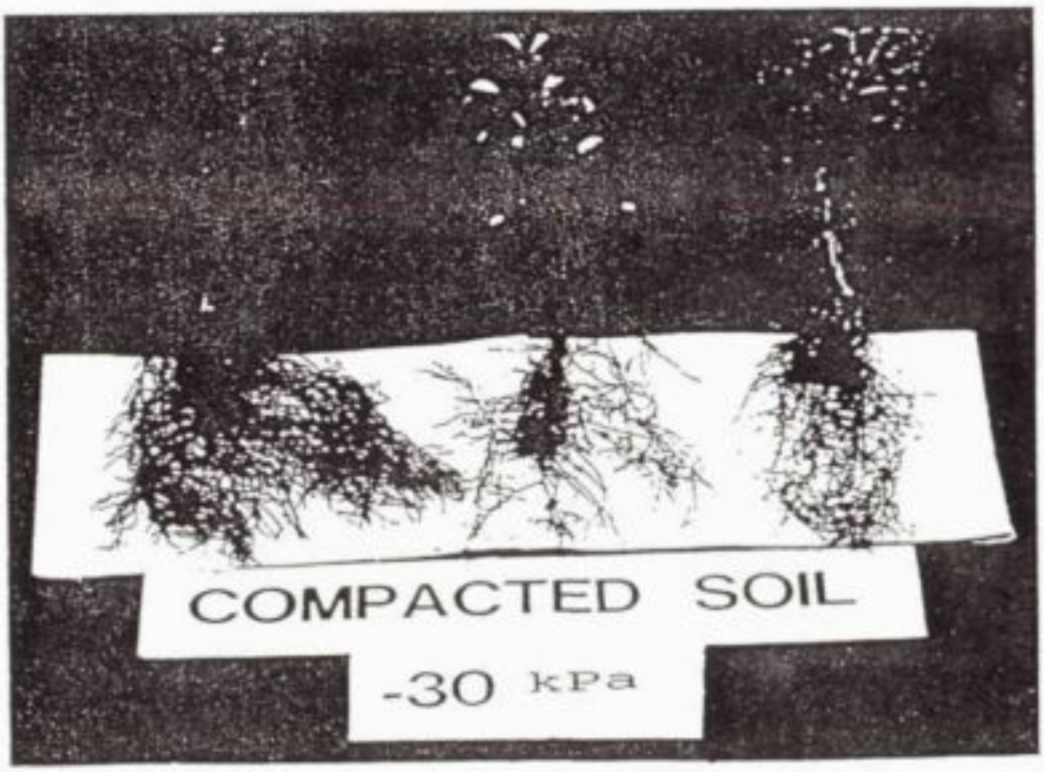


Plate 4.1. Root system of TC seedlings grown in compacted soil at -6 and -30 kPa.

Table 4.1 Citrus (TC) seedling growth and water use at two soil bulk densities and two soil water potentials

Treatment	Total dry mass (g)	Top dry mass (g)	Root dry mass (g)	Water uptake (dm^3)	WUE* ($g.dm^{-3}$)
			Non-compacted soil		
-6 kPa	2.21**	1.69	0.52	6	0.37
-30 kPa	1.14	0.77	0.37	4	0.29
			Compacted soil		
-6 kPa	7.61	4.62	2.99	12	0.63
-30 kPa	16.57	9.54	7.03	10	1.66

* WUE - water use efficiency

** these figures are given for illustration purposes, no statistical analysis was done.

This was illustrated by reducing conditions found in the soil at the end of the experiment. From a depth of 50 mm the soil showed a uniform light grey colour. Another phenomenon observed in this case was the tendency of the roots to grow upwards. This was not found in the compacted soil at -30 kPa. It can, therefore, be concluded that this was more a consequence of waterlogging (lack of oxygen) than of soil compaction per se. The much better plant growth in compacted soil at -30 kPa soil water potential was achieved despite the fact that the total water use at -30 kPa was nearly 20% lower than at -6 kPa (Table 4.1). The consequence was a much higher water use efficiency (mass of plant material per unit water used) at -30 kPa than at -6 kPa. Thus maintaining the soil water potential at the very high level (-6 kPa) not only restricted plant growth as a result of poor aeration, but also led to luxury consumption of water. This cannot be afforded where water is a scarce resource.

4.3.2 Conclusions

From the results of this study it is concluded that a dry bulk density of 1400 $kg.m^{-3}$ is too low for this type of study. A dry bulk density of 1550 $kg.m^{-3}$ was consequently used to represent "non-compacted" soil in all subsequent experiments.

Soil compaction by itself was not the only factor limiting the growth of plants, but the water status of the soil must also be taken into consideration. Soil compaction combined with high soil water levels resulted in waterlogging and impeded root growth due to a lack of oxygen. This was illustrated by the upwardly growing roots of seedlings in the compacted soil at -6 kPa, their poor top and root growth and their lower water use efficiency (WUE). One must also keep in mind that the soil used in these experiments was sterilized and that the effect of soil borne pathogens was, therefore, excluded. In a real or field situation it is to be expected that soil pathogens will have a superimposed deteriorating effect on the plants in waterlogged soils. The TC used in this experiment is a trifoliate type known to be tolerant to heavy (or compacted) soils. The results obtained show that the seedlings were doing well in the compacted soil at -30 kPa but grew poorly at -6 kPa. This shows that the effects of soil compaction must also be interpreted in terms of soil water regime.

Root development at high bulk density of 1700 $kg.m^{-3}$ was in fact quite surprisingly good where adequate aeration was ensured by a somewhat lower soil water content/potential. In a field experiment on a problem citrus grove in the same area from which this soil was collected, greatly increased root growth was obtained by simply eliminating a dense soil crust by means of an organic soil conditioner (Laker, unpublished data). Both rooting depth and root proliferation were increased. Only the top 3 to 5 mm of the soil was treated. Improved rooting depth and root proliferation were thus achieved even without deep cultivation to reduce the bulk density of the soil. This means that elimination of the crust not only increased water infiltration, but also improved soil aeration.

4.4 Experiment 2

In this experiment, the effects of high soil water potential in compacted and non-compacted soil on the growth and development of RL and TC seedlings was determined. These two types of citrus rootstocks are known for their different response to various rhizospherical conditions.

Twelve metal pots, six with compacted soil (DBD = 1700 $kg.m^{-3}$) and six with non-compacted soil (DBD = 1550 $kg.m^{-3}$), were used for the experiment. The soil water potential was maintained at -6 kPa in all the pots throughout the experimental period.

The seedlings from the nursery were transplanted into the pots on May 6, 1992. At this stage the seedlings were 20 cm tall. The water uptake by seedlings was calculated from the water-storage bottle readings (Refer to Chapter 2). The seedlings were harvested on September 28, 1992, 145 days after transplanting.

4.4.1 Results and Discussion

Soon after transplanting, the seedlings showed some wilting which was probably a result of transplant shock. Although all plants were wilted, it was more severe in TC seedlings than in RL. However, this was overcome by shading the seedlings with a 50% shadecloth. Moreover, the relative humidity was improved by wetting the floor in the greenhouse at least once per day.

4.4.1.1 Soil Water Potential

During the first four weeks after transplanting, the soil water potential was easily and continuously maintained at -6 kPa. This was especially the case with compacted soil (Figure 4.1). In non-compacted soil, there were some minute diurnal fluctuations in soil water potential (Figure 4.2) which were also found with a tensiometer standing in free water (bottom line).

As these fluctuations were also detected in free water, they were probably caused by external factors, such as temperature change at midday. These fluctuations increased somewhat as the plants developed and became more pronounced than those measured in free water (Figure 4.3). The fluctuations measured later in the growing season were therefore the result of two factors: 1) an external factor, which was also noted in free water and 2) a soil-plant factor indicating the pattern of water-uptake and the regulation of the soil water potential by the system. The second factor was more pronounced in RL (Figure 4.3) than in TC (Figure 4.4). This was probably due to the bigger leaf area and more extensive root system of RL and therefore higher transpiration rate compared to TC. Furthermore, with RL the amplitude of the fluctuations in non-compacted soil (Figure 4.5) was bigger than that in compacted soil (Figure 4.3).

The minute fluctuations in water potential of free water do not mean any change in water potential per se. However, this shows an effect of temperature change on the tensiometer membrane. These fluctuations are, however, very small. This is probably due to the high heat capacity of water compared to SiO_2 which is the main component of soil.

4.4.1.2 Water Consumption

The daily water consumptive rate of RL in non-compacted soil was slightly lower than in compacted soil for the first 12 weeks after transplanting (Figure 4.6). This was probably due to a poor contact between the root system and the soil in non-compacted soil early after transplanting. This was also indicated by the fact that the **RL** seedlings in non-compacted soil showed some severe wilting early after transplanting. However, from the 13th week onwards, once the roots had started growing actively, daily water uptake rate from the non-compacted soil increased sharply and accelerated with time until the end of the experimental period (Figure 4.6). In contrast, water uptake rate from the compacted soil during this period fell back to a constant rate, equal to that for the first nine weeks after transplanting, after a slight peak during weeks 10 to 12 (Figure 4.6).

As a result of the sharp increase in rate of water use from non-compacted soil from week 13 onwards, and the large difference in plant size between non-compacted and compacted soil during this period, the cumulative water use from the non-compacted soil was significantly higher than from the compacted soil at the end of the experiment (Figure 4.7). The difference was statistically significant and approximately 2.2 dm^3 (or 18%).

The RL seedlings in compacted soil showed some consistency in daily water consumption (Figure 4.6), thus leading to a linear increase in cumulative water consumption over time (Figure 4.7). The progressively increasing daily water consumption in the non-compacted soil gives a smooth

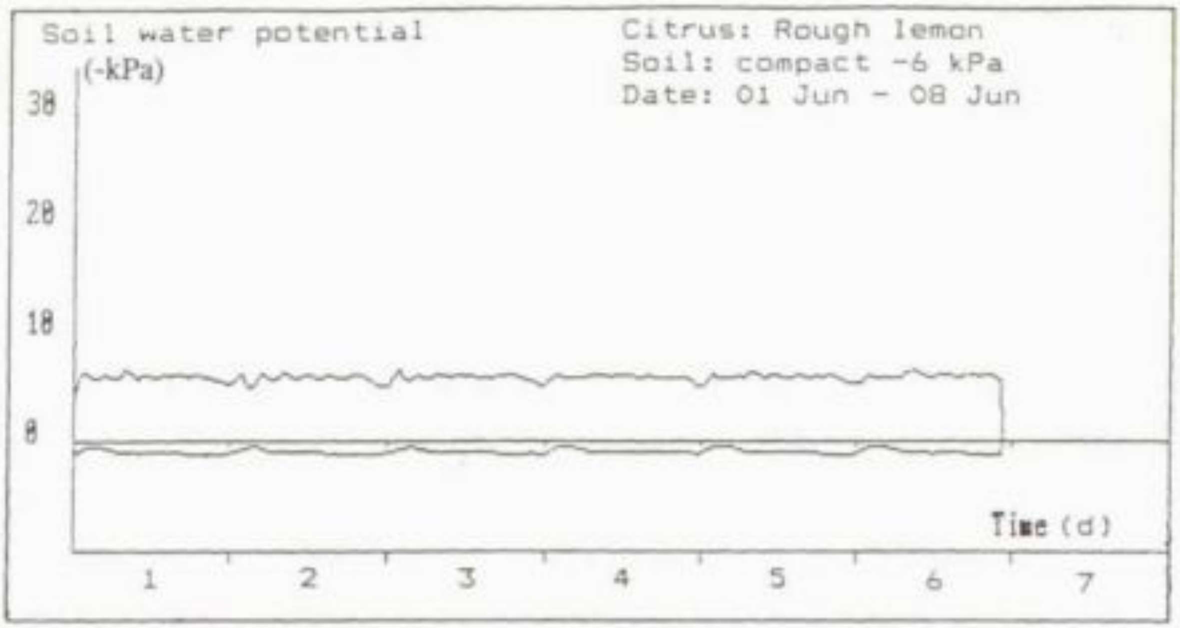


Fig. 4.1. Soil water potential in compacted soil at -6 kPa 28 days after transplanting. No fluctuations were found. The bottom line indicates water potential of free water.

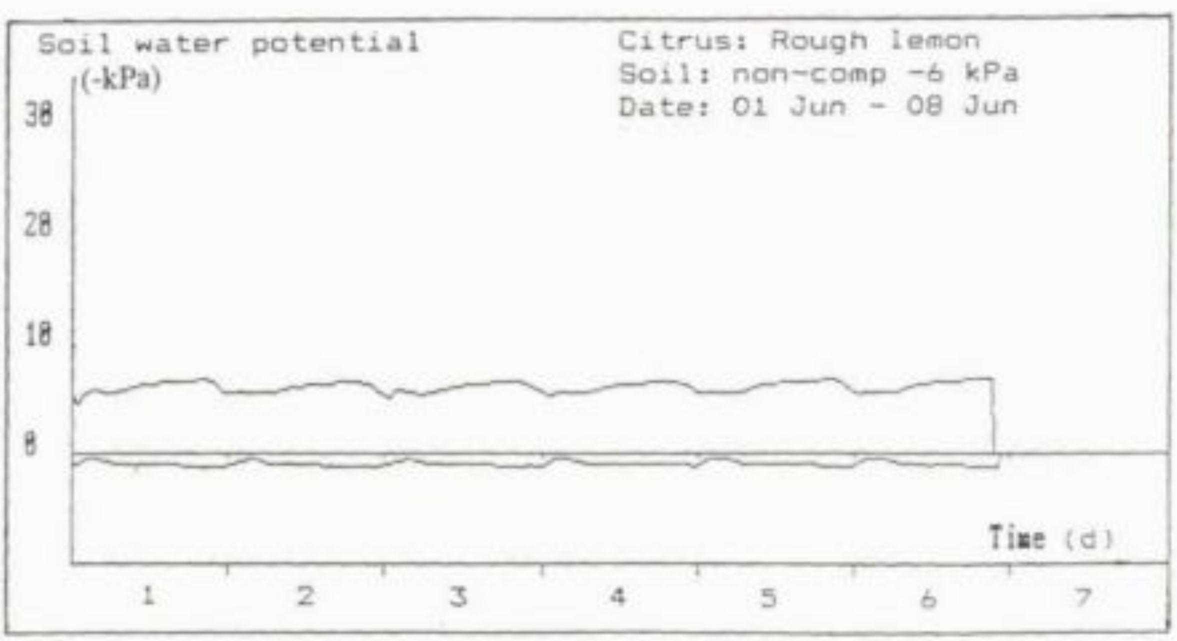


Fig. 4.2. Soil water potential in non-compacted soil at -6 kPa 28 days after transplanting. Minor diurnal fluctuations were also found in free water (bottom line).

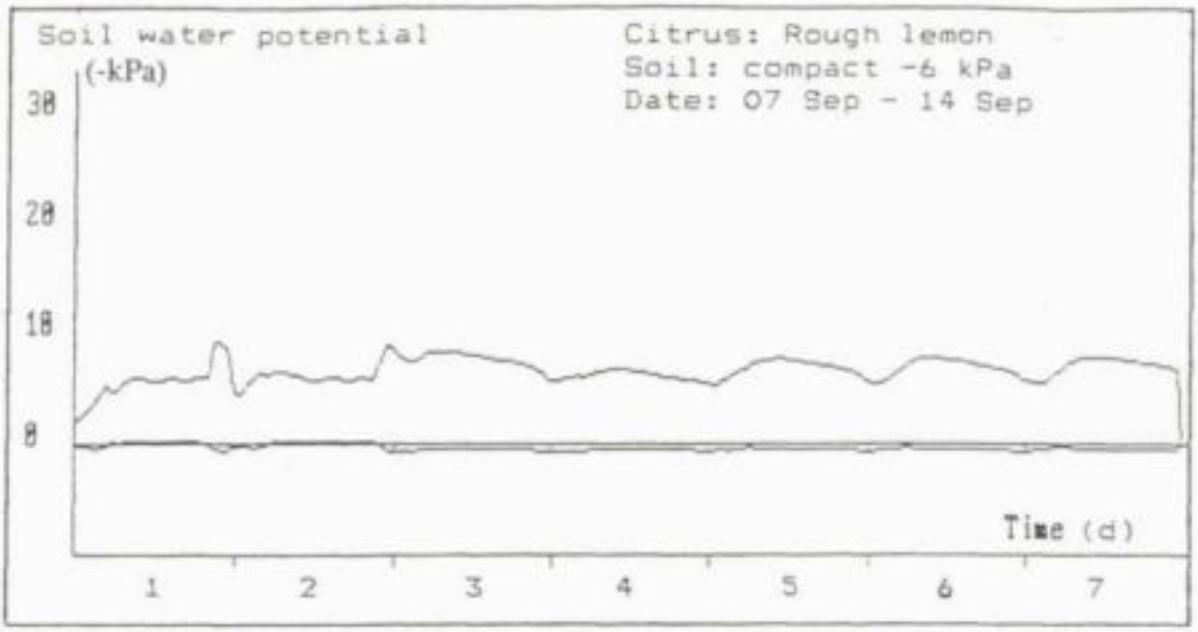


Fig. 4.3. Soil water potential in compacted soil at -6 kPa 130 days after transplanting. Diurnal fluctuations were found. The bottom line indicates water potential of free water.

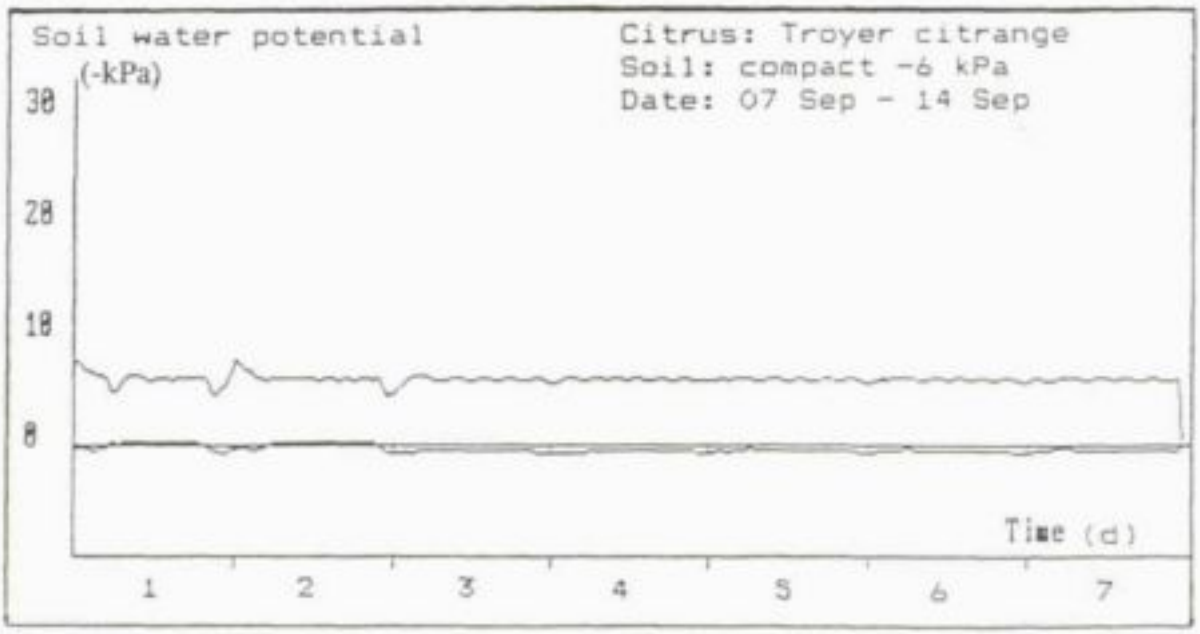


Fig. 4.4. Soil water potential in compacted soil at -6 kPa 130 days after transplanting. No fluctuations were found. The bottom line indicates water potential of free water.

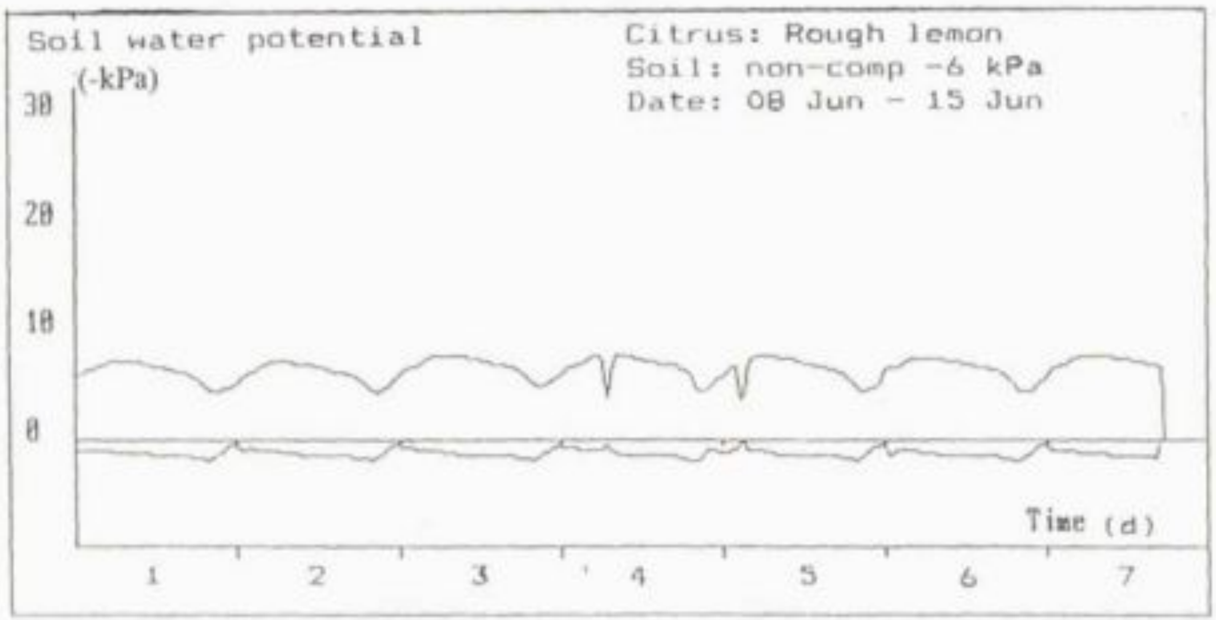


Fig. 4.5. Soil water potential in non-compacted soil at -6 kPa 130 days after transplanting. Diurnal fluctuations indicate changes in the water status of the soil. The bottom line indicates water potential of free water.

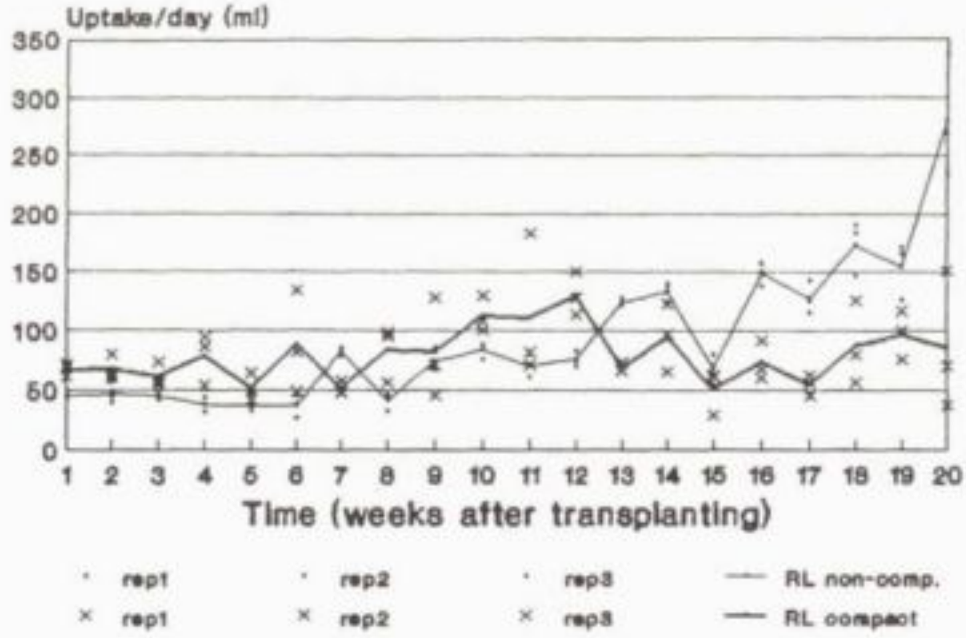


Fig. 4.6. Daily rate of water use by RL seedlings in compacted and non-compacted soil. Each line represents the mean of three values.

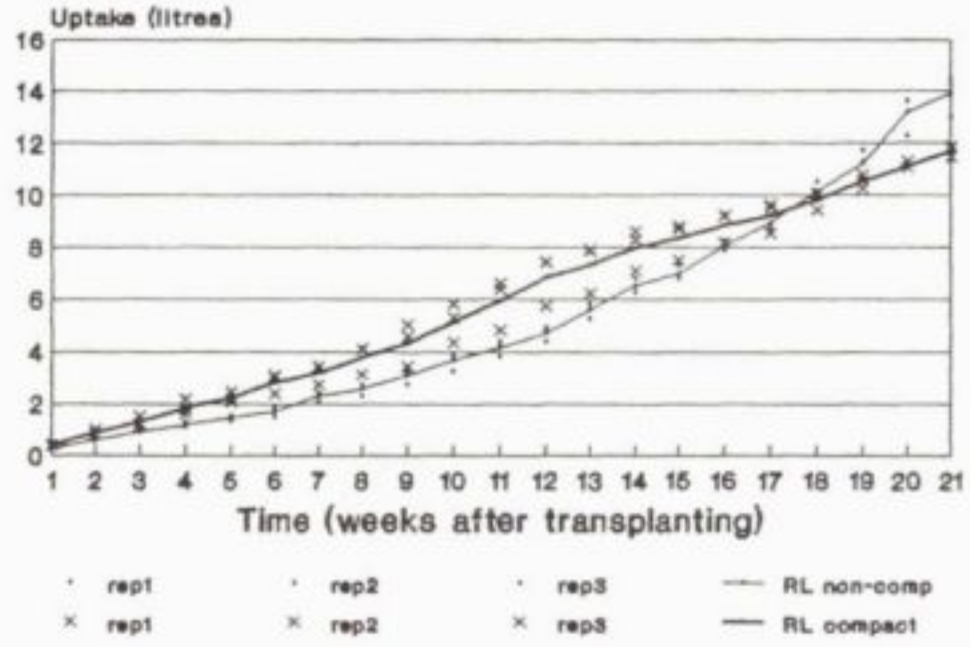


Fig. 4.7. Cumulative water consumption by RL seedlings in compacted and non-compacted soil at -6 kPa. Each line represents the mean of three values.

curve with an upward trend in cumulative water use (Figure 4.7).

Daily water consumptive rate by **TC** seedlings in non-compacted soil was lower than that for plants in compacted soil during the first six weeks after transplanting (Figure 4.8). Furthermore, the difference between the two groups remained almost constant during this period, as is evidenced by the way in which the two curves follow the same trend. This is not only similar to the trend found for RL in regard to the differences between compacted and non-compacted soil during this period, but the order of magnitude of the difference is also similar for the two citrus types.

Between the sixth and fourteenth weeks after transplanting, daily water consumption by TC was characterized by sharp weekly fluctuations, especially in non-compacted soil (Figure 4.8). It is noticeable that the oscillations for the two groups form mirror images of each other, values for the non-compacted soil being low during weeks when those for the compacted soil are high and vice versa. The overall averages for daily water consumption during the period between weeks six and fourteen remained the same for both compacted and non-compacted soil. The result is that whereas during the first six weeks there was a gradual increase in the difference of cumulative water use between compacted and non-compacted soil, this difference did not change between weeks six and fourteen (Figure 4.9), as indicated by the lines being parallel over this period.

In contrast to RL, where daily water consumption in non-compacted soil increased sharply from about thirteen weeks after planting, this did not happen in the case of TC (Compare Figures 4.6 and 4.8). For TC, the average daily water consumption in non-compacted soil for the period 14 to 21 weeks after planting was in fact again lower than from compacted soil. This was partly due to defoliation that occurred on the seedlings in this treatment. The net overall effect is that TC in compacted soil used an average of 2 dm^3 (or 29%) more water (statistically significantly higher) than those in non-compacted soil (Figure 4.9). This is the opposite of what was found for RL.

There was an obvious difference in cumulative water consumption between RL and TC both in compacted and non-compacted soil. Figures 4.10 and 4.11 show the cumulative water consumption of RL and TC in compacted and non-compacted soil, respectively. In compacted soil, the cumulative uptake of water by RL and TC was of the same magnitude for the first seven weeks after transplanting (Figure 4.10). From the 8th week, the cumulative water uptake between the two started to differ, with RL taking up over 2 dm^3 more water (statistically significantly higher) than TC at the end of the season. The difference in cumulative uptake of water probably coincided with the development and enlargement of bigger RL leaves.

In non-compacted soil, the cumulative uptake of water by RL and TC was similar for the first nine weeks after transplanting (Figure 4.11). Thereafter, the RL gradually consumed more water over time. At the end of the growing season (21st week), RL had used at least 93% more water than TC. This was probably due to better root growth and bigger leaf area of RL in this soil.

Figure 4.12 shows the daily water consumptive rate of both RL and TC in compacted soil. For the first eight weeks it was similar for the two. There was a large difference in water uptake rate

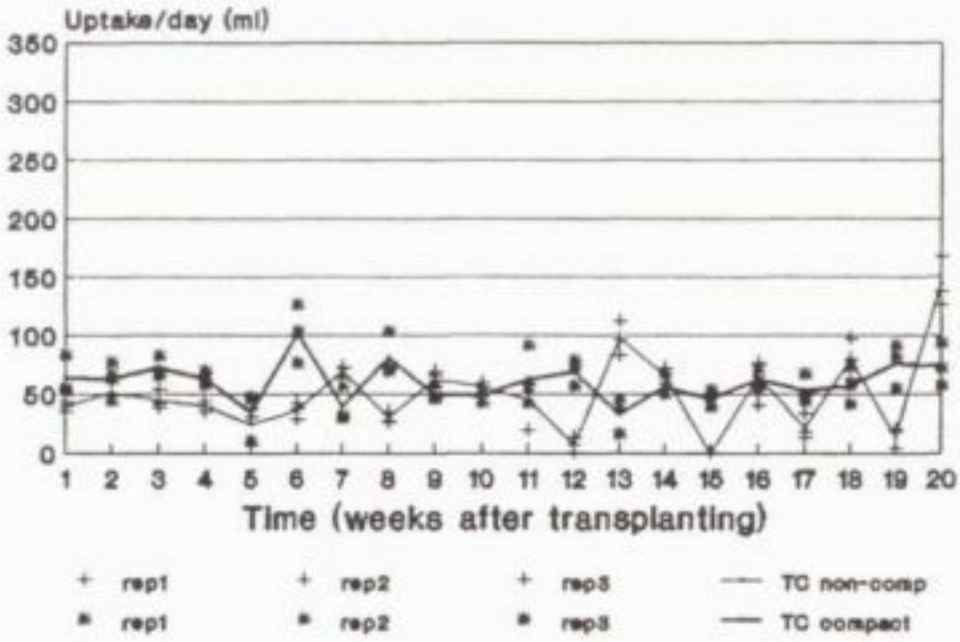


Fig. 4.8. Daily rate of water use by TC seedlings in compacted and non-compacted soil. Each line represents the mean of three values.

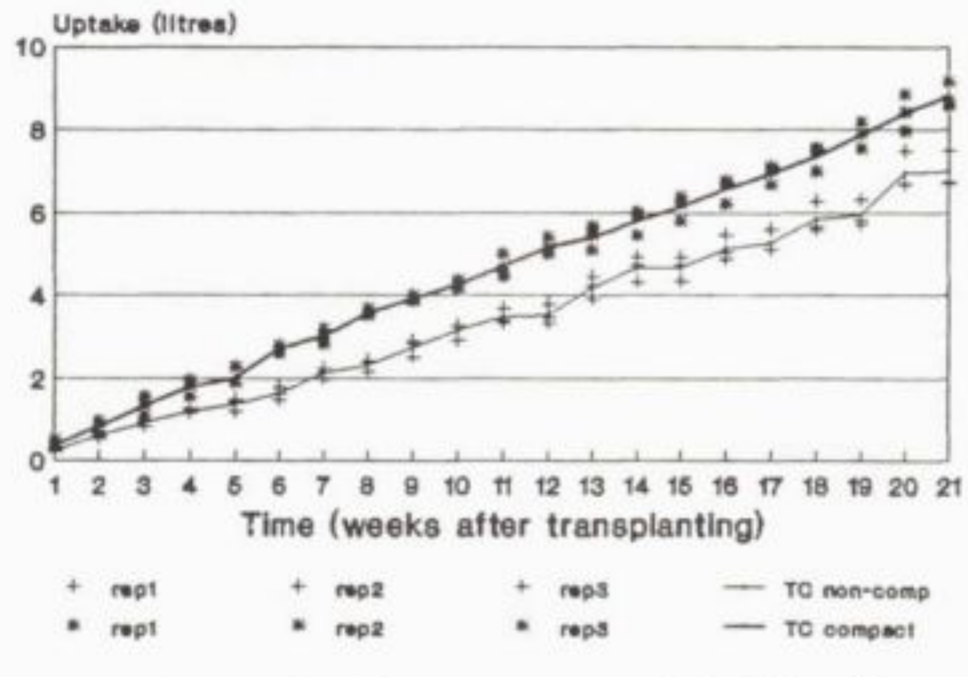


Fig. 4.9. Cumulative water consumption by TC seedlings in compacted and non-compacted soil at -6 kPa. Each line represents the mean of three values.

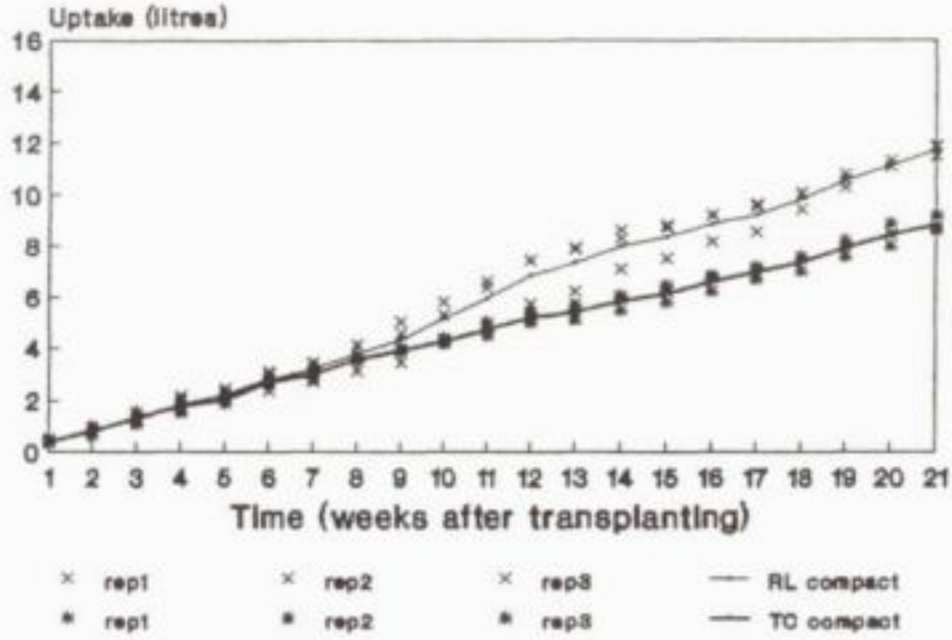


Fig. 4.10. Cumulative water consumption by RL and TC seedlings in compacted soil at -6 kPa. Each line represents the mean of three values.

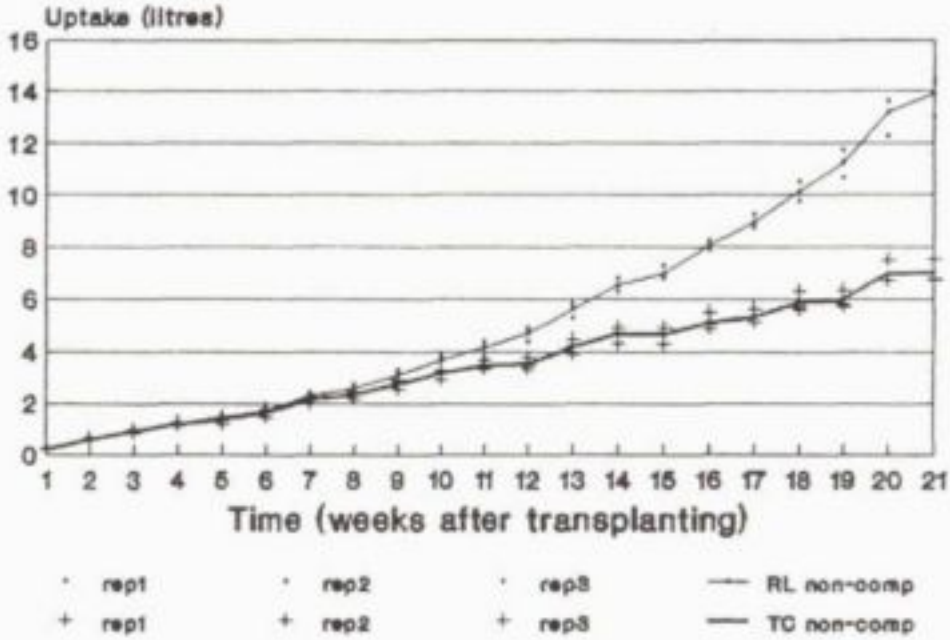


Fig. 4.11. Cumulative water consumption by RL and TC seedlings in non-compacted soil at -6 kPa. Each line shows the mean of three values.

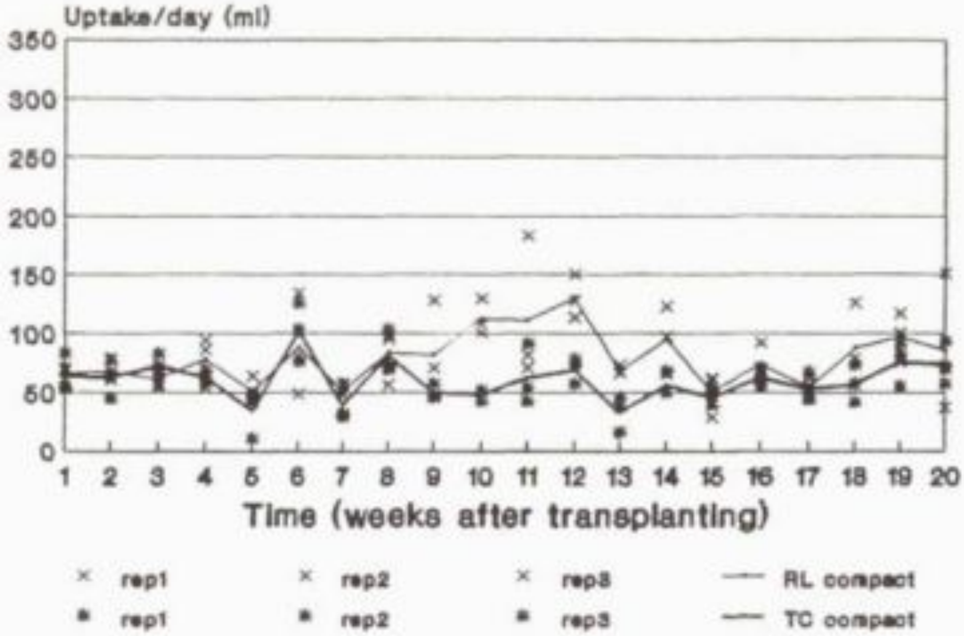


Fig. 4.12. Daily rate of water use by RL and TC seedlings in compacted soil. Each line shows an average of three values.

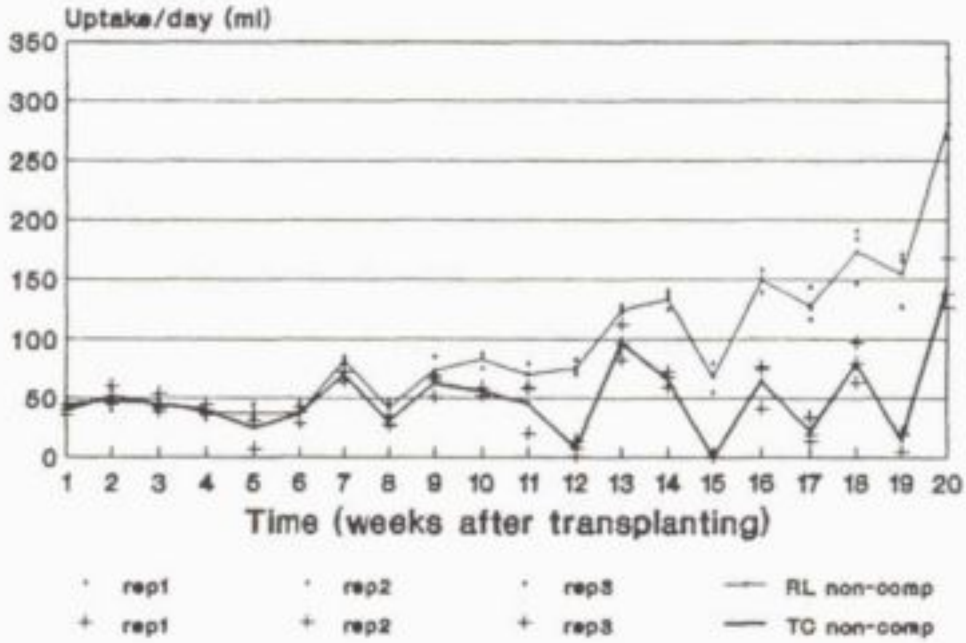


Fig. 4.13. Daily rate of water use by RL and TC seedlings in non-compacted soil. Each line shows an average of three values.

between the two from the eighth to the 14th week when RL had a slight peak, after which there was a smaller difference. The water uptake rate in non-compacted soil was similar for RL and TC during the first nine weeks after transplanting (Figure 4.13). From the 10th week onwards, RL seedlings started to take up more water per day than TC seedlings.

The consumption of water was in most cases influenced by the growth rate of seedlings. For example, there was a significant positive correlation between top growth rate and the water consumptive rate of RL seedlings in non-compacted soil (Figure 4.14). Similar relationships were also found in RL seedlings grown in compacted soil and TC in both compacted and non-compacted soil (Appendices 4.1 - 4.3).

4.4.1.3 Plant Growth and Development

There was no difference in height of RL seedlings between compacted and non-compacted soil for the first nine weeks after transplanting (Figure 4.15). There was, in fact, very little growth during this period due to transplant shock. This means that in the first nine weeks after transplanting, RL was establishing its root system. The seedlings in non-compacted soil started to grow faster than those grown in compacted soil in the 10th week. In the 21st week the seedlings in non-compacted soil were 71% taller than those in compacted soil.

As a result of compaction, the roots of RL seedlings in compacted soil could not proliferate further after nine weeks, leading to a very slow top growth rate. On the other hand, the growth rate of RL seedlings in non-compacted soil accelerated after nine weeks, giving much larger plants at the end. The gain in height 140 days after exposing the seedlings to different soil physical conditions was 55% and 164% {i.e. (height at the end less height at the beginning)/height at the beginning x 100} for compacted and non-compacted soil, respectively.

There was no difference in plant height between compacted and non-compacted soil for the first nine weeks after transplanting in TC, as was also the case with RL (Figure 4.16). However, thereafter the seedlings in compacted soil started to grow faster than those in non-compacted soil which showed extremely little growth. The seedlings in compacted soil attained 47 cm (104% gain) in 140 days after transplanting. At this time, the seedlings in non-compacted soil attained only 28 cm (22% gain). The TC in non-compacted soil remained wilted and lost many leaves for most part of the growing season. This was probably due to insufficient uptake and supply of water by plant roots, perhaps due to poor soil-root contact which was also confirmed by a lower water consumption. Consequently the rate of assimilate accumulation was low and led to poor change in plant height and development during the period of experimentation.

Figures 4.17 and 4.18 show the differences in response and sensitivity between RL and TC to various soil conditions. In both compacted and non-compacted soil (Figures 4.17 and 4.18, respectively), RL was the earliest to start growing after transplanting. In compacted soil the growth rate of RL thereafter slowed down dramatically, compared with TC (Figure 4.17). It was probably as a result of its sensitivity to compacted and somewhat waterlogged soils, that RL was ultimately negatively affected by rhizospherical conditions which led to a decline in growth. TC, on the other hand, was slow to develop initially. However, possibly due to its tolerance to soil

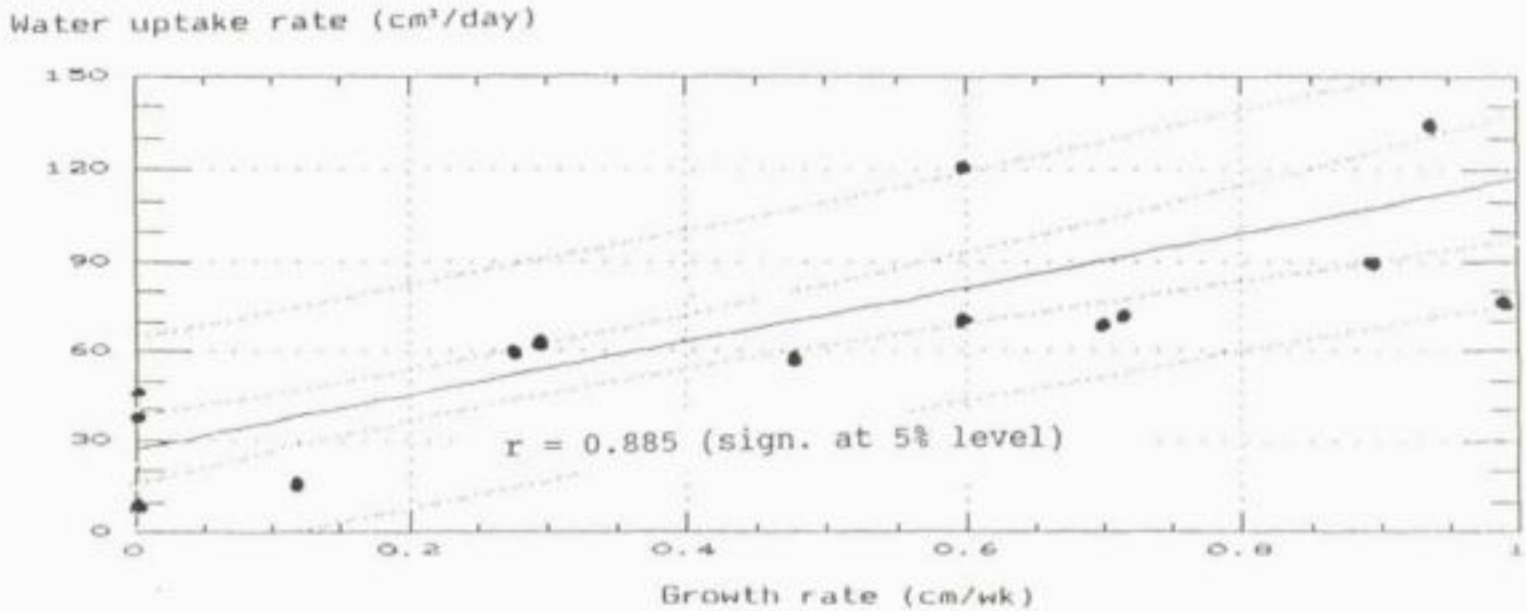


Fig. 4.14. Regression line showing a relationship between top growth rate and water consumptive rate of RL in non-compacted soil at -6 kPa.

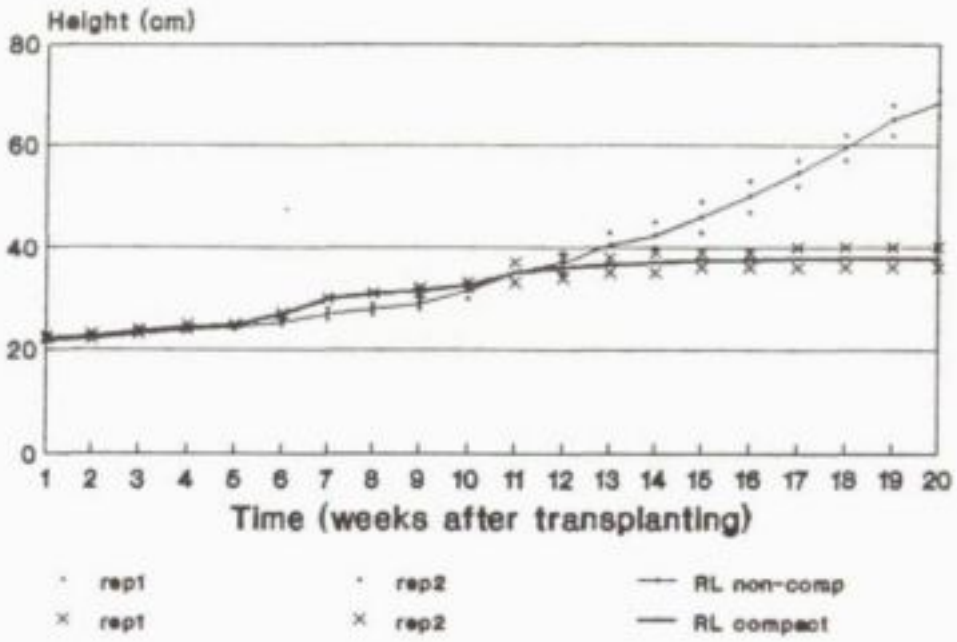


Fig. 4.15. Height of RL seedlings in compacted and non-compacted soil at -6 kPa. Each line represents an average of three values.

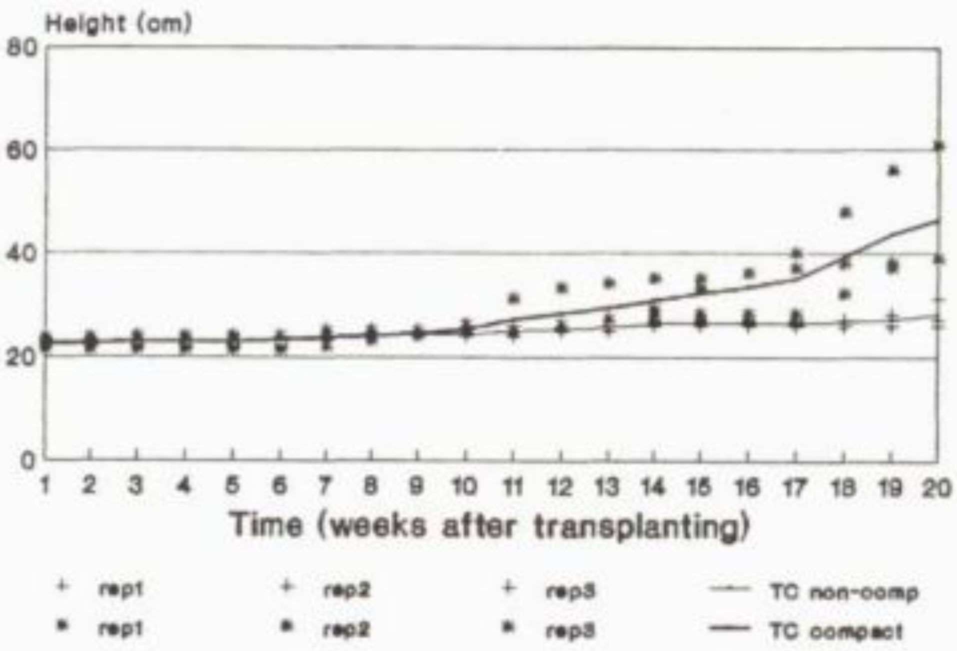


Fig. 4.16. Height of TC seedlings in compacted and non-compacted soil at -6 kPa. Each line represents an average of three values.

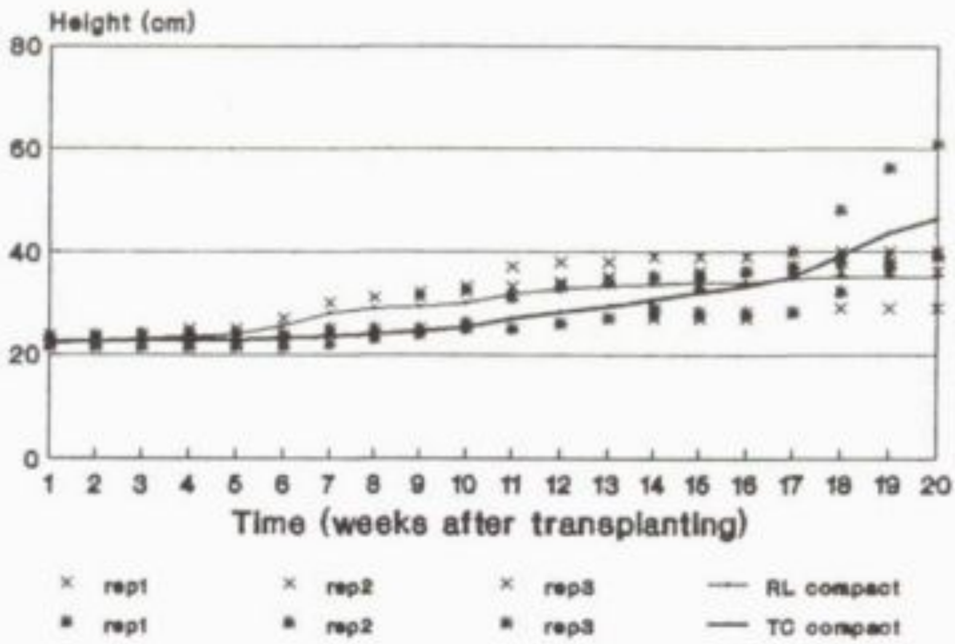


Fig. 4.17. Height of RL and TC seedlings in compacted soil at -6 kPa. Each line shows the mean of three values.

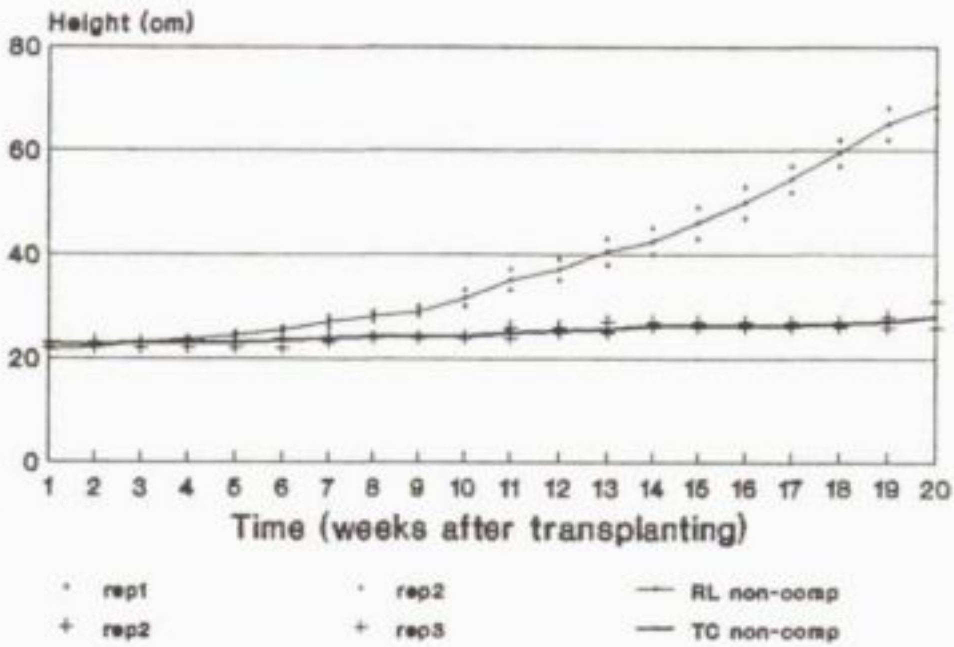


Fig. 4.18. Height of RL and TC in non-compacted soil at -6 kPa. Each line shows an average of three values.

compaction, its growth rate gradually accelerated and from 18 weeks after planting the height of the TC seedlings exceeded that of RL. In non-compacted soil, the difference in plant height was increasing over time (Figure 4.18), with RL seedlings growing faster than TC, probably due to its well developed root system. Due to poor development of the root system in TC, this rootstock grew very poorly in non-compacted soil.

4.4.1.4 Morphological and Physiological Plant Responses

Table 4.2 shows some major differences between seedlings grown in compacted and non-compacted soil (For statistical analyses, refer to Appendices 4.4 - 4.14). Compaction of the soil statistically significantly reduced the accumulated total dry mass by 54% in RL. On the other hand, there was no negative effect of compaction on TC, instead the seedlings in compacted soil had a statistically significantly higher total dry mass. Similar situations were found for top dry mass as well as root dry mass for RL and root dry mass for TC.

There was no statistically significant difference in top:root ratio and root area:root mass ratio between RL seedlings in compacted and non-compacted soil. The TC in compacted soil had a much lower top:root ratio than the others (non-compacted TC and both RL treatments), indicating poor efficiency of TC roots in the compacted soil in terms of top mass production. The root area:root mass ratio for RL seedlings in compacted and non-compacted soil did not differ significantly. TC seedlings had larger root area per root mass compared to RL. In the case of TC the RA:RM ratio in compacted soil was statistically significantly lower than in non-compacted soil.

Table 4.3 illustrates the influence that soil compaction has on several plant parameters. Soil compaction resulted in a statistically significant decline of 47% in the leaf area in RL. It also negatively affected the projected root surface area by more than 50%. Similar results were reported on spring barley (Durr et al., 1992). There was statistically significant difference in root hydraulic conductivity between seedlings in compacted and non-compacted soil. The seedlings in compacted soil had statistically significantly higher root hydraulic conductivity compared to non-compacted soil. Luxmoore et al. (1971) found that most citrus types improve their root hydraulic conductivity when grown under low oxygen levels. This is probably an acclimation response of citrus to stressful soil conditions.

The water consumption per unit total dry mass produced by RL seedlings in non-compacted soil was statistically significantly higher than in compacted soil. Soil compaction significantly reduced the water use efficiency by 45%, with only 0.92 g dry matter being produced per 1 dm^3 water consumed in compacted soil, as opposed to 1.67 g dry matter being produced in non-compacted soil. It can be concluded that RL in compacted soil was using water relatively inefficiently.

Compaction of soil resulted in higher relative water saturation and water content of the soil. The water content of the compacted soil was 25.5% (volume) while that of the non-compacted soil was 21.3% at -6 kPa soil water potential. Assuming that the soil particle density is 2656 $kg.m^{-3}$ (Carter & Johnston, 1989), the non-compacted soil had twice as much air-filled pore space compared to the compacted soil i.e. the total porosity for:

Table 4.2. The effects of soil compaction on dry mass accumulation in RL and TC seedlings

Soil treat.	Total dry mass (g)	Top dry mass (g)	Root dry mass (g)	Top:root ratio	RA:RM (cm^2/g)
			Rough lemon		
	27.04	19.67	7.37	2.67	27.6
Non-comp	27.29	18.86	8.43	2.24	28.9
	15.98	10.72	5.26	2.04	46.2
mean	**23.44**	**16.42**	**7.02**	**2.31**	**32.2**
S.E.	3.73	2.86	0.93	0.19	6.0
	10.78	7.12	3.67	1.94	35.1
Compact	8.85	5.63	3.22	1.75	23.4
	12.71	8.60	4.11	2.09	27.0
mean	**10.78**	**7.12**	**3.67**	**1.93**	**28.8**
S.E.	1.11	0.86	0.26	0.10	3.5
			Troyer citrange		
	3.20	2.06	1.14	1.81	54.4
Non-comp	6.09	3.71	2.38	1.56	58.0
	2.37	1.53	0.84	1.82	44.4
mean	**3.89**	**2.89**	**1.45**	**1.73**	**45.3**
S.E.	1.13	0.66	0.47	0.09	4.1
	5.57	2.82	2.75	1.03	42.2
Compact	8.45	5.25	3.20	1.64	39.8
	8.72	5.36	3.36	1.60	33.6
mean	**7.58**	**4.48**	**3.10**	**1.42**	**37.7**
S.E.	1.01	0.83	0.18	0.20	2.6
LSD	3.30	2.00	0.90	0.35	6.9

RA:RM - root area to root mass ratio.

Table 4.3. The effects of soil compaction on physiological and morphological parameters of RL and TC seedlings

Soil treat	Leaf area (cm^2)	Root area (cm^2)	RA/LA ratio	Water cons. (dm^3)	R.H.C* ($x10^{4}$)	WUE ($g.dm^{3}$)
			Rough lemon			
	1449	543	0.37	14.25	1.37	1.90
Non-comp	1324	545	0.41	14.46	1.18	1.89
	1013	495	0.49	13.00	1.02	1.23
mean	**1262**	**528**	**0.42**	**13.90**	**1.19**	**1.67**
S.E.	130	16	0.04	0.46	0.10	0.22
	786	250	0.34	11.88	1.46	0.91
Compact	403	132	0.33	11.46	1.47	0.77
	806	232	0.29	11.79	1.47	1.08
mean	**665**	**205**	**0.32**	**11.71**	**1.47**	**0.92**
S.E.	131	37	0.02	0.13	0.003	0.09
			Troyer citrange			
	129	112	0.87	7.52	-	0.43
Non-comp	239	215	0.90	6.71	-	0.91
	99	68	0.68	6.76	-	0.35
mean	**155**	**131**	**0.82**	**7.00**	-	**0.56**
S.E.	43	44	0.07	0.26	-	0.17
	96	119	1.24	8.69	-	0.64
Compact	289	209	0.72	8.57	-	0.99
	269	180	0.67	9.15	-	0.95
mean	**218**	**169**	**0.88**	**8.80**	-	**0.86**
S.E.	61	27	0.18	0.18	-	0.11
LSD	162	103	0.16	0.46	0.20	0.26

RA/LA - root area:leaf area ratio.
Water cons. - water consumption in litres.
* R.H.C. - root hydraulic conductivity ($cm^3.cm^{-2}.Pa^{-1}.s^{-1}$).
WUE - water use efficiency.

non-compacted soil	compacted soil
= (1 - 1550/2656) 100	= (1 - 1700/2656) 100
= 41.6%	= 36.0%

therefore, the air-filled pore space was:-

= 41.6 - 21.3%	= 36.0 - 25.5%
= 20.3%	= 10.5%

The 10.5% air-filled pore space in the compacted soil is in the order of the 10% level below which there is normally a drastic negative effect on plant growth and far below the critical level of 15% indicated by Nel (1981) for citrus. In contrast, the 20.3% for the non-compacted soil is in the middle of the optimum range for citrus identified by Nel (1981).

In TC, no statistically significant difference was found in leaf area as a result of soil compaction. Seedlings grown in non-compacted soil had a projected root surface area 22% less than that of plants in compacted soil. However, this was not statistically significant. There was no statistically significant difference in projected root area:leaf area ratio between seedlings grown in compacted and non-compacted soil. This is because both the leaf area and the projected root area were about 50% less for the plants grown in non-compacted soil than in compacted soil. This further indicates that it is due to tolerance that the TC can grow well under compacted soil conditions.

Compared with RL, the TC tended to use water inefficiently, especially when grown in non-compacted soil. The water use efficiency was statistically significantly reduced to 65% in non-compacted soil, with 1 dm^3 water required to produce 0.86 g and 0.56 g dry matter for compacted and non-compacted soil, respectively. This shows that seedlings in non-compacted soil used a lot of water while they were wilted with minimum growth. Also, most of the photosynthesizing capacity was shed through defoliation which resulted in both direct loss of dry mass and reduced accumulated photosynthates.

4.4.2 Conclusions

In conclusion, soil compaction had some negative effects on growth and development of RL seedlings. The total dry mass, top dry mass, root dry mass, leaf area, root surface area, and water use efficiency were reduced by more than 50% as a result of soil compaction. The opposite was found with TC seedlings. The TC plants in compacted soil had a higher total dry mass, top dry mass, root dry mass, leaf area, root surface area, and water use efficiency. However, the roots of RL seedlings showed a higher efficiency for producing a large top growth (per root mass) compared to the roots of TC seedlings.

This explains the differences that exist between RL and TC rootstocks. It also explains why TC is better suited for wet, fine-textured soils than RL which does better in relatively dry, sandy soils. This experiment led to a need for more investigation into the effects of the interaction between soil compaction and soil water potential, and the possibility of impaired nutrient uptake as a result of rhizospherical conditions on citrus seedlings. The RL rootstock, due to its sensitivity to soil compaction and soil water potential, was then used for the rest of this study.

CHAPTER 5

EFFECTS OF SOIL COMPACTION AND SOIL WATER POTENTIAL ON NUTRIENT STATUS OF YOUNG ROUGH LEMON PLANTS

5.1 Introduction

A limited number of studies have been found which report on the effects of waterlogged conditions on citrus development. Very few studies have revealed a general dependance of nutrient accumulation on an aerobic metabolism. No information was found on the effects of both soil compaction and constantly high soil water content on nutrient uptake by young citrus. The aim of this study was to determine the effects of the interaction between high soil water potential and soil compaction (poor aeration) on the development and nutrient status of RL seedlings. An understanding of these relationships between edaphic factors, irrigation scheduling, nutrient uptake and plant development could help to identify irrigation practices that must be followed in order to avoid waterlogged rhizospherical stresses and impaired nutrient uptake that may lead to plant decline in certain soil-water combinations. There is also a lack of knowledge of the extent to which transport of some nutrient elements and water is limited by oxygen supply in the roots.

5.2 Materials and Treatments

The medium-textured red apedal Hutton 3 soil (Table 2.1), with a clay content of 24%, from the M. Le Roux research farm of the University of Pretoria near Cullinan was used in this experiment. A total number of 15 pots were filled with soil - with six non-compacted (DBD = 1550 $kg.m^{-3}$) and nine compacted (DBD = 1700 $kg.m^{-3}$) soils, and three levels of soil water potential as follows:

	Soil treatment	
Soil water potential	Non-compacted	compacted
-10 kPa	3 pots	3 pots
-20 kPa	3 pots	3 pots
-40 kPa	-	3 pots
Total	6 pots	9 pots

The RL seeds were germinated in a vermiculite growing medium on July 7, 1992. Small seedlings were irrigated every morning with deionized water and fertigated with full-strength Hoagland's solution once a week.

Seedlings were transplanted into the pots on October 20, 1992 when they were 15 cm tall. At transplanting, the seedlings were covered with transparent plastic bags in order to minimize wilting. The soil water potential was regulated and maintained using the Pero facility. The daily, weekly, and cumulative water consumption by seedlings was calculated every week from the readings of the water-storage bottles (Refer to Chapter 2). The seedlings were harvested on February 24, 1993, 130 days after transplanting.

5.3 Results and Discussion

5.3.1 Soil Water Potential

Early in the growing season, the mean soil water potential at -10 kPa was maintained at the specified level (Figures 5.1 and 5.2). However, there were marked diurnal fluctuations of soil water potential in compacted soil at this stage (Figure 5.2). The results with the larger plants towards the end of the experiment were very similar to those for the early parts of the growing season (Figures 5.3 and 5.4).

At -20 kPa soil water potential, there were diurnal fluctuations in soil water potential readings in both compacted and non-compacted soil throughout the growing season (Figures 5.5 and 5.6). Early in the season these fluctuations were smaller in non-compacted soil (Figure 5.5) than in compacted soil (Figure 5.6). Later in the season when the seedlings were big, the diurnal fluctuations were pronounced both in non-compacted (Figure 5.7) and in compacted soil (Figure 5.8). The amplitude of the fluctuations in compacted soil were very similar for the early and late parts of the experiment (Figures 5.6 and 5.8). The amplitude of fluctuations for the non-compacted soil late in the season was slightly smaller than for the compacted soil, but of the same order of magnitude (Figures 5.7 and 5.8).

As the soil water potential in non-compacted soil declined from -10 to -20 kPa, there was a major increase in amplitude of diurnal fluctuations. In compacted soil, however, the difference was small.

At -40 kPa soil water potential, the diurnal fluctuations were irregular and not as high as at -20 kPa throughout the growing season (Figures 5.9 and 5.10). Moreover, seedlings in this treatment used less water, which may also explain the irregular fluctuations in soil water potential. A break in soil water potential measurements in Figures 5.9 and 5.10 was due to loss of water in the tensiometer (due to leakage)(such drops are not real measurements of soil water potential).

5.3.2 Water Consumption

During the first six weeks after transplanting, the seedlings in both compacted and non-compacted soil at -10 kPa had consumed the same amount of water (Figure 5.11). From the seventh week, the seedlings in non-compacted soil started using more water per day (Figure 5.12) than those in compacted soil. This difference in water uptake increased over time. At the end of the growing season, seedlings in non-compacted soil had used 35% more water (statistically significantly different) than those in the compacted soil.

At -20 kPa soil water potential, there was no significant difference in the amount of water used by seedlings from compacted and non-compacted soil (Figure 5.13). The daily consumptive rate

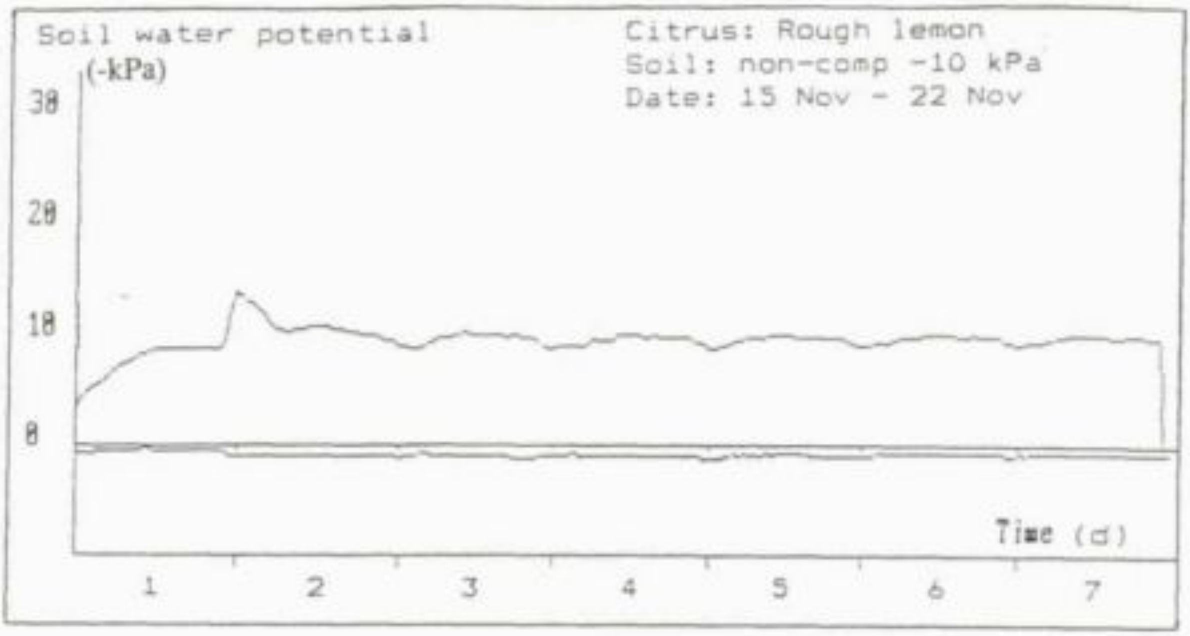


Fig. 5.1. Soil water potential in non-compacted soil at -10 kPa 30 days after transplanting. No fluctuations were found. The bottom line indicates water potential of free water.

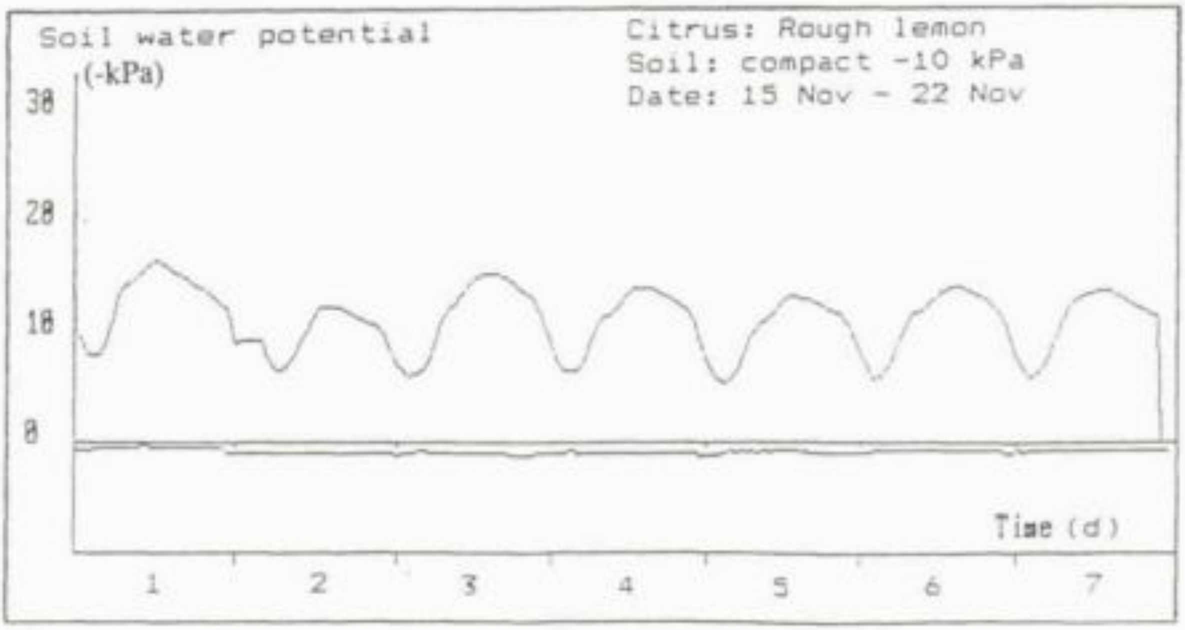


Fig. 5.2. Soil water potential in compacted soil at -10 kPa 30 days after transplanting. Pronounced diurnal fluctuations. The bottom line indicates water potential of free water.

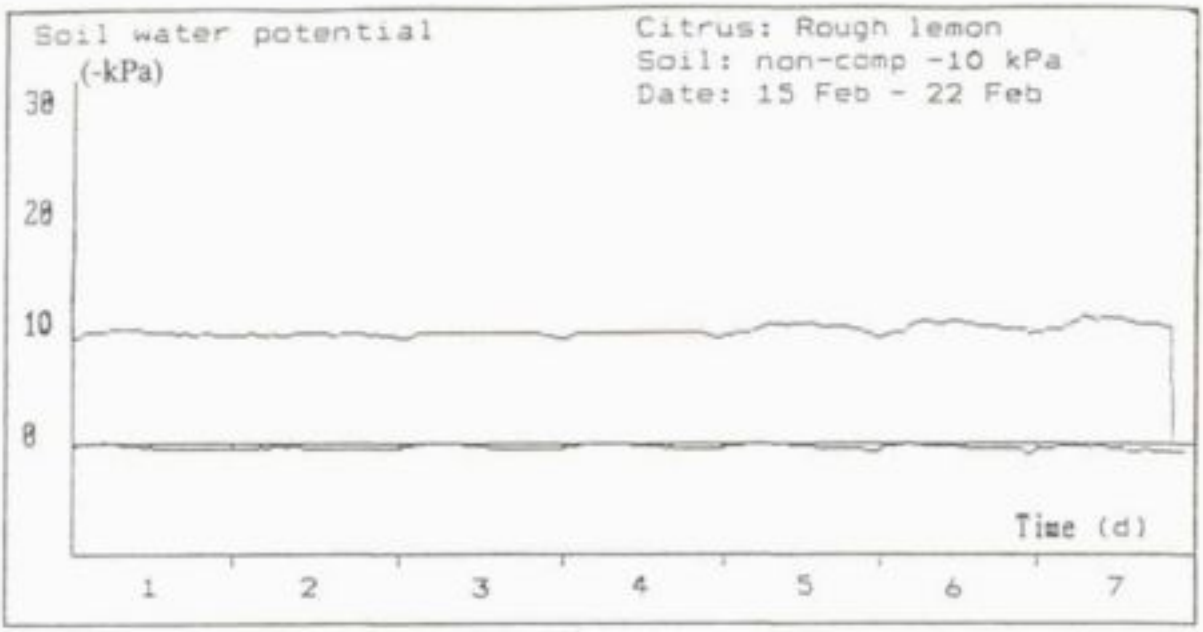


Fig. 5.3. Soil water potential in non-compacted soil at -10 kPa 130 days after transplanting. No fluctuations were found. The bottom line indicates water potential of free water.

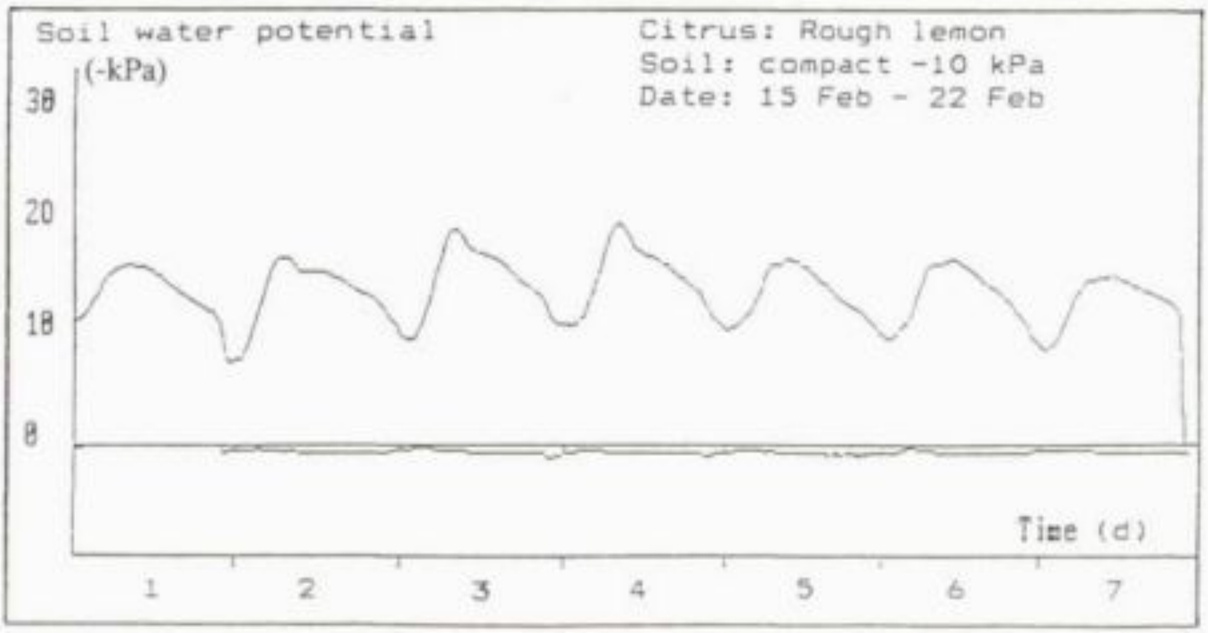


Fig. 5.4. Soil water potential in compacted soil at -10 kPa 130 days after planting. Fluctuations were found. The bottom line indicates water potential of free water.

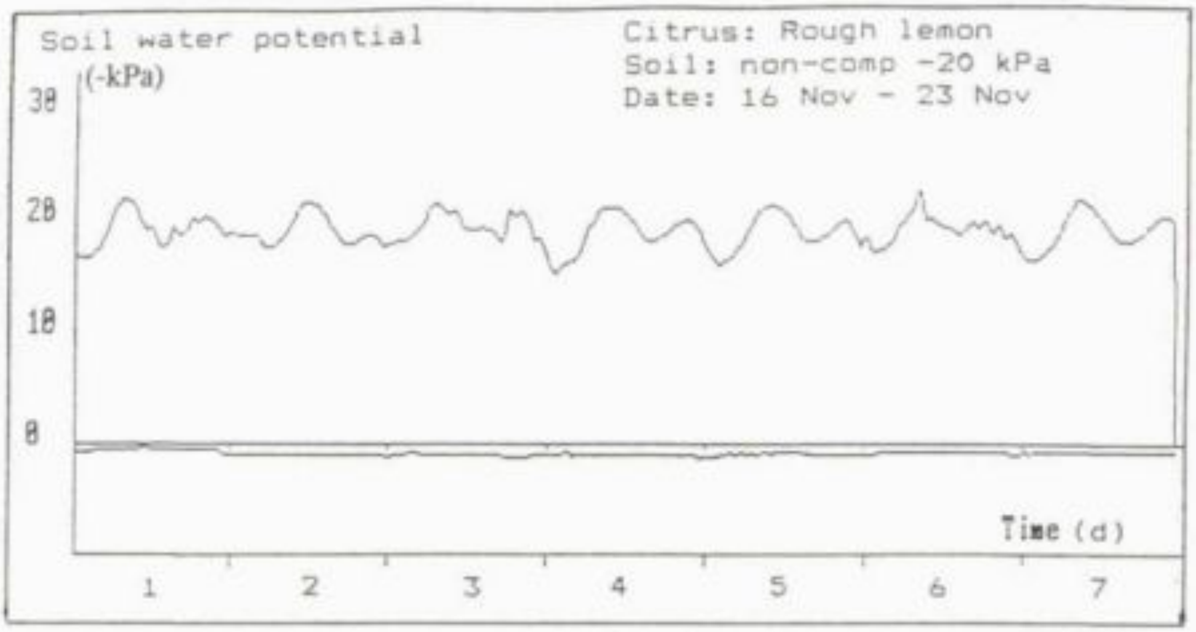


Fig. 5.5. Soil water potential in non-compacted soil at -20 kPa 30 days after planting. The bottom line shows the water potential of free water.

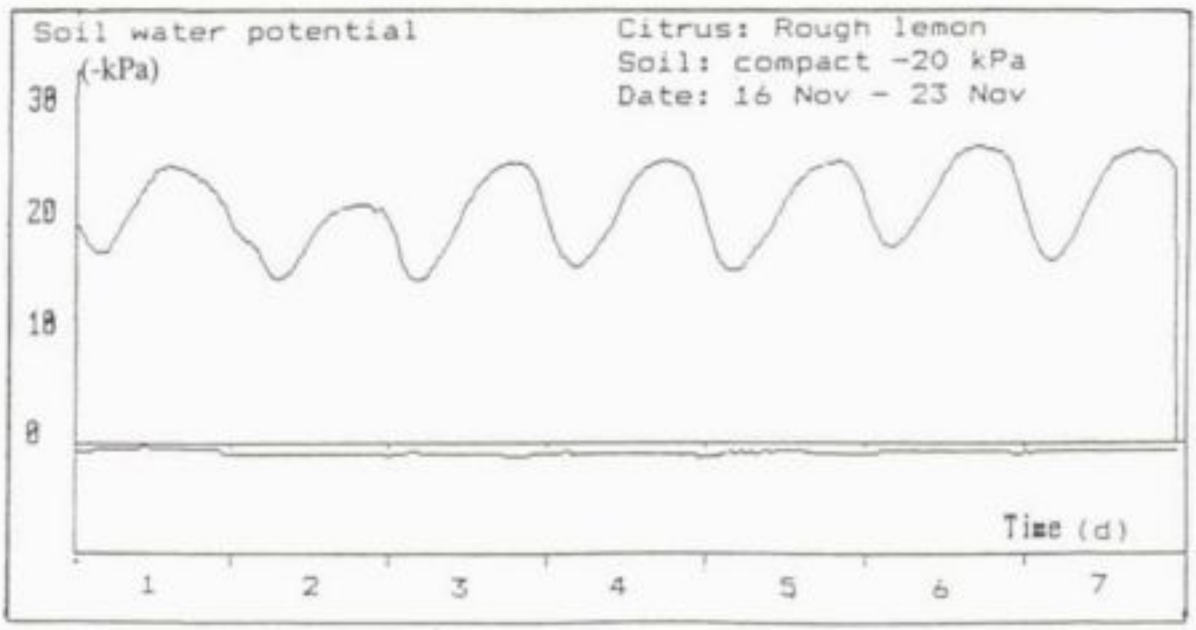


Fig. 5.6. Soil water potential in compacted soil at -20 kPa 30 days after planting. Pronounced fluctuations were found. The bottom line indicates water potential of free water.

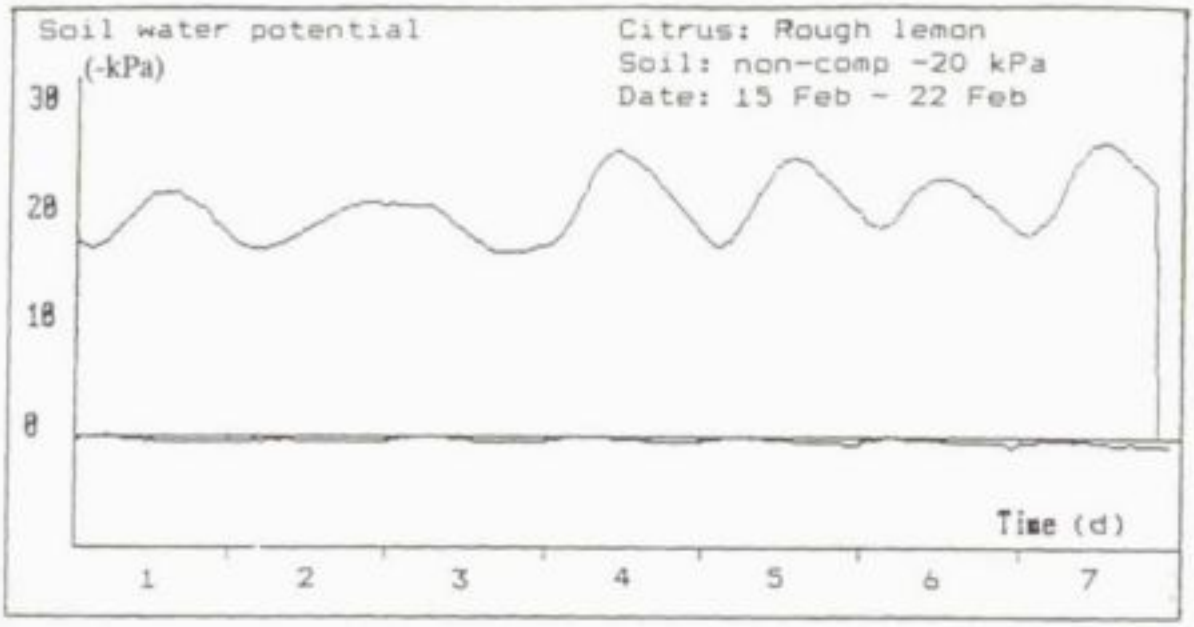


Fig. 5.7. Soil water potential in non-compacted soil at -20 kPa 130 days after planting. Diurnal fluctuations were found. The bottom line indicates water potential of free water.

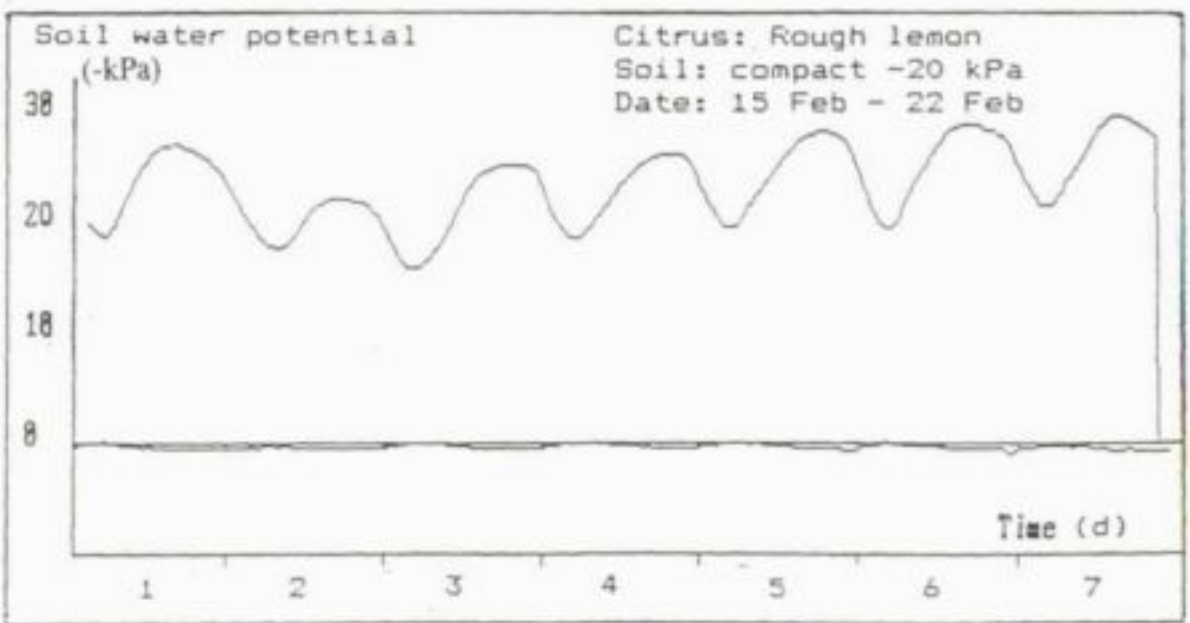


Fig. 5.8. Soil water potential in compacted soil at -20 kPa 130 days after planting. The bottom line indicates water potential of free water.

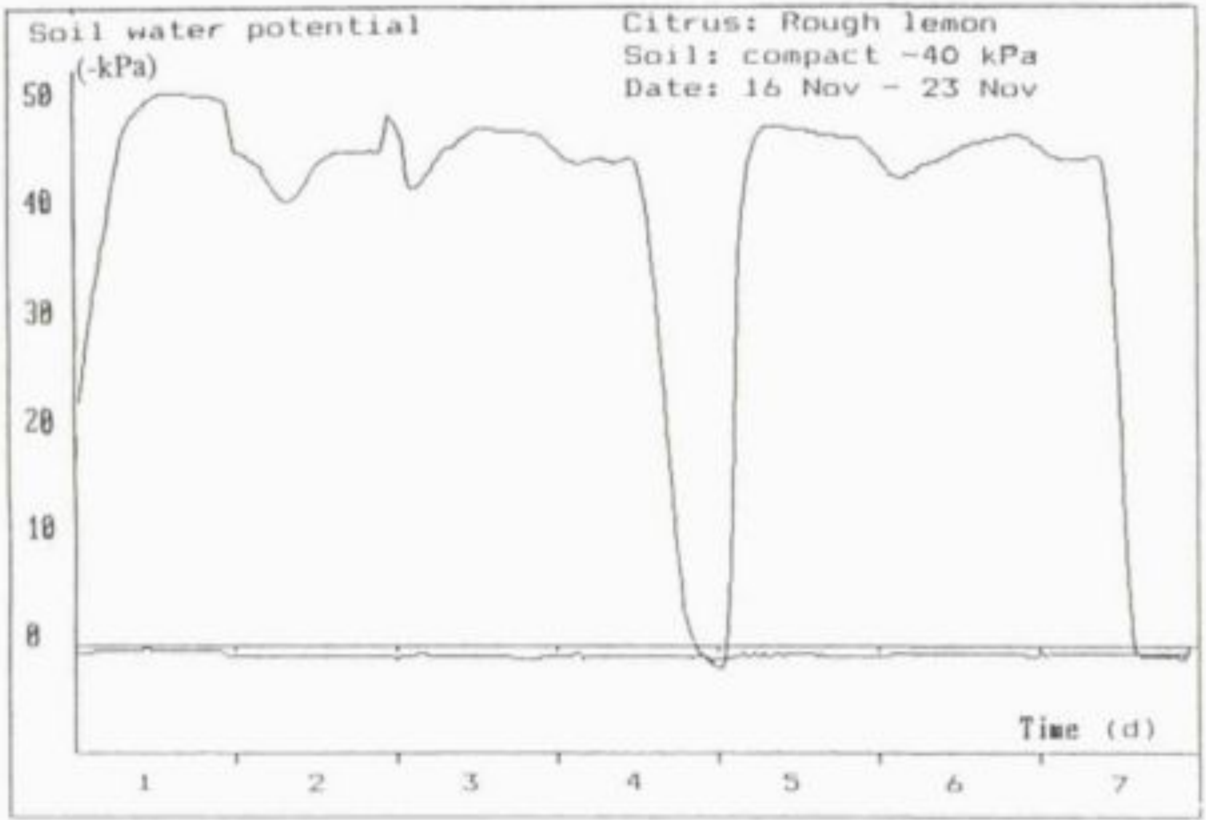


Fig. 5.9. Soil water potential in compacted soil at -40 kPa 30 days after planting. A rise in soil water potential indicates loss of data as the tensiometer loses water. The bottom line indicates water potential of free water.

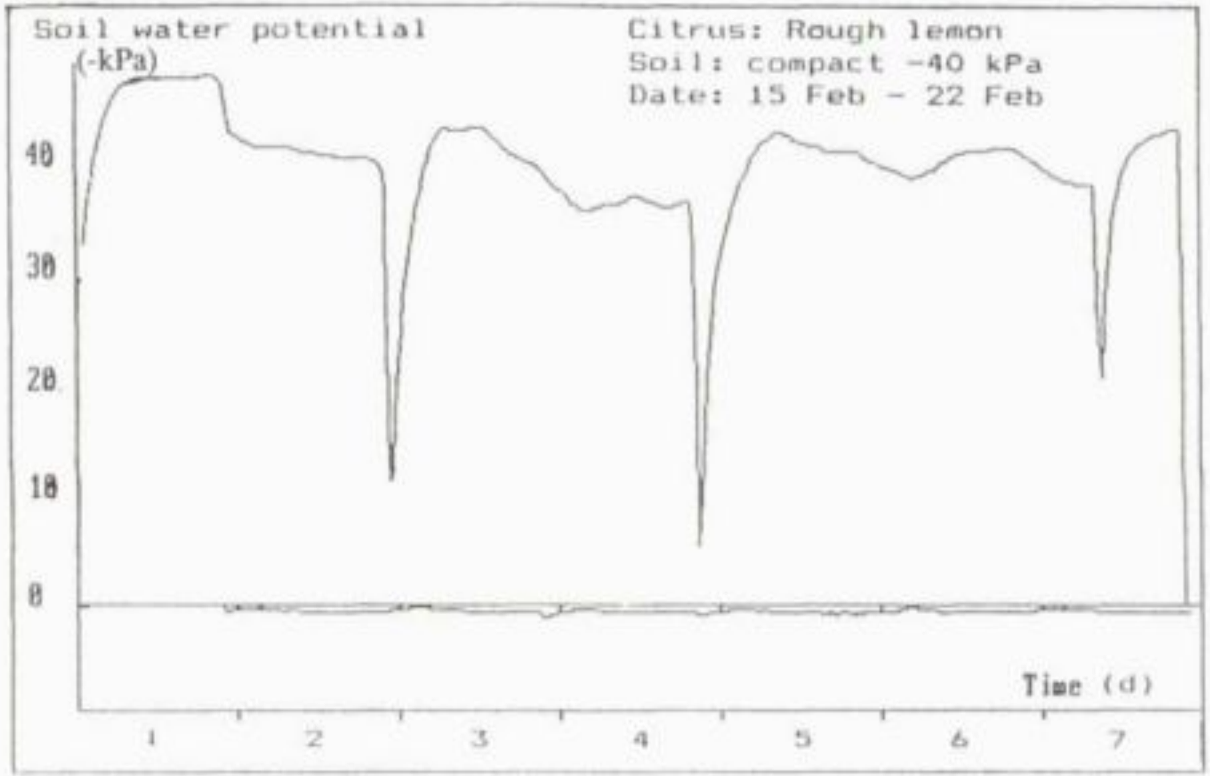


Fig. 5.10. Soil water potential in compacted soil at -40 kPa 130 days after planting. Rises in soil water potential indicate a loss of data as the tensiometer loses water. The bottom line indicates water potential of free water.

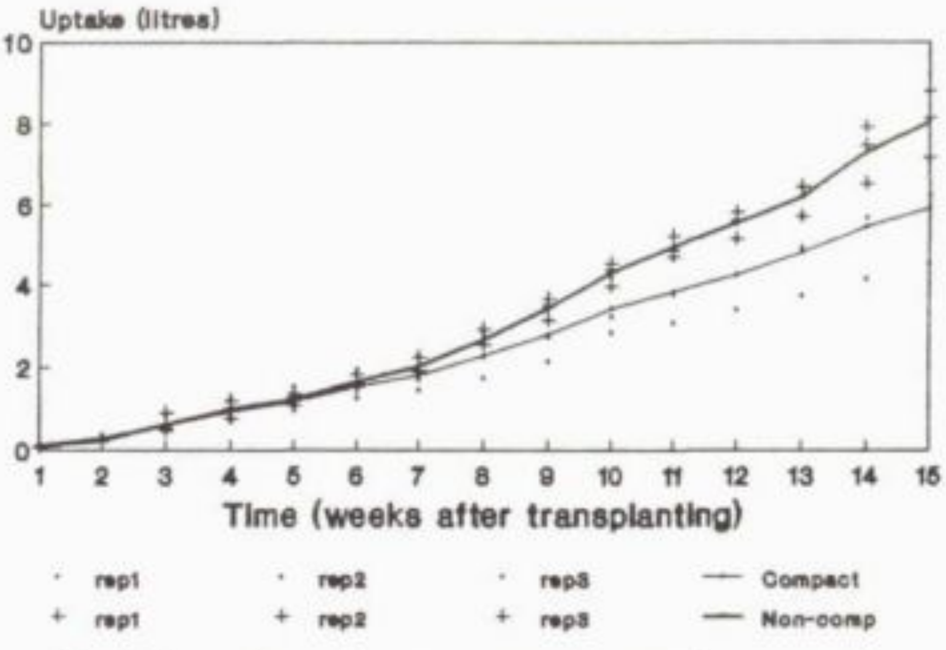


Fig. 5.11. Cumulative water uptake by RL in compacted and non-compacted soil at -10 kPa. Each line represents an average of three values.

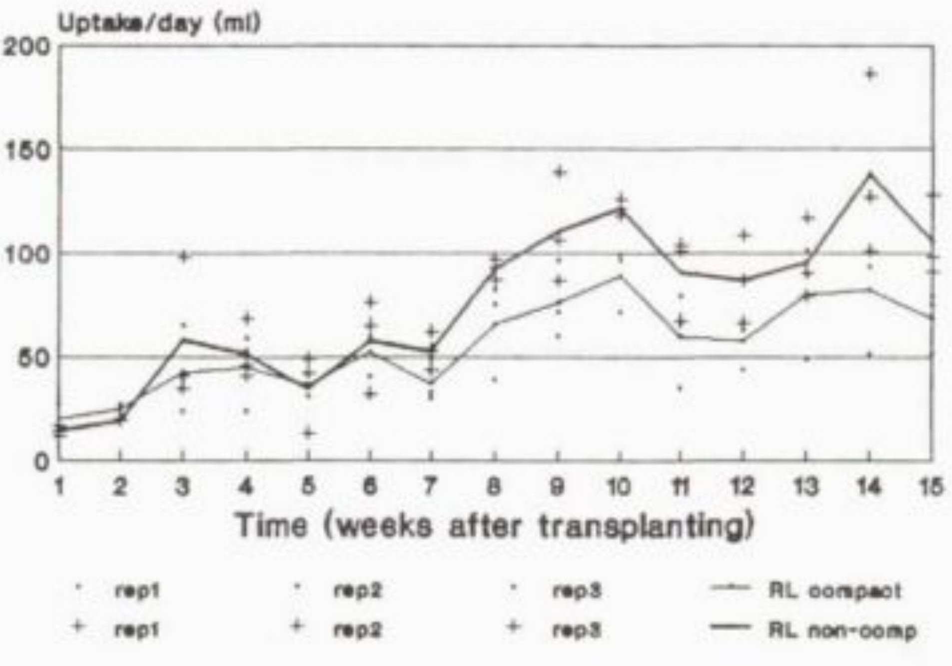


Fig. 5.12. Daily rate of water use by RL in compacted and non-compacted soil at -10 kPa.

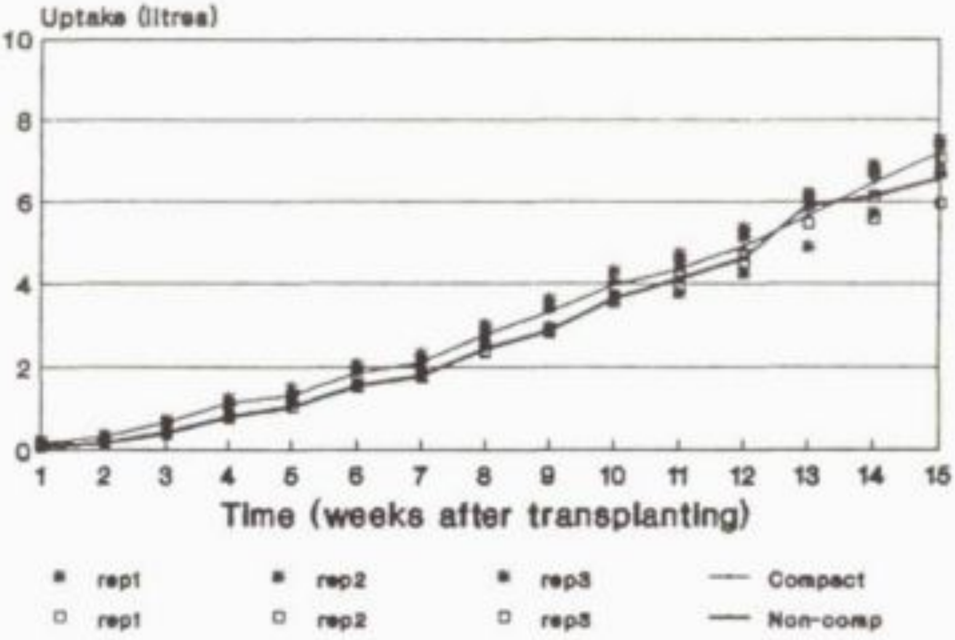


Fig. 5.13. Cumulative water uptake by RL in compacted and non-compacted soil at -20 kPa.

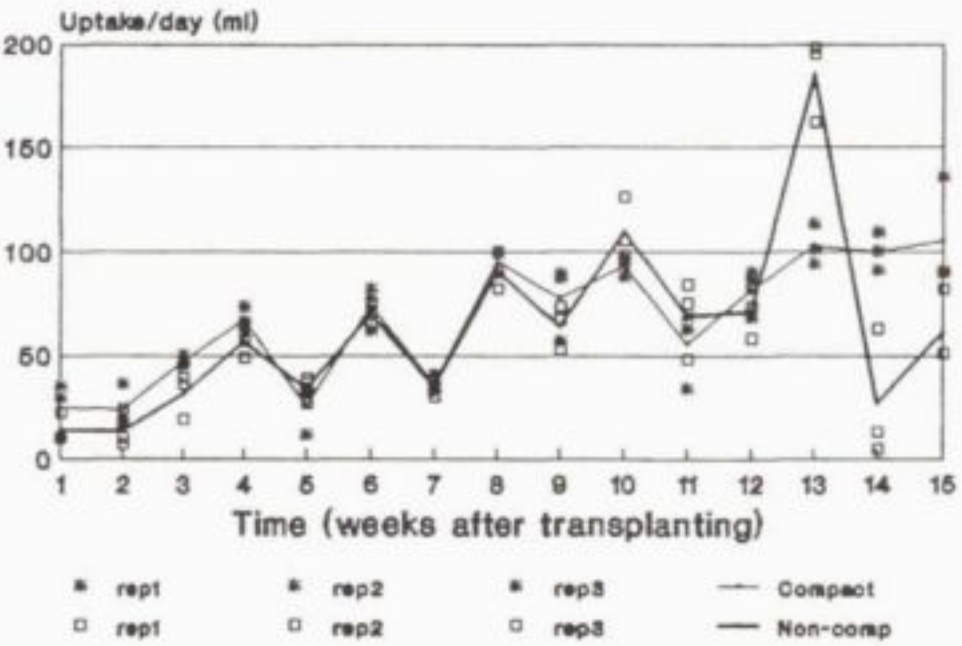


Fig. 5.14. Daily rate of water use by RL in compacted and non-compacted soil at -20 kPa.

of water was also similar for these treatments (Figure 5.14).

Figures 5.15 and 5.16 illustrate the effect of soil water potential on water consumption by seedlings grown in compacted soil. Seedlings at -20 kPa used statistically significantly more (6.84 dm^3) water compared to those at -10 kPa (5.94 dm^3) and -40 kPa (5.46 dm^3). The difference in water consumption started five weeks after transplanting and got bigger over time. Although seedlings at -10 kPa were exposed to more water than in the other two levels of soil water potential, they could not take-up more water than those at -20 kPa, probably due to soil waterlogging stress at -10 kPa. The soil water content at -20 kPa probably resulted in less stressful aeration conditions for the compacted soil as compared to that at -10 kPa. The possibility of waterlogging stress at -10 kPa in the compacted soil was confirmed by a dark bottom soil layer in these pots at the end of the experiment, whereas at -20 and -40 kPa the soil had its original brownish colour. Moreover, the soil from -10 kPa had a foul smell as a result of chemical reduction processes which were not found in the -20 and -40 kPa treatments.

In **non-compacted** soil, the seedlings at -10 kPa used more water than at -20 kPa (Figures 5.17 and 5.18). The difference in cumulative water uptake started in the seventh week after transplanting resulting in statistically significantly more (23%) water used by seedlings at -10 kPa at the end of the season. This indicates that water was more freely available at -10 kPa and that there was no waterlogging problem. As a result the seedlings could use it relatively inefficiently compared to those at -20 kPa.

There was a positive correlation between the growth rate and the daily consumptive rate of water by the seedlings. For example, in the compacted soil at -20 kPa, an increase in growth rate led to a higher water consumption (Figure 5.19). When the growth rate decreased, there was a decrease in water consumptive rate. This relationship was also found in other treatments (Appendices 5.1 to 5.4).

5.3.3 Plant Growth and Development

Soil compaction had a great effect on height of RL seedlings at -10 kPa. In the first five weeks after transplanting, there was no difference in plant height as a result of the treatments (Figure 5.20). However, from the sixth week onwards, the seedlings in non-compacted soil started to grow faster than in compacted soil. In the 12th and 13th weeks, there was some growth surge in seedlings growing in compacted soil but this soon declined until the end of the experimental period. Such an alternating fast and slow change in plant height in compacted soil can be due to plant response to waterlogging, which led to decreased levels of plant-available photosynthetic reserves most of the time. Since waterlogging negatively affects the uptake of water by plants, it also leads to a considerable reduction in carbon dioxide assimilation (Marler & Davies, 1989). Van Noort (1969) also reported that both top length and leaf area per top growth of citrus depend on the availability of plant reserves. This means that perhaps a critical level of available reserves must be met before subsequent top growth begins and once the photosynthetic reserves are depleted, the top growth declines again. On the other hand, the seedlings in non-compacted soil were growing continuously without irregular growth pattern. At the end of the season, the seedlings in non-compacted soil were statistically significantly taller (77%) than in compacted

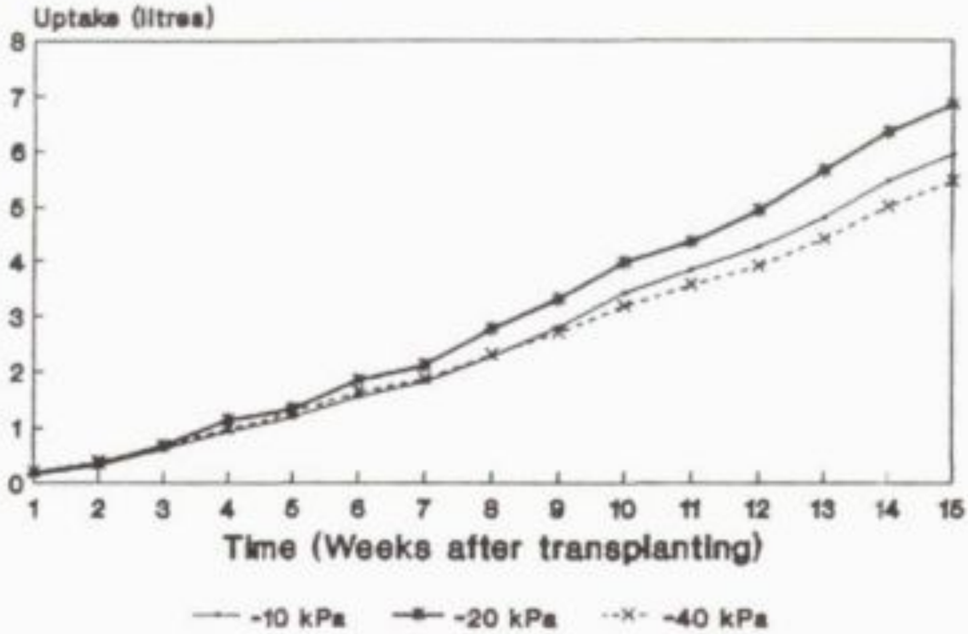


Fig. 5.15. Cumulative water uptake by RL in compacted soil at -10, -20, and -40 kPa.

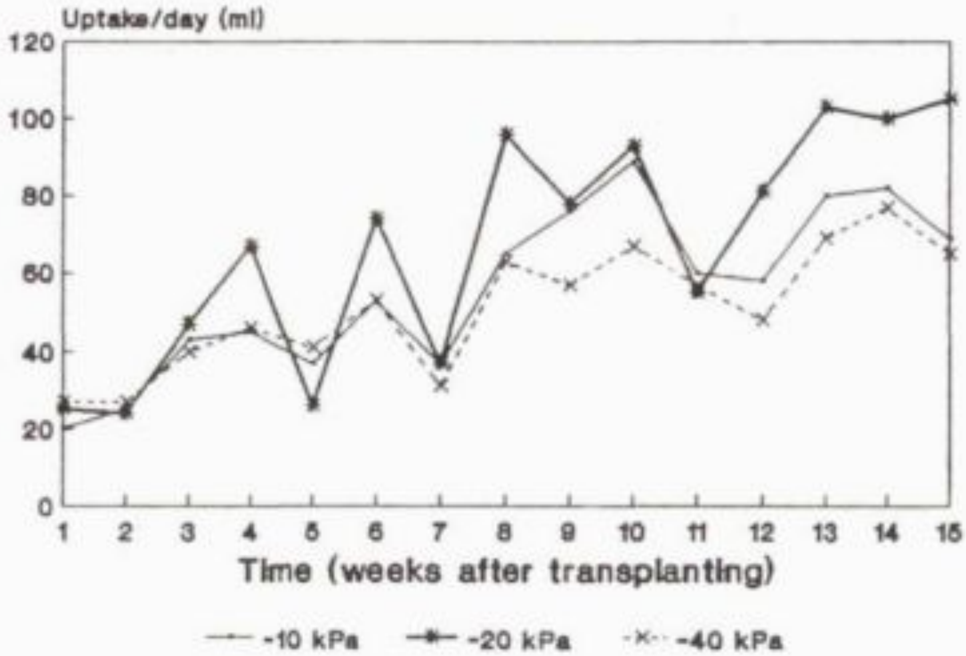


Fig. 5.16. Daily rate of water use by RL in compacted soil at -10, -20, and -40 kPa.

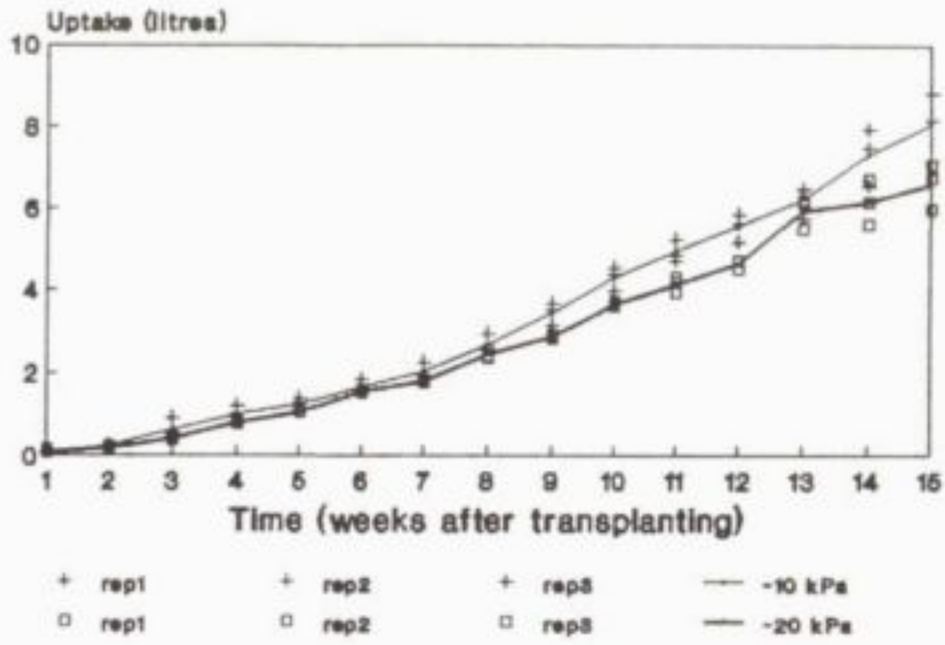


Fig. 5.17. Cumulative water uptake by RL in non-compacted soil at -10 and -20 kPa.

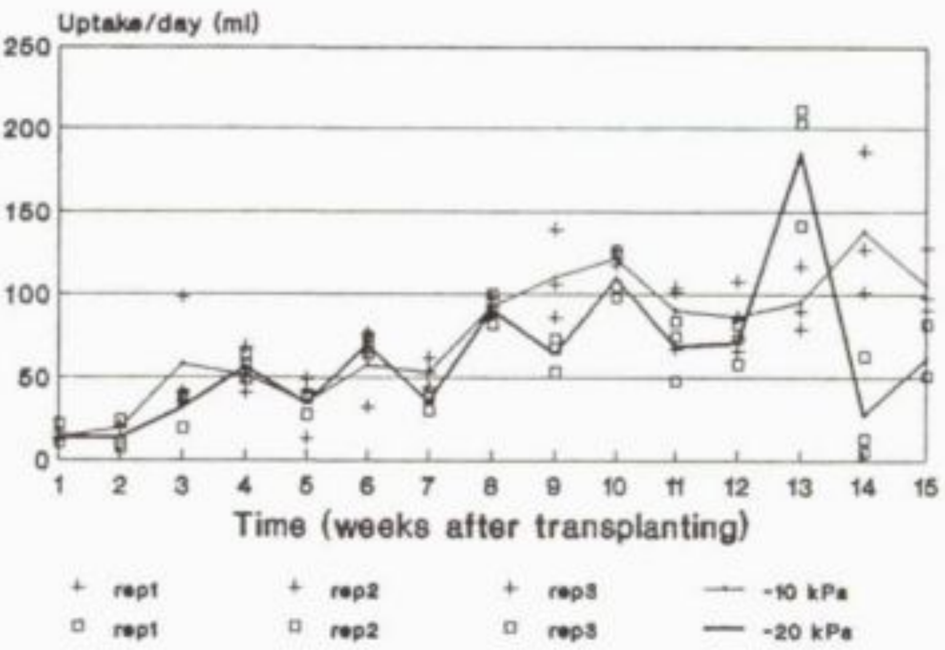


Fig. 5.18. Daily rate of water use by RL in non-compacted soil at -10 and -20 kPa.

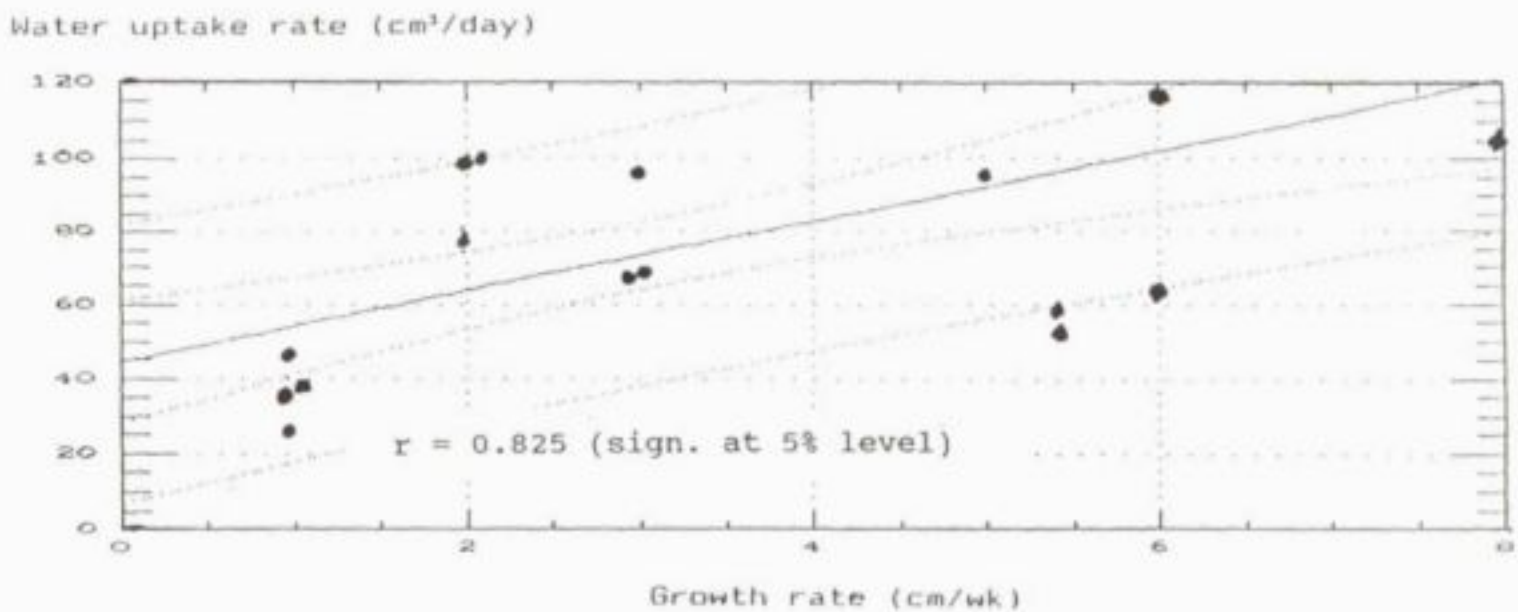


Fig. 5.19. Regression line showing a relationship between growth rate and water consumptive rate of RL in compacted soil at -20 kPa.

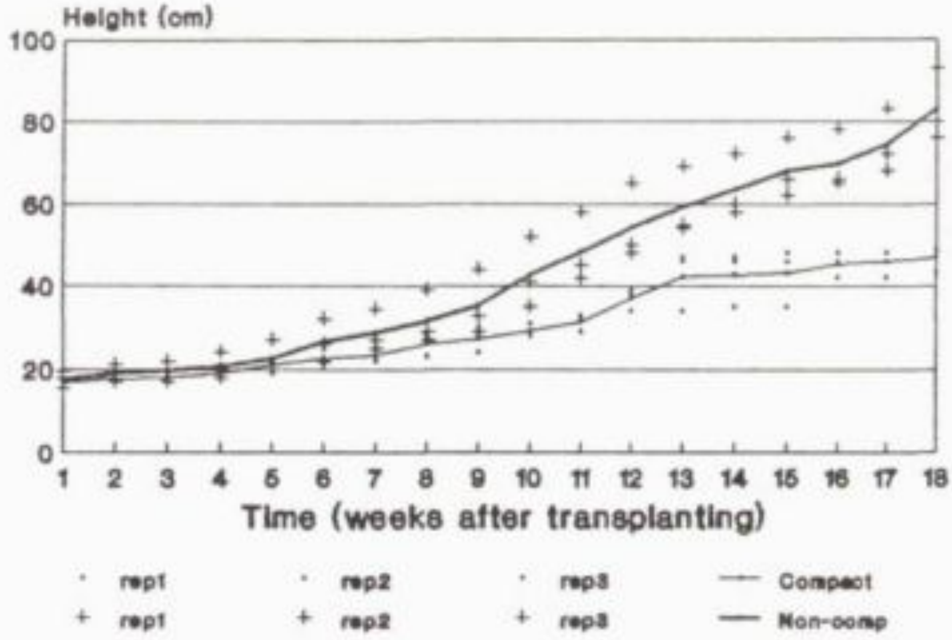


Fig. 5.20. Height of RL in compacted and non-compacted soil at -10 kPa.

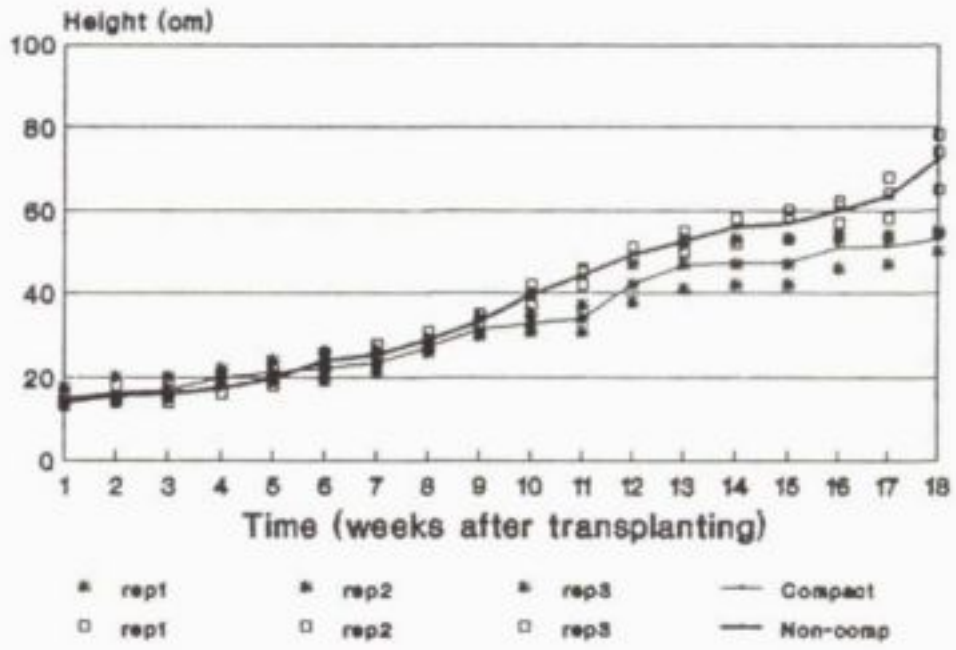


Fig. 5.21. Height of RL in compacted and non-compacted soil at -20 kPa.

soil (83 and 47 cm, respectively). This indicates that seedlings in non-compacted soil at -10 kPa were not subject to poor aeration and could continuously synthesize enough photosynthates for top growth and for increase in leaf area.

At -20 kPa, the soil compaction also led to a decline in plant height (Figure 5.21), but the difference in plant height between compacted and non-compacted soil was smaller than at -10 kPa. The seedlings in compacted soil at -20 kPa reached a final height of 52 cm and 72 cm in non-compacted soil. This difference was statistically significant. Whereas at -10 kPa the seedlings in the non-compacted soil started growing faster than those in the compacted soil from week six onwards, this difference started to show only after week nine at -20 kPa.

The effect of soil water potential on plant height in compacted soil is shown in Figure 5.22. It is important to note the growth patterns by seedlings from different soil water potentials. During the first seven weeks there was very little difference between the growth rates of the seedlings at the three different soil water potentials. At the end of week seven the height was identical. From week eight to week 11 the seedlings followed different growth patterns, but by week 11 their height was again very similar. The plants at -20 and -40 kPa had practically the same height. At -40 kPa growth during week 12 was slow and came to a standstill during weeks 13 to 15. The seedlings at -10 and -20 kPa grew rapidly during weeks 12 and 13, after which their growth rate decreased rapidly. It appears that there was a high water demand during this period, which the -40 kPa could not satisfy. By week 15 the seedlings at -40 kPa had obviously recovered, because during week 16 they showed a sharp growth flush relative to the seedlings at -10 and -20 kPa. During weeks 17 and 18 the seedlings at -40 kPa grew at practically the same rate as those at -20 kPa. The height of seedlings at -20 kPa was statistically significantly higher than at -10 and -40 kPa at the end of the experimental period.

There was a gradual increase in plant height at both -10 and -20 kPa in the non-compacted soil (Figure 5.23). The irregular growth patterns of seedlings in compacted soil were not found in non-compacted soil. In the first nine weeks the growth rate of seedlings at both soil water potentials was slow and very similar, the latter shown by the fact that the curves remain parallel. From week 10 onwards, the growth rate increased. Growth rate at -10 kPa increased more than at -20 kPa, with the result that the differences in plant height for the two treatments increased during the period 10 to 18 weeks. The plants at -10 kPa were statistically significantly larger than those at -20 kPa.

It should be noted that whereas the seedlings in non-compacted soil grew better at -10 than at -20 kPa, the reverse was true for the compacted soil. These results illustrate the interaction between dry bulk density, soil water potential and aeration and their influence on the development of citrus seedlings.

5.3.4 Morphological and Physiological Plant Responses

Soil compaction and soil water potential had a significant effect on morphological and physiological plant responses. At both -10 and -20 kPa, soil compaction resulted in a statistically significant reduction of dry mass accumulation (Table 5.1). At both soil water potentials the total

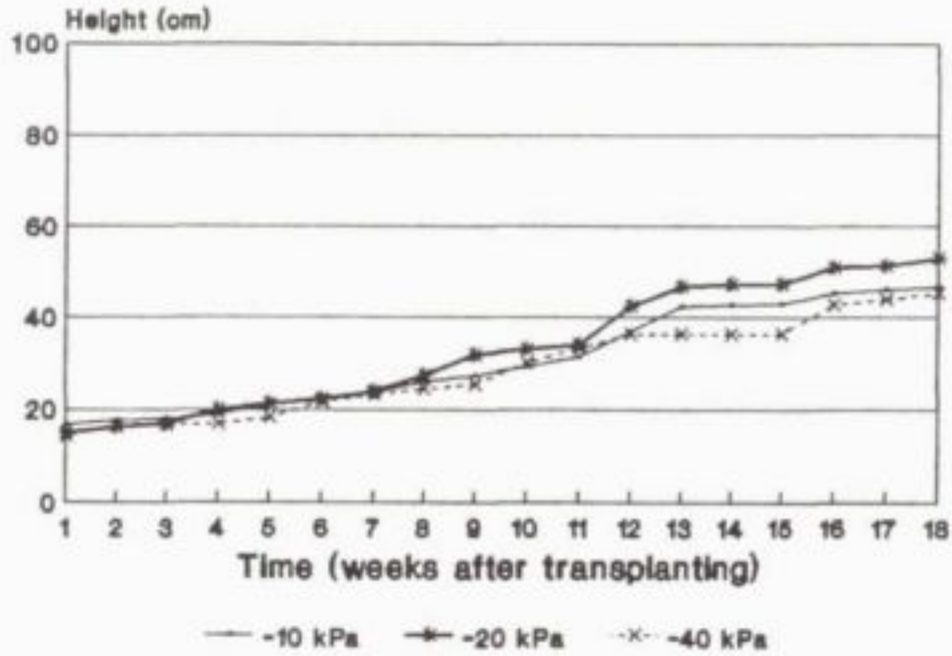


Fig. 5.22. Height of RL in compacted soil at -10, -20, and -40 kPa.

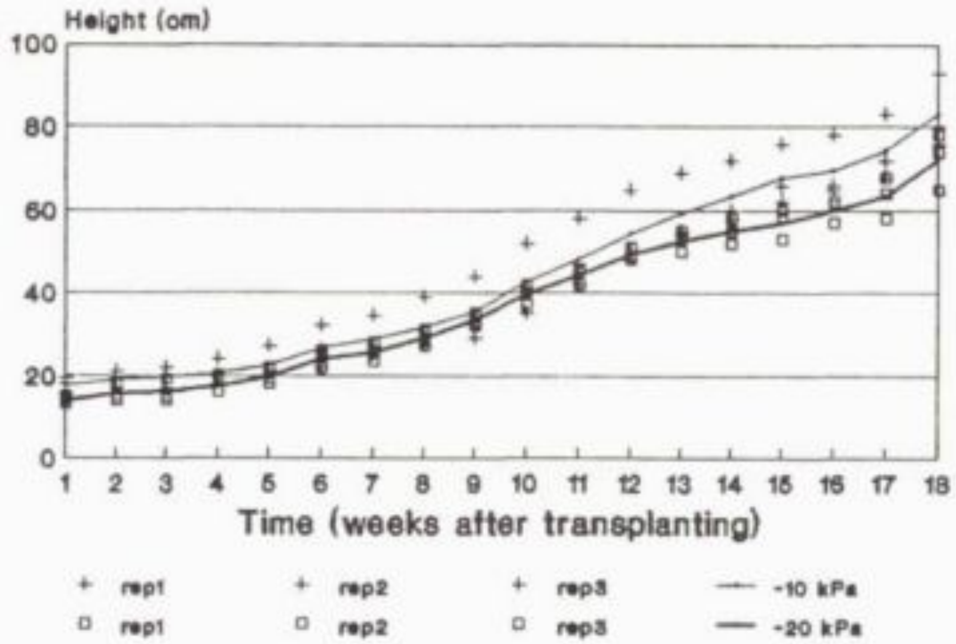


Fig. 5.23. Height of RL in non-compacted soil at -10 and -20 kPa.

dry mass, top dry mass, root dry mass, and water use efficiency of the seedlings in compacted soil were statistically significantly lower than those of the seedlings in non-compacted soil (For statistical analyses, refer to Appendices 5.5 to 5.36). There was no statistically significant difference in top:root ratio between seedlings in compacted and non-compacted soil at -10 kPa. At -20 kPa, the top:root ratio was also significantly negatively affected by non-compaction of soil.

Different soil water potentials had effects on plant development at both soil bulk densities studied. In non-compacted soil the seedlings at -10 kPa had a statistically significantly higher total and top dry mass accumulation than at -20 kPa. However, the root dry mass was the same for seedlings from both treatments. Stolzy et al. (1959) also found that -9 kPa produced significantly higher total plant mass and top growth compared to -60 kPa. According to Bielorai & Mendel (1969), the rate of photosynthesis in citrus seedlings is high at relatively higher soil water content. Both the water use efficiency and the top:root ratio were similar at -20 and -10 kPa.

In compacted soil, the seedlings grown at -40 kPa showed some symptoms of drought stress. Seedlings in compacted soil at -20 kPa had a statistically significantly higher total dry mass and top dry mass than those at both -10 and -40 kPa. Similar results were reported by Smajstrla et al. (1985) where better seedlings were obtained at -20 kPa compared to -10 or -40 kPa. According to these authors, -10 kPa was observed to be continuously wet and thus limiting oxygen diffusion rate or leaching nitrogen as evidenced by a yellowing of leaves in this treatment. Frank et al. (1991) also found that a considerable increase in air-filled porosity and oxygen flux occurs at -25 kPa soil water potential. It was found that below this level, the water supply to the roots was apparently insufficient to sustain maximum development of seedlings. In the present study, however, both the root mass and top:root ratio were similar for seedlings at different soil water potentials.

The leaf area was statistically significantly higher for seedlings in non-compacted soil at -10 kPa than at -20 kPa (Table 5.2). This was also true with the total water consumption per plant. In compacted soil, however, the seedlings at -20 kPa had a slightly, but statistically insignificantly higher leaf area, and total water consumption per leaf area compared to those seedlings grown at -10 and -40 kPa. The total water consumption was statistically significantly higher in compacted soil at -20 kPa than at -10 and -40 kPa.

Soil compaction had a significant negative effects on several plant parameters. At -10 kPa, the compaction of soil resulted in a statistically significant reduction in leaf area, root surface area, and water consumption. However, the total water consumption per leaf area was not statistically significantly different between compacted and non-compacted soil.

At -20 kPa the water consumption per leaf area was statistically significantly higher in compacted than in non-compacted soil. There was a statistically significant difference in root area:leaf area ratio among treatments, with soil compaction resulting in a low ratio. However, the soil water potential treatments did not have significant effects on the root area:leaf area ratio.

Table 5.1. The effects of soil compaction and soil water potential on dry mass accumulation and water use efficiency of RL seedlings

Soil treat	Total dry mass (g)	Top dry mass (g)	Root dry mass (g)	Top:root ratio	WUE ($g.dm^{-3}$)
	-10 kPa soil water potential				
	13.43	11.59	1.84	6.30	1.498
Non-comp	13.18	9.95	3.23	3.08	1.810
	16.01	12.56	3.45	3.64	1.934
mean	**14.21**	**11.37**	**2.84**	**4.34**	**1.747**
S.E.	0.91	0.76	0.50	0.99	0.130
	6.08	4.91	1.17	4.20	1.294
Compact	8.84	7.22	1.62	4.46	1.221
	9.53	7.80	1.73	4.51	1.489
mean	**8.15**	**6.64**	**1.51**	**4.40**	**1.335**
S.E.	1.05	0.88	0.17	0.10	0.080
	-20 kPa soil water potential				
	12.88	10.35	2.53	5.09	2.127
Non-comp	12.30	8.98	3.32	2.70	1.799
	12.66	10.02	2.64	3.80	1.766
mean	**12.61**	**9.78**	**2.83**	**3.86**	**1.897**
S.E.	0.17	0.41	0.25	0.69	0.120
	11.37	9.40	1.97	4.77	1.482
Compact	7.48	6.26	1.22	5.13	1.089
	10.56	8.89	1.67	5.32	1.402
mean	**9.80**	**8.18**	**1.62**	**5.05**	**1.324**
S.E.	1.19	0.97	0.22	0.16	0.120
	-40 kPa soil water potential				
	7.46	6.07	1.39	4.37	1.142
Compact	6.45	4.70	1.75	2.69	1.224
	8.13	6.56	1.57	4.18	1.586
mean	**7.35**	**5.78**	**1.57**	**3.75**	**1.317**
S.E.	0.49	0.56	0.10	0.53	0.140
LSD	1.39	1.22	0.48	1.02	0.205

WUE - water use efficiency.

Table 5.2. The effects of soil compaction and soil water potential on morphological and physiological plant parameters of RL seedlings

Soil treat.	Leaf area (cm^2)	Root area (cm^2)	RA:LA ratio	RA:RM ratio (cm^2/g)	Water uptake (dm^3)	Uptake per LA (dm^3)	Soil H_2O content (%)
			-10 kPa soil water potential				
	985	288	0.293	156	8.81	8.95	
Non-comp	957	283	0.295	88	7.15	7.48	
	1051	293	0.278	85	8.16	7.76	
mean	**997**	**288**	**0.289**	**101**	**8.04**	**8.06**	**21.6**
S.E.	28	3	0.005	23	0.48	0.45	
	673	142	0.211	121	4.52	6.71	
Compact	628	131	0.208	81	7.05	11.22	
	741	179	0.221	103	6.24	8.42	
mean	**681**	**151**	**0.213**	**100**	**5.94**	**8.78**	**17.3**
S.E.	33	15	0.004	12	0.75	1.31	
			-20 kPa soil water potential				
	903	322	0.357	127	5.95	6.59	
Non-comp	883	282	0.320	85	6.71	7.60	
	920	271	0.294	103	7.03	7.64	
mean	**902**	**292**	**0.324**	**103**	**6.56**	**7.28**	**16.6**
S.E.	11	16	0.018	12	0.32	0.34	
	761	147	0.193	75	7.51	9.87	
Compact	594	115	0.194	94	6.65	11.20	
	777	151	0.194	90	7.36	9.47	
mean	**711**	**138**	**0.194**	**85**	**7.17**	**10.18**	**16.5**
S.E.	59	11	0.001	6	0.27	0.52	
			-40 kPa soil water potential				
	685	121	0.176	87	6.33	9.24	
Compact	470	120	0.255	69	5.08	10.82	
	766	127	0.166	81	4.98	6.50	
mean	**640**	**123**	**0.199**	**78**	**5.46**	**8.85**	**13.0**
S.E.	88	2	0.028	5	0.43	1.26	
LSD	84	18	0.042	28	0.84	1.44	

RA:RM - root area to root mass ratio.

Given the water content of the soil in different treatments (Table 5.2) and assuming that the soil particle density is 2656 $kg.m^{3}$ (Carter & Johnston, 1989), there was no major difference in air-filled pore space among the treatments for this specific soil. For example, using the calculation method by Nel & Bennie (1984) and Patt et al. (1966) the air-filled pore space in different treatments was as follows:

The total pore space was:

Non-compacted soil	**Compacted soil**
= (1 - 1550/2656) 100	= (1 - 1700/2656) 100
= 41.6%	= 36.0%

Therefore, the air-filled pore space was:

At -10 kPa soil water potential:-

= 41.6 - 21.6%	= 36.0 - 17.3%
= 20%	= 18.7%

At -20 kPa soil water potential:

= 41.6 - 16.6%	= 36.0 - 16.5%
= 25%	= 19.5%

At -40 kPa soil water potential:

= 36.0 - 13% = 23%

Since a minimum threshold of air-filled pore space for most dryland plant species is about 10% (Allmaras et al., 1988; Ayres et al., 1972; Patt et al., 1966), the results show that the differences in seedling performance among the treatments were not entirely resulting from a limited air-filled pore space. Moreover, the results may indicate that excess water in the soil has a negative effect even if it does not limit the air-filled pores, especially under compacted soil conditions. Hence a predisposal effect of excess water on plant roots has been documented (Blaker & MacDonald, 1981; Stolzy et al., 1965a; Tucker, Parsons & Futch, 1992). According to these authors, excess water in the rhizosphere stresses the roots such that they become susceptible to other factors such as soilborne pathogens.

Table 5.3 illustrates the large negative effects of soil compaction on RL seedlings at -10 kPa. Compaction of the soil had greater effects on root growth than on top growth at both -10 and -20 kPa. These results are in agreement with those of Kongsgrud (1969) (cited by Olien, 1987) where greater loss in roots than in top growth occurred in black currants and apples. At -20 kPa the negative effects of soil compaction on top growth was much smaller than at -10 kPa, despite the fact that its relative effect on root growth was as large as at -10 kPa.

Table 5.3. Relative negative effects of soil compaction on RL seedlings at two soil water potentials

Parameter	Relative decline due to soil compaction (%)*	
	-10 kPa	**-20 kPa**
Total mass (g)	43 (4)	23 (5)
Top mass (g)	42 (5)	16 (7)
Leaf area (cm^2)	32 (6)	21 (6)
Root dry mass (g)	47 (3)	43 (3)
Root volume (dm^3)	50 (1)	44 (2)
Root area (cm^2)	48 (2)	53 (1)
WUE ($g.dm^{-3}$)	24 (7)	26 (4)

* {(value for non-compacted soil - value for compacted soil)/value for non-compacted soil} x 100 for each soil water potential.
The number in parenthesis indicates the ranking of parameters as a result of reduction effect.

In non-compacted soil, a decrease or increase in soil water potential from -10 to -20 kPa (or vice versa) did not have major effects on the plant parameters (Table 5.4). This means that as long as this soil is not compacted, excess levels of water are unlikely to cause waterlogging problems to young RL rootstock. If the problems due to excess water do occur under such conditions, their symptoms are delayed compared to compacted soil conditions.

In compacted soil, a change in soil water potential from -20 kPa to -10 or -40 kPa had a bigger negative influence on both top and total plant mass compared to non-compacted soil (Table 5.4). The effects of soil water potential in compacted soil were more higher at -40 than at -10 kPa. The least affected plant parameters were root dry mass and root area at -40 and -10 kPa, respectively.

The differences induced by soil water potentials at a specific level of soil bulk density were generally much smaller than those induced by soil compaction at a specific soil water potential (Compare Tables 5.3 and 5.4). Whereas soil compaction had a bigger influence on root growth than on top growth (Table 5.3), differences in soil water potential had a bigger influence on top growth than on root growth (Table 5.4). Several reasons can account for these differences in plant response. Firstly, compacted soil physically impedes root growth and development due to reduced soil porosity. This physical impairment does not have the same effect on top growth as it has on root growth. Secondly, the top growth (especially the leaf area) is very sensitive to the availability of soil water. A change (decline) in soil water potential leads to a great response in leaf/top growth than in root growth. This is probably one of the defence mechanisms with which RL seedlings minimize the loss of water to the atmosphere, especially when the soil water potential is relatively low.

Table 5.4. Relative negative effects of maintaining soil water potentials on RL seedlings in compacted and non-compacted soil

Parameter	Relative decline (%)		
	Non-compacted soil*	Compacted soil**	
	-20 kPa	**-10 kPa**	**-40 kPa**
Total dry mass (g)	11 (2)	17 (2)	25 (2)
Top dry mass (g)	14 (1)	19 (1)	29 (1)
Leaf area (cm^2)	10 (3)	4 (6)	10 (5)
Root dry mass (g)	0	7 (4)	3 (7)
Root volume (dm^3)	0	10 (3)	17 (3)
Root area (cm^2)	0	10 gain	11 (4)
WUE ($g.dm^{-3}$)	9 gain	5 (5)	7 (6)

* Relative to the values at -10 kPa for non-compacted soil.

** Relative to the values at -20 kPa for compacted soil.

5.3.5 Nutrient Status of Leaves

The RL seedlings in compacted and non-compacted soil at specific soil water potential levels had statistically significant differences in nutrient status (Table 5.5). At -10 kPa, the concentration of N, P and K was significantly higher in seedlings grown in compacted than in non-compacted soil. The concentration of Ca and Mg was statistically significantly higher in seedlings grown in non-compacted soil than those in compacted soil.

The Ca:Mg ratio was statistically significantly higher in seedlings grown in non-compacted soil while the K:Mg, K:Ca and K:(Ca+Mg) ratios were higher in compacted soil. The iron (Fe) concentration was statistically significantly higher in seedlings grown in non-compacted soil than in compacted soil while no significant differences were found in Mn, Zn, and Cu concentrations between the treatments.

Table 5.5. Nutrient status (concentration) of young RL leaf tissue sampled 130 days after transplanting

Soil treat.	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Na (%)	Ca:Mg ratio	K:Mg ratio
				-10 kPa soil water potential				
	2.26	0.20	0.14	3.02	0.43	0.02	7.02	0.33
Non-comp	2.33	0.24	0.17	2.98	0.42	0.02	7.10	0.40
	2.51	0.22	0.15	3.06	0.42	0.02	7.29	0.36
mean	**2.37**	**0.22**	**0.15**	**3.02**	**0.42**	**0.02**	**7.14**	**0.36**
S.E.	0.07	0.01	0.01	0.02	0.003	-	0.08	0.02
	2.65	0.21	0.18	2.47	0.42	0.02	5.88	0.43
Compact	2.71	0.30	0.19	2.55	0.37	0.02	6.89	0.51
	2.71	0.23	0.19	2.65	0.41	0.02	6.46	0.46
mean	**2.69**	**0.25**	**0.19**	**2.56**	**0.40**	**0.02**	**6.41**	**0.47**
S.E.	0.02	0.03	0.003	0.05	0.02	-	0.29	0.02
				-20 kPa soil water potential				
	2.23	0.21	0.18	3.17	0.44	0.02	7.20	0.41
Non-comp	2.67	0.22	0.15	3.44	0.46	0.02	7.48	0.33
	2.63	0.21	0.15	3.14	0.41	0.02	7.66	0.37
mean	**2.51**	**0.21**	**0.16**	**3.25**	**0.44**	**0.02**	**7.45**	**0.37**
S.E.	0.14	0.003	0.01	0.10	0.01	-	0.13	0.02
	2.87	0.25	0.21	2.94	0.40	0.02	7.35	0.52
Compact	2.66	0.19	0.21	2.51	0.40	0.02	6.28	0.52
	2.98	0.22	0.21	2.87	0.37	0.02	7.76	0.57
mean	**2.84**	**0.22**	**0.21**	**2.77**	**0.39**	**0.02**	**7.13**	**0.54**
S.E.	0.09	0.02	-	0.13	0.01	-	0.44	0.17
				-40 kPa soil water potential				
	3.11	0.26	0.20	2.86	0.41	0.02	6.98	0.49
Compact	3.10	0.26	0.17	2.91	0.51	0.02	5.71	0.33
	2.74	0.22	0.18	2.31	0.41	0.02	5.63	0.44
mean	**2.98**	**0.25**	**0.18**	**2.69**	**0.44**	**0.02**	**6.11**	**0.42**
S.E.	0.12	0.01	0.01	0.19	0.03	-	0.44	0.05
LSD	0.16	0.03	0.01	0.19	0.03	-	0.52	0.05

Table 5.5 continued ...

Soil treat.	K:Ca ratio	K:(Ca+Mg) ratio	Fe (ppm)	Mn (ppm)	Cu (ppm)	Zn (ppm)
		-10 kPa soil water potential				
	0.05	0.04	842	70.5	3.0	40.5
Non-comp	0.06	0.05	845	54.0	7.5	123.0
	0.05	0.04	929	46.5	12.0	61.5
mean	**0.05**	**0.04**	**872**	**57.0**	**7.5**	**75.0**
S.E.	0.003	0.003	29	7.1	2.6	24.8
	0.07	0.06	479	82.5	9.0	54.0
Compact	0.07	0.07	483	61.5	10.5	54.0
	0.07	0.06	545	88.5	1.5	54.0
mean	**0.07**	**0.06**	**502**	**77.5**	**7.0**	**54.0**
S.E.	-	0.003	21	8.2	2.8	-
		-20 kPa soil water potential				
	0.06	0.05	522	60.0	18.0	46.5
Non-comp	0.04	0.04	872	76.5	9.0	42.0
	0.05	0.04	483	51.0	4.5	64.5
mean	**0.05**	**0.04**	**626**	**62.5**	**10.5**	**51.0**
S.E.	0.006	0.003	124	7.5	4.0	6.9
	0.07	0.06	788	66.0	31.5	63.0
Compact	0.08	0.07	600	102.0	9.0	48.0
	0.07	0.06	551	84.0	22.5	88.5
mean	**0.07**	**0.06**	**646**	**84.0**	**21.0**	**66.5**
S.E.	0.003	0.003	72	10.4	6.5	11.8
		-40 kPa soil water potential				
	0.07	0.06	599	55.5	24.0	99.0
Compact	0.06	0.05	420	60.0	16.5	42.0
	0.08	0.07	314	37.5	16.5	69.0
mean	**0.07**	**0.06**	**444**	**51.0**	**19.0**	**70.0**
S.E.	0.006	0.006	83	6.9	2.5	16.5
LSD	0.007	0.007	127	13.3	6.5	23.9

Table 5.6. Nutrient content per top of young RL seedlings sampled 130 days after transplanting. These data were obtained by multiplying the data above by a corresponding top dry mass

Soil treat.	N (mg)	P (mg)	K (mg)	Ca (mg)	Mg (mg)	Fe (mg)	Mn (mg)	Cu (mg)	Zn (mg)
				-10 kPa soil water potential					
	262	23.2	16.2	350	49.8	9.8	0.82	0.03	0.47
Non-comp	232	23.9	16.9	297	41.8	8.4	0.54	0.07	1.22
	315	27.6	18.8	384	52.8	11.7	0.58	0.15	0.77
mean	**270**	**24.9**	**17.3**	**344**	**48.1**	**9.9**	**0.65**	**0.09**	**0.82**
S.E.	24	1.4	0.8	25	3.3	1.0	0.09	0.04	0.22
	130	10.3	8.8	121	20.6	2.3	0.41	0.04	0.27
Compact	196	21.7	13.7	184	26.7	3.5	0.44	0.08	0.39
	211	17.9	14.8	207	32.0	4.2	0.69	0.01	0.42
mean	**179**	**16.6**	**12.4**	**171**	**26.4**	**3.3**	**0.51**	**0.04**	**0.36**
S.E.	25	3.4	1.8	26	3.3	0.6	0.09	0.02	0.05
				-20 kPa soil water potential					
	231	21.7	18.6	328	45.5	5.4	0.62	0.19	0.48
Non-comp	240	19.8	13.5	309	41.3	7.8	0.69	0.08	0.38
	264	21.0	15.0	315	41.1	4.8	0.51	0.05	0.65
mean	**245**	**20.8**	**15.7**	**317**	**42.6**	**6.0**	**0.61**	**0.11**	**0.50**
S.E.	10	0.6	1.5	6	1.4	0.9	0.05	0.04	0.08
	270	23.5	19.7	276	37.6	7.4	0.62	0.30	0.59
Compact	167	11.9	13.1	157	25.0	3.8	0.69	0.06	0.30
	265	19.6	18.7	255	32.9	4.9	0.75	0.20	0.79
mean	**234**	**18.3**	**17.2**	**229**	**31.8**	**5.4**	**0.69**	**0.19**	**0.56**
S.E.	34	3.4	2.1	37	3.7	1.1	0.04	0.07	0.14
				-40 kPa soil water potential					
	189	15.8	12.1	174	24.9	3.6	0.34	0.15	0.60
Compact	146	12.2	8.0	137	24.0	2.0	0.28	0.08	0.20
	180	14.4	11.8	152	26.9	2.1	0.25	0.11	0.45
mean	**172**	**14.1**	**10.6**	**154**	**25.3**	**2.6**	**0.29**	**0.11**	**0.42**
S.E.	13	1.0	1.3	11	0.9	0.5	0.03	0.02	0.12
LSD	37	3.9	2.6	39	4.5	1.4	0.10	0.07	0.22

For most nutrient elements, a different situation was found when the nutrients were expressed as mass content per top (Table 5.6). For example, the N, P, and K content per top was statistically significantly higher in seedlings grown in non-compacted than in compacted soil, which is the opposite of the pattern when expressed as concentration for these nutrients. This confirms the occurrence of a "concentration factor" in the smaller plants in the compacted soil (i.e. the opposite of a dilution factor described by Labanauskas et al. 1971). However, as Labanauskas et al. (1971) stated, other factors must also have been involved since the concentration and the total mass content of other nutrient elements were not affected in the same direction.

At -20 kPa, the N and K concentration was statistically significantly higher in the compaction treatment than in non-compaction (Table 5.5). The P and Na concentration, and Ca:Mg ratio were not statistically different in the two soil treatments. The Ca and Mg concentration was significantly higher in seedlings grown in non-compacted soil than in compacted soil. The K:Mg, K:Ca, and K:(Ca+Mg) ratios were statistically significantly higher in seedlings grown in compacted than in non-compacted soil. No significant difference was found in Fe, Mn, Zn, and Cu concentration between different treatments at -20 kPa. However, the mass content pattern of several nutrient elements was somewhat different from the ranking of the concentration (Table 5.6). For example, the N, P, and K content per top was statistically different between the treatments, which was not true with the concentration of these nutrient elements. The Ca and Mg content per top was statistically significantly higher in plants grown in non-compacted soil. No significant difference was found in Fe, Mn, Zn, and Cu content per top between the soil treatments.

There was no significant effect as a result of different soil water potential treatments on N, P, K, Mg, Na concentration and K:Mg, K:(Ca+Mg) ratio in non-compacted soil (Table 5.5). However, the Ca concentration and Ca:Mg ratio were statistically significantly higher in seedlings at -20 than -10 kPa while Fe concentration was significantly higher in those grown at -10 than at -20 kPa.

Manganese, Cu, and Zn concentrations were not significantly different between seedlings at these two soil water potential levels in non-compacted soil. On the other hand, the P, Ca, Fe, and Mg content per shoot was statistically significantly higher in seedlings at -10 than at -20 kPa (Table 5.6). With other nutrient elements, however, no statistically significant differences were found as a result of the treatments.

In compacted soil, the N concentration was statistically significantly higher in seedlings at -40 kPa than at -20 or -10 kPa (Table 5.5). This was due, in part, to the concentration factor since the seedlings at -40 kPa were smaller than those at -20 or -10 kPa. Moreover, the N content per top was the lowest in seedlings at -40 kPa than at -20 or -10 kPa (Table 5.6). However, K, Ca, and Fe content per top, and Ca:Mg and K:Mg ratios were statistically significantly higher in seedlings at -20 than at -40 or -10 kPa. It is important to note that even the concentration of these nutrient elements (Table 5.5) was significantly higher at -20 kPa, which indicates that it was not as a result of a dilution factor.

Both Cu and Zn concentrations were statistically significantly lower in seedlings at -10 than at -20 or -40 kPa while Mn concentration was significantly lower in those grown at -40 kPa (Table 5.5). The P, Ca, Mg, and Na concentration, and K:Ca and K:(Ca+Mg) ratios were not statistically significantly different among the treatments. No significant difference was found in N and P content in seedlings among the three levels of soil water potential in the compacted soil (Table 5.6). Seedlings at -40 kPa had a statistically significantly lower level of Mg, Fe, and Mn content. On the other hand, the seedlings at -10 kPa had a statistically significantly lower Cu and Zn content per shoot which did not seem to be affected by the dilution factor. It is also important to note that seedlings at -10 kPa had some inconsistencies in nutrient status which could not be explained by a dilution factor concept. In this case it showed that changes in plant nutrition brought about by soil compaction and soil water potential tend to overshadow the importance of a dilution factor, especially when more drastic nutritional upsets were caused by a possible waterlogging and oxygen deficiency to the roots (Labanauskas, et al., 1971).

5.4 Conclusions

The compaction of soil resulted in poor performance of RL seedlings. Moreover, the relatively high soil water potential together with compaction was more stressful to the development of seedlings. A -10 kPa soil water potential in compacted soil was too wet while a -40 kPa was relatively dry for growth and development of young citrus plants.

In non-compacted soil, an increase in soil water potential resulted in better performance of seedlings. As the soil water potential declined, there was a concomitant decrease in plant performance. However, as the soil water potential increased, a point was reached where the water use efficiency started to decrease.

At -10 kPa, a high concentration of N, P and K was found in seedlings grown in compacted soil. However, the opposite was true for Ca, Fe and Mg which were higher in seedlings grown in non-compacted soil. For most nutrient elements there was an occurrence of a "concentration factor" whereby smaller size seedlings tended to have higher concentration but low content (mg per pot) of several nutrient elements.

At -20 kPa, the N and K concentration was higher in seedlings from the compaction treatment. No "concentration factor" occurrence was observed in this soil water potential treatment.

No effects were found as a result of soil water potential treatments in non-compacted soil on N, P, K and Mg. However, Ca concentration was higher in seedlings grown at -20 kPa than at -10 kPa. In compacted soil, the N concentration was higher in seedlings at -40 kPa while the concentration of other nutrient elements was higher at -20 kPa.

CHAPTER 6

PERFORMANCE OF ROUGH LEMON SEEDLINGS AT DIFFERENT SOIL WATER POTENTIALS AND SOIL PHYSICAL CONDITIONS

6.1 Introduction

Management of soil requires an understanding of when compaction becomes excessive and harmful, and how it affects root growth and health and the occurrence of soilborne pathogens (Allmaras et al., 1988). If a compacted soil has a high water content, its aeration is reduced thus leading to inadequate oxygen for root respiration. According to Frank et al. (1991), in the wet range of plant-available water, a small change in soil water potential results in a big change in soil aeration. The diffusion of oxygen in the soil is determined by the macro soil porosity and the degree to which these pores are filled with water. High water content and low soil aeration, two factors associated with a saturated soil, influence root decay of citrus (Stolzy et al., 1965a). A lack of oxygen restricts the development of root system.

Carter & Johnston (1989) found that decreasing the volume of macro pores in Charlottetown fine sandy loam from 14.5% to 8.5% resulted in an increase in relative water saturation from 57% to 74%. They further concluded that poor soil aeration, associated with the periodic occurrence of high relative water saturation, was the cause for an increase in root rot severity.

In this study, the relationships between soil water potential and soil compaction and their effects on young RL growth and development were determined for a real problem citrus soil. The aim was to identify the optimum range of soil water potential for RL rootstock under compacted soil conditions in such soil and to study the plant growth patterns under different rhizospherical conditions.

6.2 Experiment 1

6.2.1 Materials and Treatments

The topsoil of Sterkspruit form (Soil Classification Working Group, 1991) from Moosrivier citrus estate near Marble Hall was used in this study. Sterkspruit soils are real problem duplex soils which would never be recommended for citrus production. Citrus groves are also found on such soils in Swaziland. The topsoil of these soils comprise the entire effective rooting depth.

The particle size distribution of the topsoil used was: 43.2% coarse sand, 13.8% fine sand, 11.9% very fine sand, 5.2% silt, and 27.7% clay. A total of 12 pots were filled with soil. The soil in all the pots was compacted to a dry bulk density of 1700 $kg.dm^3$.

The RL seeds were germinated in vermiculite on November 19, 1992. The growing medium was irrigated with deionized water daily. After germination, the seedlings were fertigated with full-strength Hoagland's solution once a week. The seedlings were then transplanted into the compacted soil on March 30, 1993 when they were 10 cm tall. Soil water potentials in the pots were maintained using the Pero facility. Initially, the soil water potential was maintained at -20 kPa from one week before transplanting until four weeks after transplanting, when the seedlings started to produce new growth. From four weeks after transplanting (April 26, 1993) six different soil water potential treatments were imposed, each with two replications. The soil water potential treatments were: -5, -10, -20, -30, -40 and -50 kPa.

6.2.2 Results and Discussion

During the first two weeks after different levels of soil water potential were imposed, the seedlings at -50 kPa died. This was probably due to a too low soil water potential for plant growth in this soil. The seedlings at -5 and -40 kPa were also showing some stress symptoms, and they did not grow for the first few weeks. This was probably due to excessively high and too low soil water potential in these two treatments, respectively. Five weeks after the differential treatment started, the seedlings at -40 kPa died while those at -5 kPa died six weeks after the differential treatments started. Seedlings at -10, -20 and -30 kPa were better than in the other treatments during the first few weeks after transplanting.

6.2.2.1 Soil Water Potential

Figure 6.1 shows the soil water potential during the first four weeks before different treatments were imposed. The soil water potential was maintained well at -20 kPa. In the fifth week there was a gradual increase and decrease in soil water potential to reach the pre-set levels (Figure 6.2). Figure 6.3 shows the soil water potential of all treatment levels in the seventh week after transplanting (third week of differential treatment). It was noted that at -5 kPa there were no diurnal fluctuations in soil water potential readings. However, with a decrease in soil water potential (i.e. from -5 through -50 kPa) there was a concomitant increase in amplitude of diurnal fluctuations. This indicates effects of a relatively low hydraulic conductivity of this soil, especially if the soil water potential decreases. Later in the growing season, there were pronounced diurnal fluctuations in soil water potential readings at all treatment levels, probably due to relatively high water demand by seedlings (Figure 6.4). However, the amplitude of fluctuations was higher at both -20 and -30 kPa than at -10 kPa (Refer to Chapter 2).

6.2.2.2 Water Consumption

The uptake of water by seedlings started to differ during the first week after differential treatments were imposed, with seedlings at -10 kPa using more water than those at -20 and -30 kPa (Figure 6.5). The seedlings at -20 kPa used less water compared to those in other treatments. At the end of the growing season, the seedlings at -10 kPa had used 3.0 dm^3 while those at -20 and -30 kPa had used 1.8 and 2.8 dm^3, respectively. The daily consumptive rate of water use was higher in the first few weeks in all treatments (Figure 6.6). It gradually declined to a

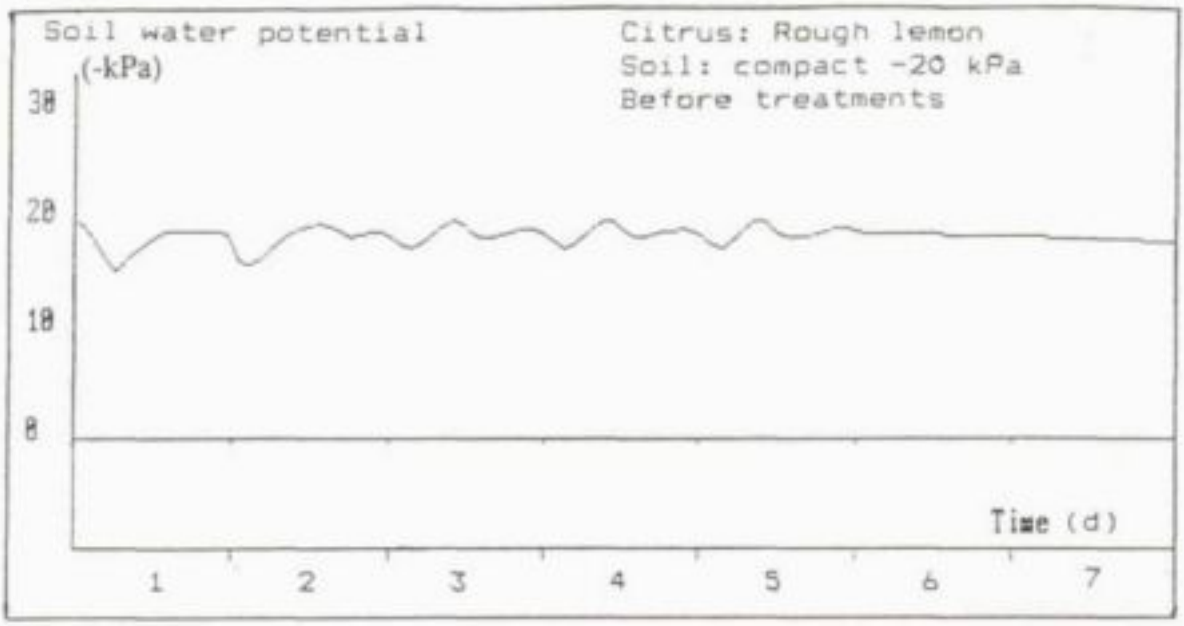


Fig. 6.1. Soil water potential (-20 kPa) in compacted soil before treatments.

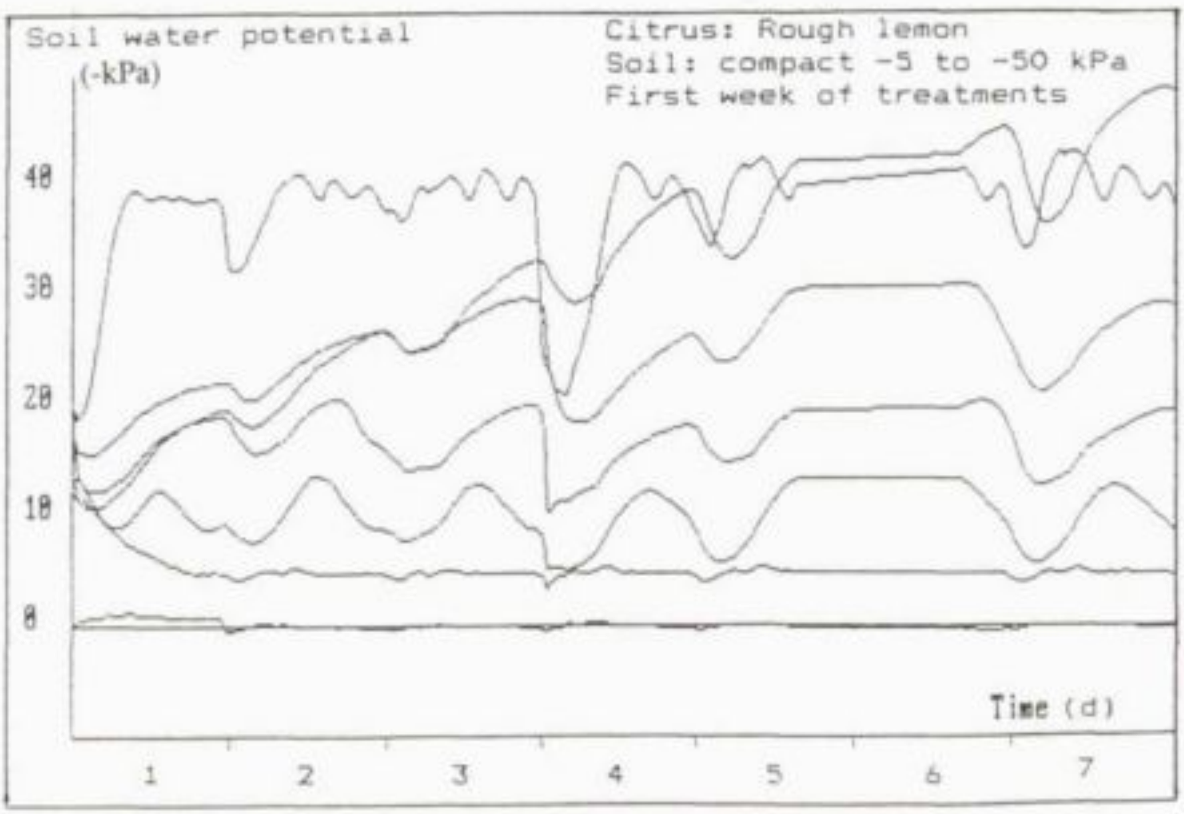


Fig. 6.2. Soil water potential at the beginning of different treatment levels. A rise on the third day was due to fertigation. The bottom line indicates water potential of free water.

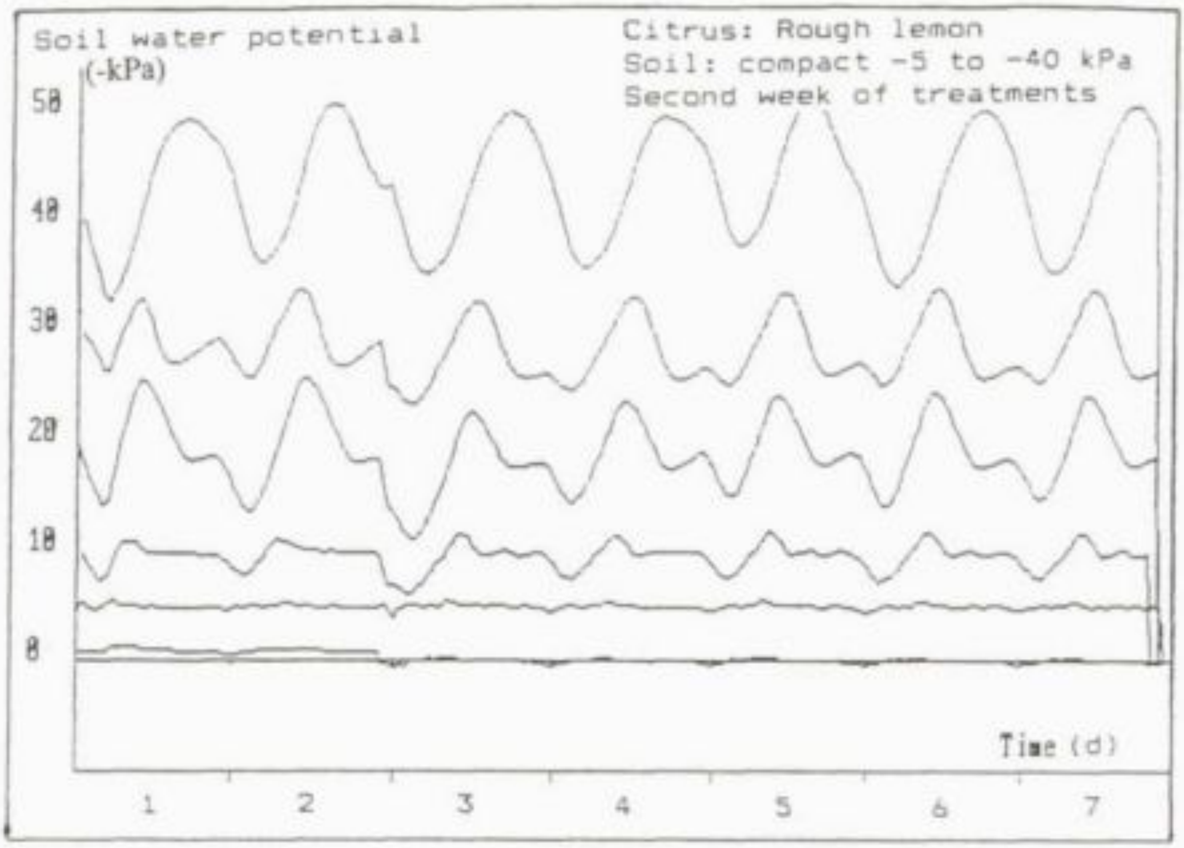


Fig. 6.3. Soil water potential at different levels in compacted soil. The bottom line indicates water potential of free water.

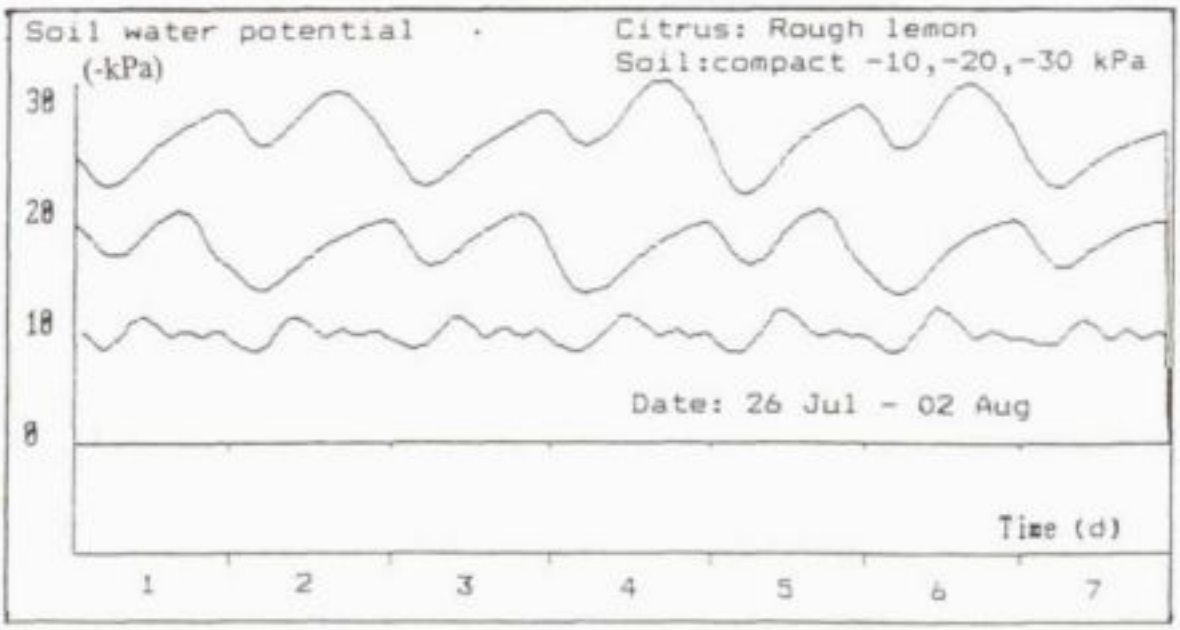


Fig. 6.4. Soil water potential at -10, -20 and -30 kPa in compacted soil.

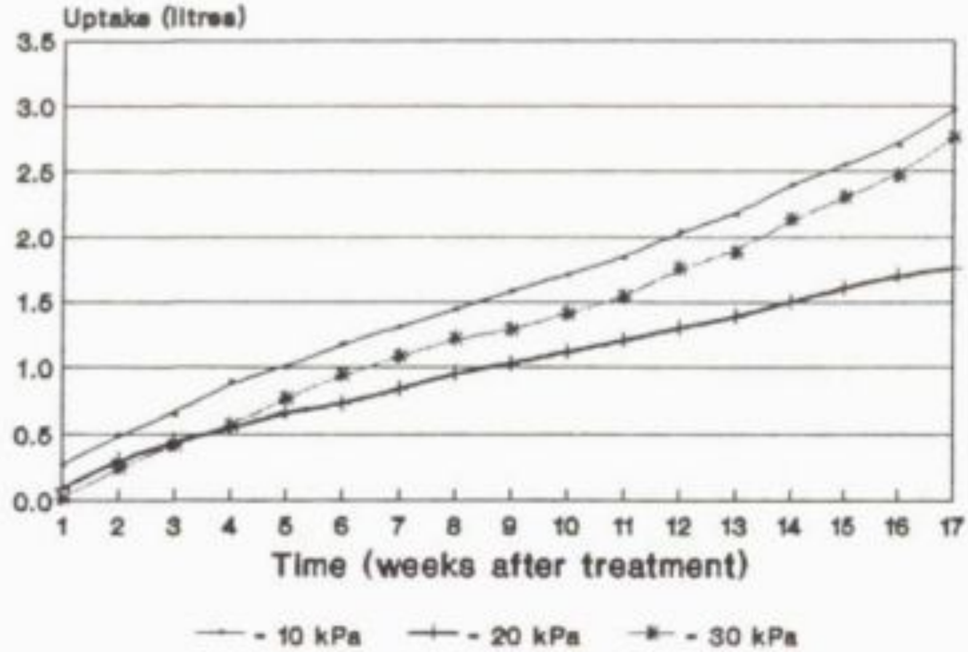


Fig. 6.5. Cumulative uptake of water by RL in compacted soil at -10, -20, and -30 kPa.

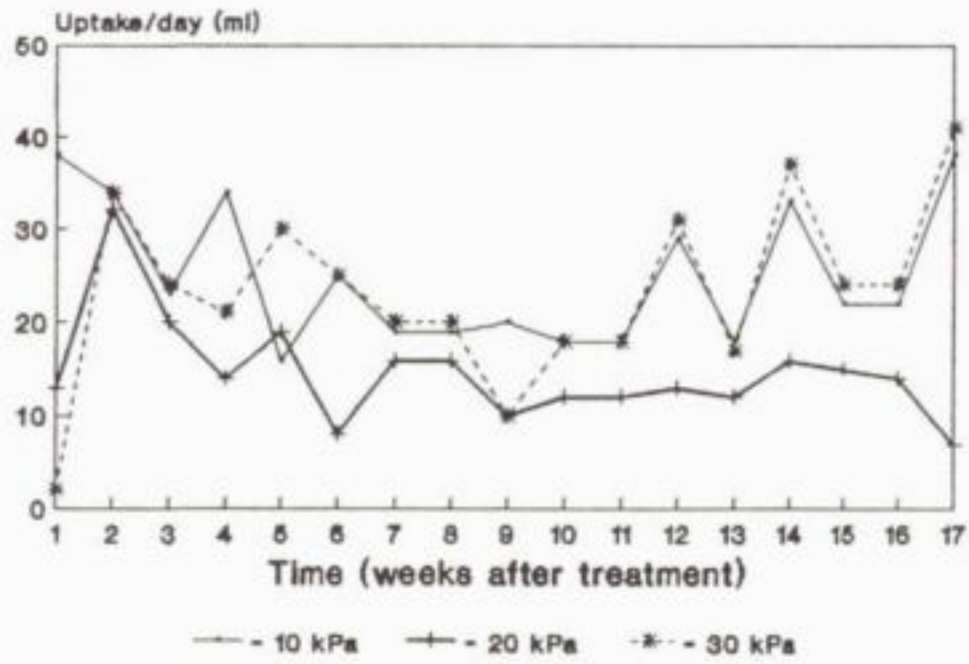


Fig. 6.6. Daily rate of water use by RL in compacted soil at -10, -20, and -30 kPa.

minimum in the ninth week after which it started to increase again. However, at -20 kPa, the consumptive rate of water use was decreasing until the end of the growing season. This can be associated with a decline in the quality of seedlings at this soil water potential which showed some symptoms of stress. The overall decrease in consumptive rate of water use in the ninth week in all treatments and thereafter an increase in the last few weeks (for -10 and -30 kPa) can be due to a drop in temperature during the winter season. As the temperature started to increase in spring, the consumptive rate of water use also increased.

6.2.2.3 Plant Growth and Development

The plant height was the same in all treatments during the first six weeks (Figure 6.7). From the seventh week onwards, the seedlings at -30 kPa started to grow faster than those at -20 and -10 kPa. From the 10th week onwards, the seedlings at -10 kPa started to grow while those at -20 kPa did not grow well throughout the growing season. Later in the season, the seedlings at -20 kPa started to show some symptoms of stress, with the leaves curling and turning yellow and some died. The curling of leaves was also observed during midday in seedlings at -10 kPa. The leaves of seedlings in this treatment were also turning yellow, which may indicate the level of stress resulting from insufficient oxygen diffusion rate in the soil. Seedlings at -30 kPa were better than in other treatments in terms of size and leaf colour and did not show any visible stress symptoms. At the end of the season, the seedlings at -30 kPa had reached an average height of 32 cm while those at -10 kPa were 21 cm.

At -10 kPa there was a positive correlation between the growth rate and consumptive rate of water use (Figure 6.8). As the growth rate increased, it was followed by an increase in water uptake rate. Similar results were found at -30 kPa (Appendix 6.1).

6.2.2.4 Morphological and Physiological Plant Responses

The seedlings at -30 kPa were significantly larger than those at -10 kPa. The total dry mass and top dry mass of the seedlings at -30 kPa was higher than in the other treatment (Table 6.1). However, the root dry mass was higher in seedlings at -10 kPa. The top:root ratio was lower in seedlings at -10 kPa than those at -30 kPa. This indicates the efficiency of the RL roots to maintain top growth of the seedlings at -30 kPa. It also shows that the excess water at -10 kPa had a more negative impact on the top growth than on the root system of seedlings.

The water use efficiency was higher for seedlings at -30 kPa than at -10 kPa. The seedlings at -10 kPa used the water inefficiently, probably due to its luxurious availability compared to those at -30 kPa. It indicates that the seedlings at -10 kPa were stressed due to excess water, hence the dry matter production was lower than in plants at -30 kPa despite the high amount of water used by the seedlings at -10 kPa.

Although there was no significant difference in leaf area between seedlings at -10 and -30 kPa, seedlings at -10 kPa had numerous small leaves, which is one of the characteristics of waterlogging stress (Table 6.2). The result is that the average area per leaf was higher in

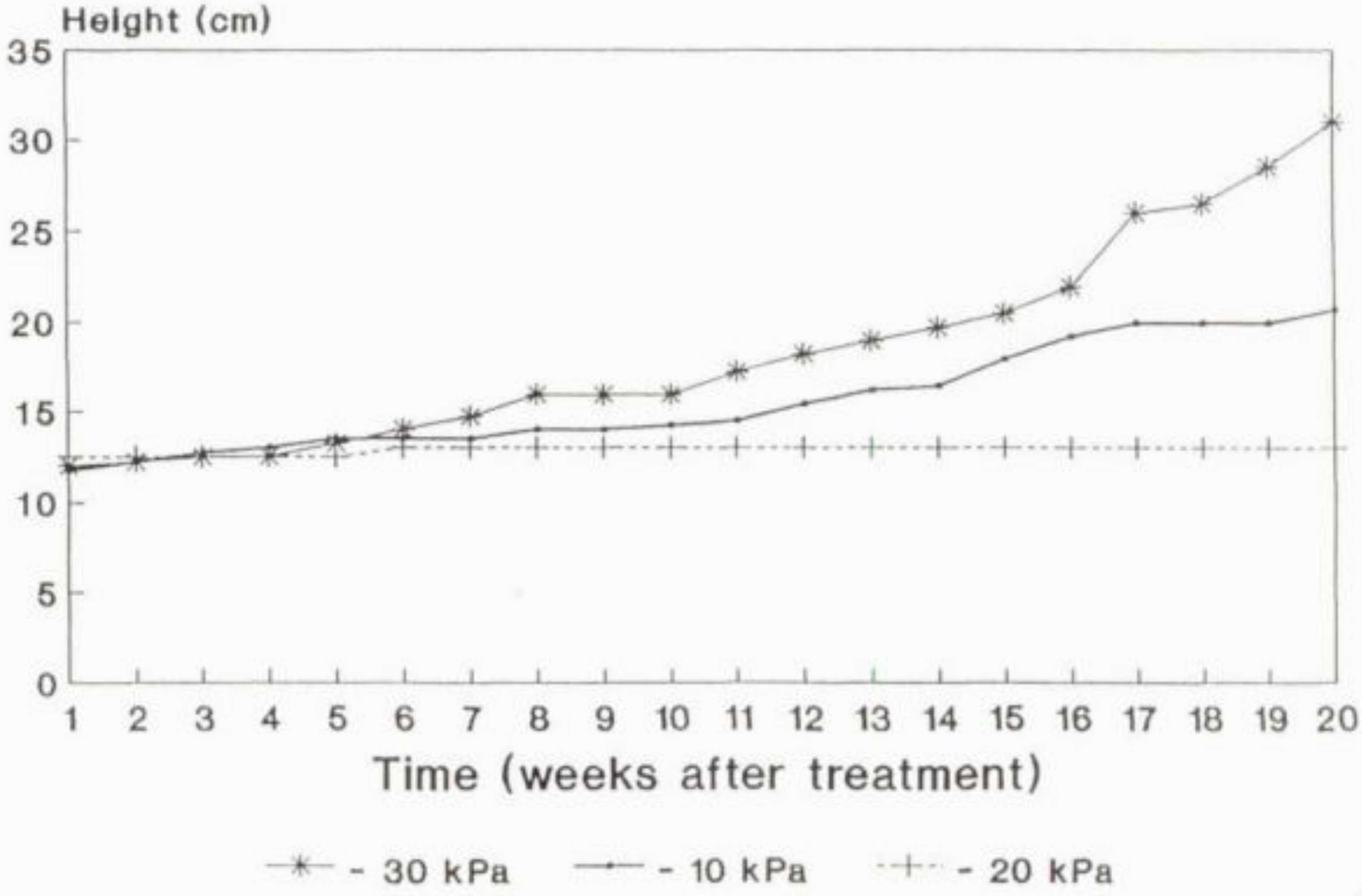


Fig. 6.7. Height of RL in compacted soil at -10, -20, and -30 kPa.

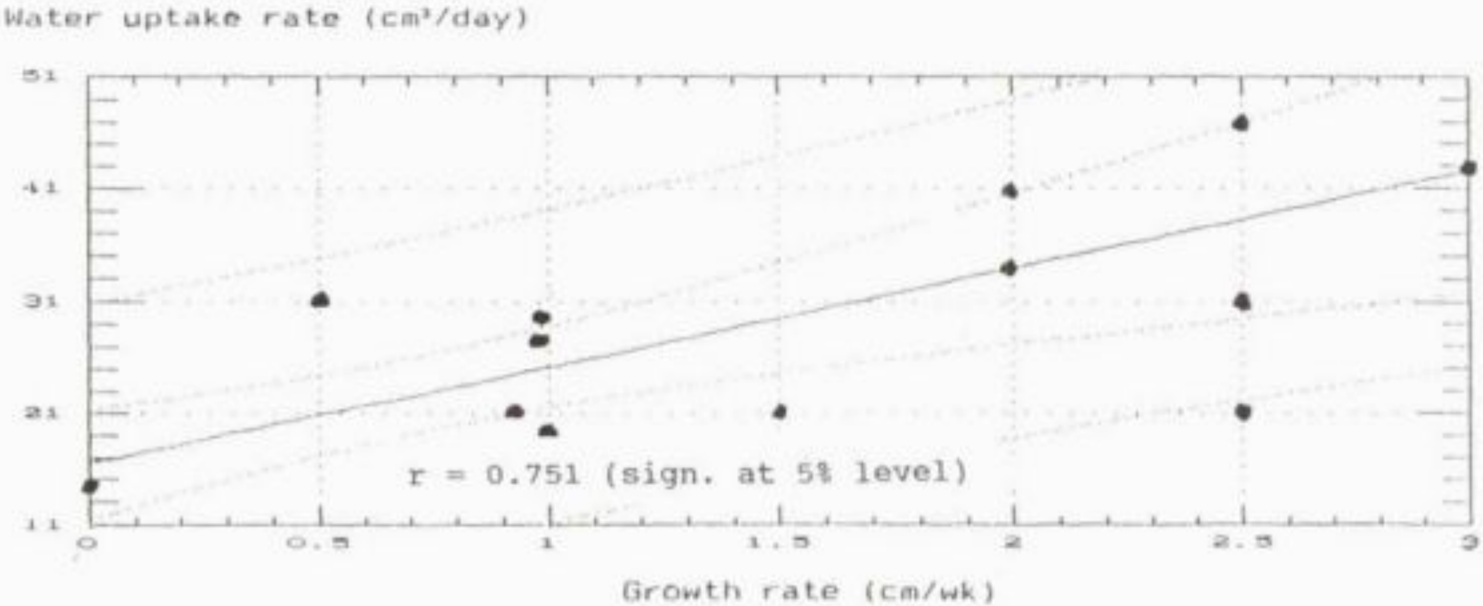


Fig. 6.8. Regression line showing a relationship between growth rate and water consumptive rate of RL in compacted soil at -10 kPa.

seedlings at -30 kPa than at -10 kPa. The projected root surface area was higher for seedlings at -30 kPa than at -10 kPa.

Table 6.1. Effects of soil water potential on dry mass accumulation by RL seedlings grown in compacted soil

Soil water potential (kPa)	Total dry mass (g)	Top dry mass (g)	Root dry mass (g)	Top: root ratio	Water cons. (dm^3)	WUE ($g.dm^{-3}$)
	2.47	1.37	1.10	1.25	2.88	0.86
-10	2.79	1.81	0.98	1.85	3.06	0.91
mean	**2.63**	**1.59**	**1.04**	**1.53**	**2.97**	**0.89**
	3.27	2.43	0.84	2.89	2.69	1.22
-30	3.53	2.57	0.96	2.68	2.83	1.25
mean	**3.40**	**2.50**	**0.90**	**2.78**	**2.76**	**1.24**

WUE - water use efficiency.
some data not available (seedlings died), therefore
no statistical analysis was done on these data.

Table 6.3 shows that the seedlings at -5 kPa had a severely limited oxygen supply. In this treatment, the air porosity was far below 10% which is considered to be a minimum threshold for most agricultural crops (Allmaras, et al., 1988; Patt, et al., 1966). At -10 kPa, the air-filled porosity was 11.79% which is slightly more than the threshold minimum. Therefore, the poor performance of these seedlings may have resulted from low oxygen diffusion rate which is a critical factor. On the other hand, seedlings at -40 and -50 kPa may have died as a result of drought stress resulting from the poor soil hydraulic conductivity. A soil water potential of -30 kPa in this experiment seemed to be an optimum balance between soil water potential and air-space for RL seedlings in this specific soil when compacted. Although the water content at this treatment level was not very high, seedlings may have been able to use the available water and oxygen as dictated by the hydraulic conductivity and the O.D.R. of the soil at a given soil air-porosity efficiently.

Table 6.2. Effects of soil water potential on certain physiological and morphological parameters of RL seedlings grown in compacted soil

Soil water potential (kPa)	Leaf area (cm^2)	No. leaves per plant	Average area per leaf (cm^2)	Root area (cm^2)	RA:LA ratio
	212.3	33	6.43	84.5	0.40
-10	253.1	32	7.45	91.1	0.36
mean	**232.7**	**33**	**6.94**	**87.8**	**0.38**
	119.1	14	8.50	97.4	0.82
-30	280.9	26	10.80	106.8	0.38
mean	**200.0**	**20**	**9.65**	**102.1**	**0.60**

RA:LA - root area to leaf area ratio.
some data not available (seedlings died), therefore
no statistical analysis was done on these data.

Table 6.3. The effect of soil water potential and soil compaction on the soil water content and air porosity

Soil water potential (kPa)	Measured soil water content (cm^3/cm^3)	Calculated air-filled porosity (%)
- 5	30.3	5.69
- 10	24.2	11.79
- 20	21.9	14.09
- 30	19.0	16.99
- 40	16.7	19.29
- 50	16.5	19.49

However, the small number of replications in this study and the uncertainty about the results necessitated a follow-up experiment whereby the effects of soil water potential at -10, -20, and -30 kPa could be closely monitored. Moreover, since this study was conducted in winter when the seedlings were not growing very actively, there was a need to repeat these treatments under optimum climatic conditions when the seedlings are actively growing for better studies of cause-effect relationships.

6.3 Experiment 2

6.3.1 Materials and Treatments

This was a follow-up experiment and the focus was on the effects of only three levels of soil water potential (-10, -20 and -30 kPa) on plant performance. The same type of soil from Moosrivier as was used in the previous experiment (Refer to section 6.2.1) was used in this experiment. RL seeds were germinated in vermiculite on May 11, 1993. The seedlings were transplanted into the pots on August 25, 1993 when they were 10 cm tall and harvested on November 25. The soil water potential was kept at -10 kPa in all pots until the seedlings started to produce new growth tips. Different treatments were started on September 6, 1993. Only three soil water potential levels, -10, -20 and -30 kPa were imposed on a soil with dry bulk density of 1700 $kg.dm^{-3}$. Each treatment was replicated four times.

6.3.2 Results and Discussion

The seedlings at -10 and -30 kPa showed some signs of stress within the first few weeks after the start of differential treatments. At -10 kPa, the seedlings became defoliated and later in the season started to develop small, pale leaves, which is one of the common symptoms of waterlogging stress. At -30 kPa the leaves were slowly desiccating and falling without any new leaf initiation. This was probably an indication of drought stress at this soil water potential, especially during the summer season when the water demand by seedlings was high.

6.3.2.1 Water Consumption

There was a continuous increase in difference in the cumulative water uptake by seedlings at different soil water potentials (Figure 6.9). In the first week of treatments the seedlings at -30 kPa used less water than those at -10 and -20 kPa. From the second week onwards, the seedlings at -10 kPa started to use more water than those at -20 kPa probably due to excess water in the soil. Towards the end of the experimental period, the seedlings at -20 kPa started to use more water than at -10 and -30 kPa thus lowering the magnitude of the difference in cumulative water consumption between -20 and -10 kPa. This was probably due to a relatively larger size of the seedlings at -20 kPa towards the end of the experimental period.

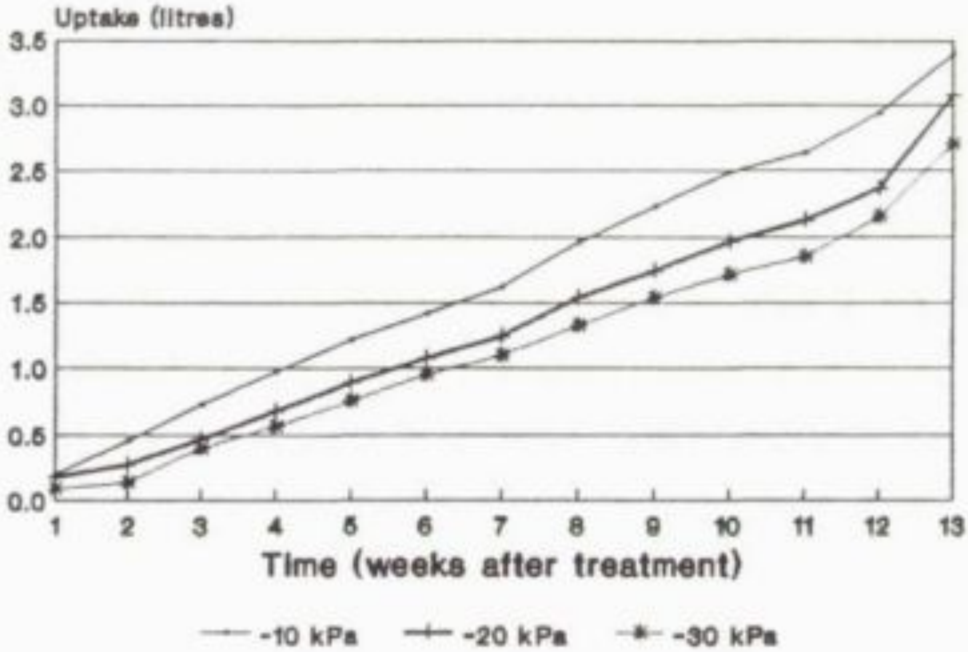


Fig. 6.9. Cumulative water consumption by RL in compacted soil at -10, -20, and -30 kPa.

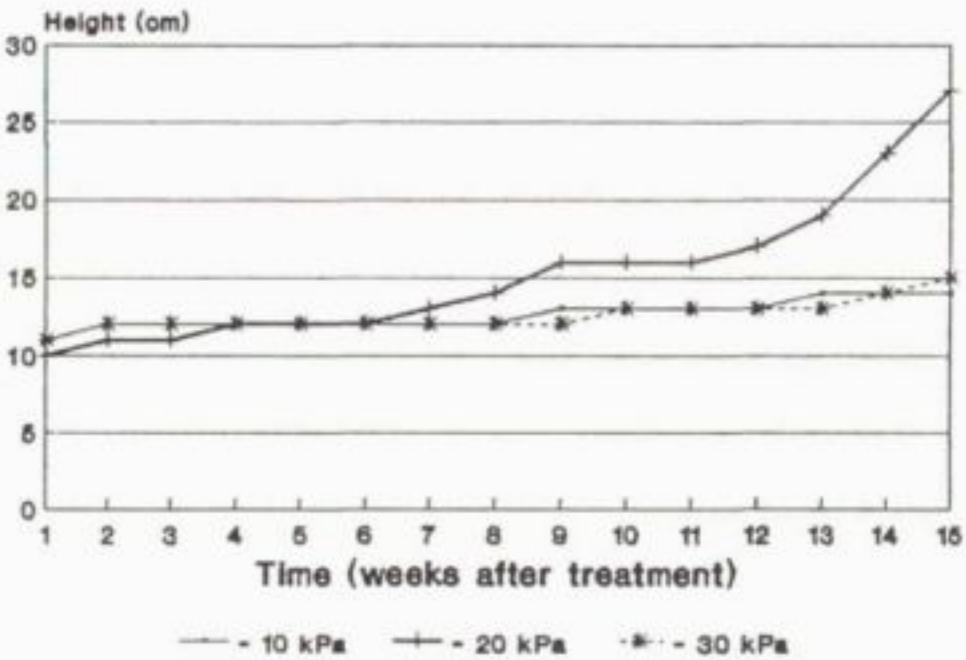


Fig. 6.10. Height of RL in compacted soil at -10, -20, and -30 kPa.

6.3.2.2 Plant Growth and Development

The seedlings from various treatments showed some differences in growth patterns. Although all the seedlings were generally stressed, the plants at -20 kPa were growing faster for a number of days which was then followed by a period of minimum or no growth (Figure 6.10). In both -10 and -30 kPa the period of minimum growth was longer than at -20 kPa. Even when the seedlings at -10 and -30 kPa were growing, an increase in plant height was very low which indicates the level of stress that existed under such conditions. At the end of the experimental period, the seedlings at -20 kPa reached a height of 27 cm while those at -10 and -30 kPa were 18 cm and 20 cm, respectively.

At -20 kPa, where the seedlings did not show stress symptoms, a positive correlation between growth rate and the water consumptive rate was found (Figure 6.11). However, the relatively stressed seedlings at -10 and -30 kPa did not show this relationship (Appendices 6.3 and 6.4).

6.3.2.3 Morphological and Physiological Plant Responses

Table 6.4 shows significant differences in plant parameters as a result of differences in soil water potential in this compacted soil. The total dry mass, top dry mass, root dry mass and the water use efficiency were all statistically significantly higher in seedlings at -20 kPa (For statistical analyses, refer to Appendices 6.5 to 6.13).

The water consumption was relatively higher for seedlings at -10 kPa, while the top:root ratio was statistically significantly higher for seedlings at -30 kPa. The seedlings at -30 kPa seemed to be more stressed than those at -10 and -20 kPa. At -10 kPa, the seedlings used the water inefficiently, probably due to excess water availability in the soil. On the other hand, the seedlings at -30 kPa were deprived of water, which resulted in minimized growth thus reducing the water use efficiency by plants.

The leaf area and root surface area were statistically significantly higher in seedlings at -20 kPa (Table 6.5). However, the root area:leaf area ratio was higher at -10 and -30 kPa. The results in Tables 6.4 and 6.5 indicate that the seedlings at -10 kPa were negatively affected by waterlogging stress while those at -30 kPa were affected by the low availability of water probably due to poor hydraulic conductivity of this specific soil when compacted.

The different seasons may have affected the results of these experiments. In this experiment, the poor performance at -10 kPa probably indicates that the high temperature during the growing season led to vigorous physiological processes in seedlings and thus increasing their sensitivity to waterlogging. At -30 kPa, the higher demand for water together with poor hydraulic conductivity of the soil may have led to drought stress.

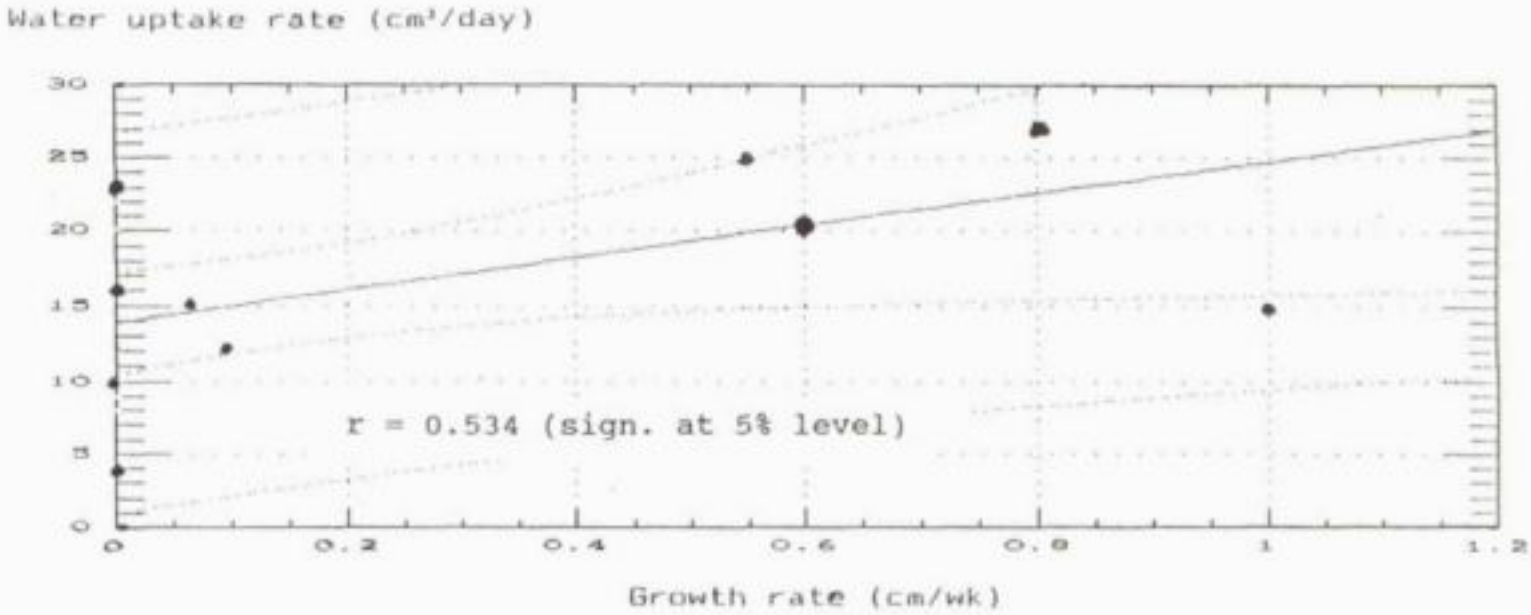


Fig. 6.11. Regression line showing a relationship between growth rate and water consumptive rate of RL in compacted soil at -20 kPa.

Table 6.4. Effects of different levels of soil water potential on certain plant parameters of RL seedlings grown in compacted soil

Soil water potential (kPa)	Total dry mass (g)	Top dry mass (g)	Root dry mass (g)	Top: root ratio	Water cons. (dm^3)	WUE ($g.dm^{-3}$)
	1.24	0.55	0.69	0.80	4.02	0.308
- 10	0.58	0.26	0.32	0.81	3.34	0.173
	0.67	0.31	0.36	0.86	3.25	0.206
mean	**0.83**	**0.37**	**0.46**	**0.82**	**3.54**	**0.229**
S.E.	0.21	0.09	0.12	0.02	0.24	0.041
	2.69	1.39	1.30	1.07	3.36	0.800
- 20	1.74	0.90	0.84	1.07	2.81	0.619
	2.12	1.24	0.88	1.41	3.26	0.650
mean	**2.18**	**1.18**	**1.01**	**1.17**	**3.15**	**0.690**
S.E.	0.28	0.14	0.15	0.11	0.17	0.056
	0.29	0.20	0.09	2.22	3.29	0.088
- 30	0.27	0.19	0.08	2.38	2.85	0.095
mean	**0.28**	**0.20**	**0.09**	**2.30**	**3.07**	**0.092**
S.E.	0.01	0.01	0.01	0.08	0.22	0.004
LSD	0.69	0.24	0.26	0.25	0.45	0.100

WUE - water use efficiency.
some data not available (seedlings died).

Table 6.5. Effects of soil water potential on leaf area and root area of RL seedlings grown in compacted soil

Soil water potential (kPa)	Leaf area (cm^2)	Root area (cm^2)	RA:LA ratio
	94.2	55.0	0.58
- 10	74.4	44.6	0.60
	55.3	35.8	0.65
mean	**74.6**	**45.1**	**0.61**
S.E.	11.2	5.5	0.02
	241.2	76.5	0.32
- 20	209.8	59.8	0.29
	283.3	65.1	0.23
mean	**244.8**	**67.1**	**0.28**
S.E.	21.3	4.9	0.03
	50.6	25.9	0.51
- 30	37.5	20.6	0.55
mean	**44.1**	**23.3**	**0.53**
S.E.	6.6	2.7	0.02
LSD	34.3	10.7	0.05

RA:LA - root area to leaf area ratio.
some data not available (seedlings died).

In the first experiment, the seedlings at -30 kPa used 2.76 dm^3 of water while 3.07 dm^3 were used in the second experiment. The seedlings at -10 kPa used 2.79 dm^3 in the first experiment and 3.54 dm^3 in the second experiment. At -20 kPa, 3.15 dm^3 water was used in the second experiment. These data show the effects of the growing season not only on water consumption but also on plant development and water use efficiency by citrus seedlings.

The results of this experiment necessitated some more information on the effects of the interaction between soil compaction and soil water potential for this specific soil.

6.4 Experiment 3

6.4.1 Materials and Treatments

The main focus of this experiment was on the effects of the interaction between soil compaction and soil water potential on seedling development. The soil from Moosrivier citrus farm (Refer to section 6.2.1) was used. The seedlings, 15 cm tall, were obtained from Casmar (Citrus Foundation Block) near Rustenburg. They were transplanted into pots with compacted (DBD = 1700 $kg.dm^{-3}$) and non-compacted (DBD = 1550 $kg.dm^{-3}$) soil on November 29, 1993. The soil water potential was kept at -10 kPa before and after transplanting until the seedlings started to develop some growth tips. Three soil water potential levels, -10, -20 and -30 kPa were imposed and each treatment was replicated twice both in compacted and non-compacted soil. The experiment was terminated on January 24, 1994.

6.4.2 Results and Discussion

In compacted soil, the seedlings at -30 kPa showed some signs of stress in the first week after treatment. The leaves were wilted and defoliation occurred in the second week probably due to drought stress resulting from poor hydraulic conductivity of the soil under such conditions. In the third week, the seedlings in this treatment died.

6.4.2.1 Soil water potential

When the soil water potential was kept at -10 kPa before treatments, there were higher diurnal fluctuations in non-compacted soil (Figure 6.12).

Figure 6.13 shows the soil water potential in both compacted and non-compacted soil at -20 kPa. The diurnal fluctuations in soil water potential were similar in both compacted and non-compacted soil. A similar situation was also found at -30 kPa (Figure 6.14). The diurnal fluctuations in soil water potential were more pronounced in relatively dry soil compared to wet soil in both compacted and non-compacted soil (Figures 6.15 and 6.16, respectively)(Refer to section 5.3.1).

6.4.2.2 Water Consumption

At -10 kPa, the seedlings in compacted soil used more water in the first four weeks than those in non-compacted soil (Figure 6.17). Since the seedlings in both compacted and non-compacted soil at this soil water potential were not limited by the availability of water, the root system in compacted soil may have been in better contact with the soil earlier than in non-compacted soil thus taking up more water early in the season. As a result of poor contact between the feeder roots and the soil in non-compacted soil treatment early in the season, the seedlings in this treatment used less water. However, from the sixth week onwards, the seedlings in non-compacted soil started to use more water. At the end of the season, the seedlings in this

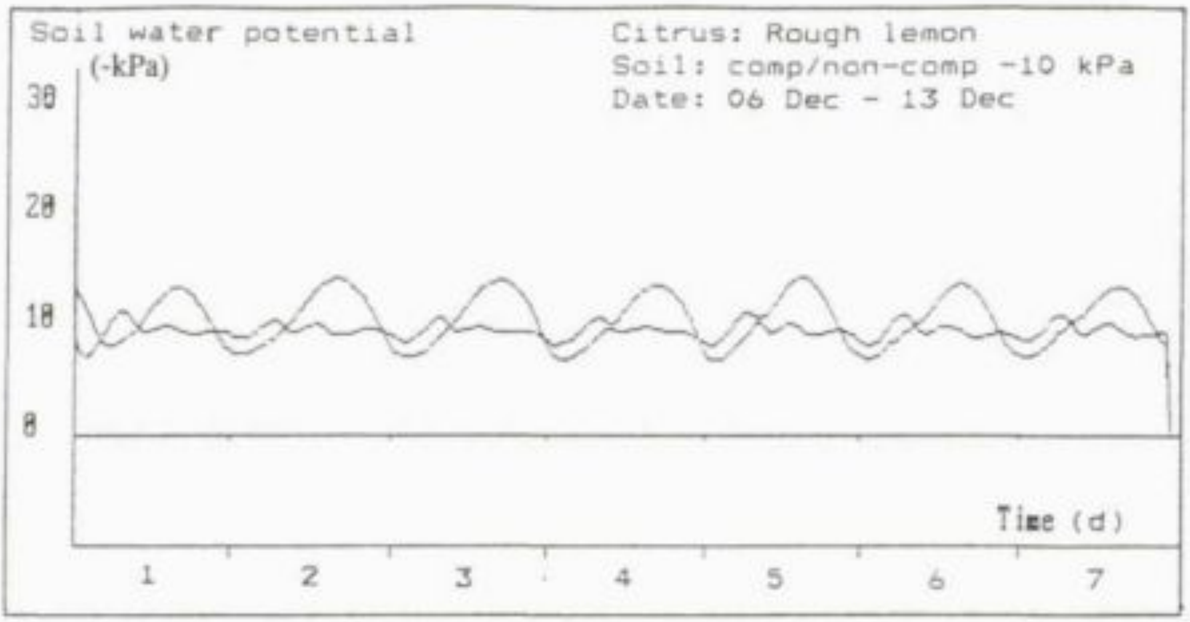


Fig. 6.12. Soil water potential in compacted and non-compacted soil at -10 kPa. Diurnal fluctuations occurred in loose soil.

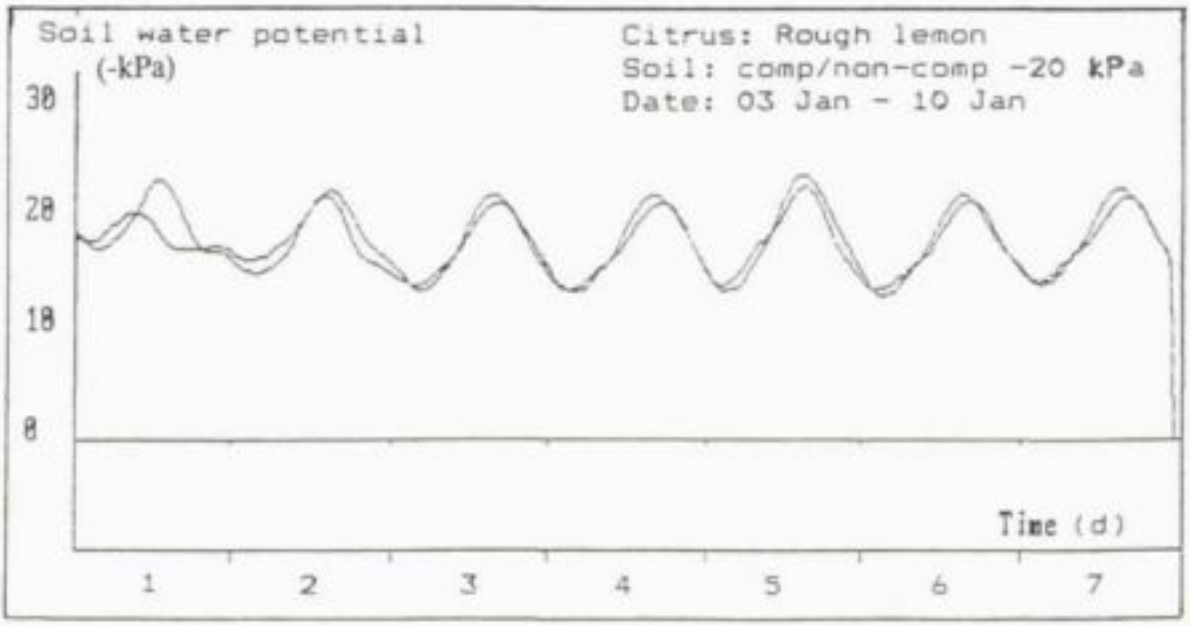


Fig. 6.13. Soil water potential in compacted and non-compacted soil at -20 kPa.

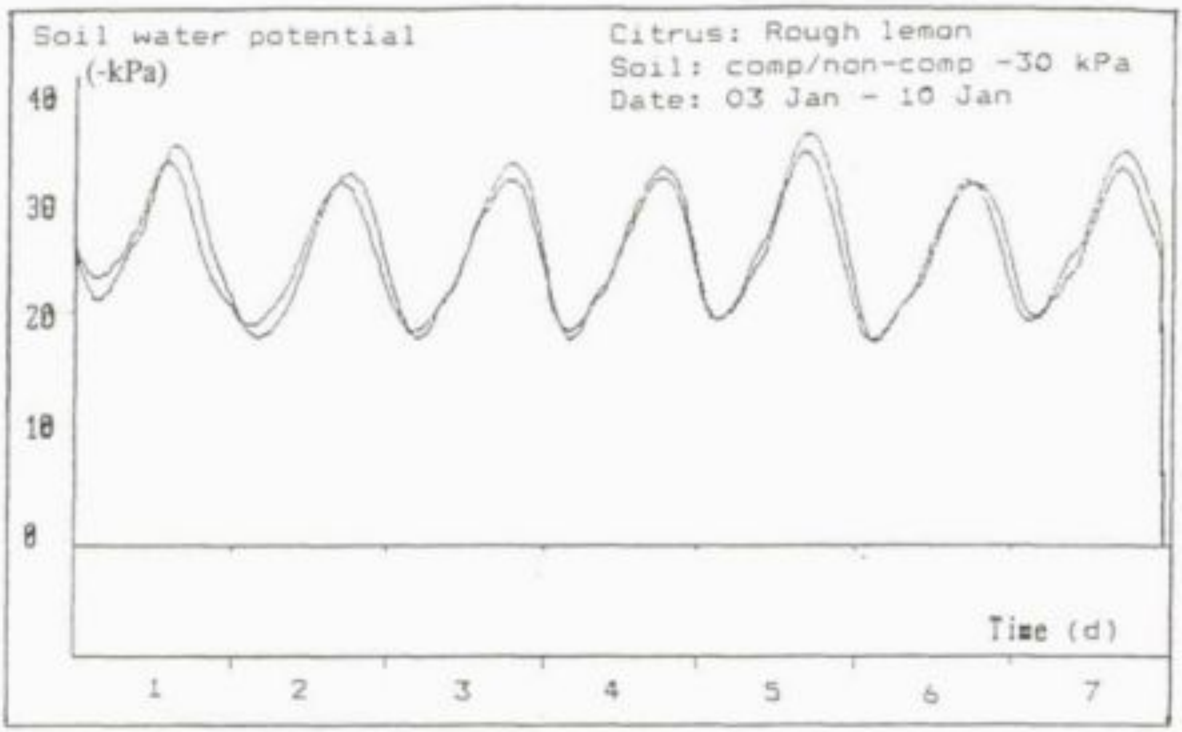


Fig. 6.14. Soil water potential in compacted and non-compacted soil at -30 kPa.

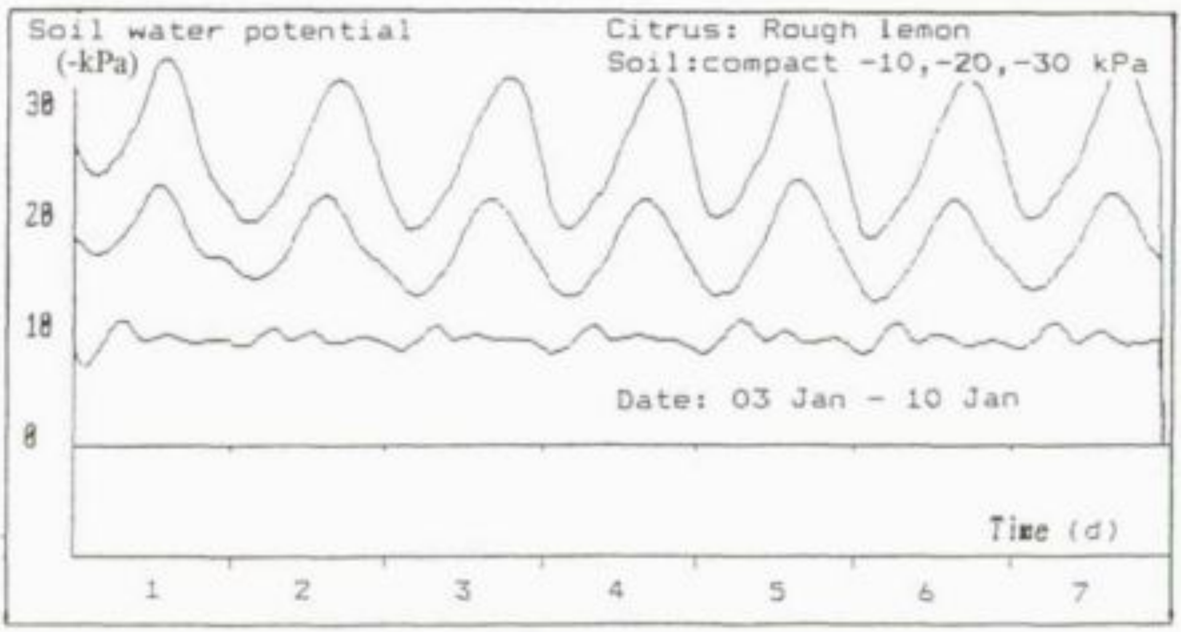


Fig. 6.15. Soil water potential in compacted soil at -10, -20 and -30 kPa.

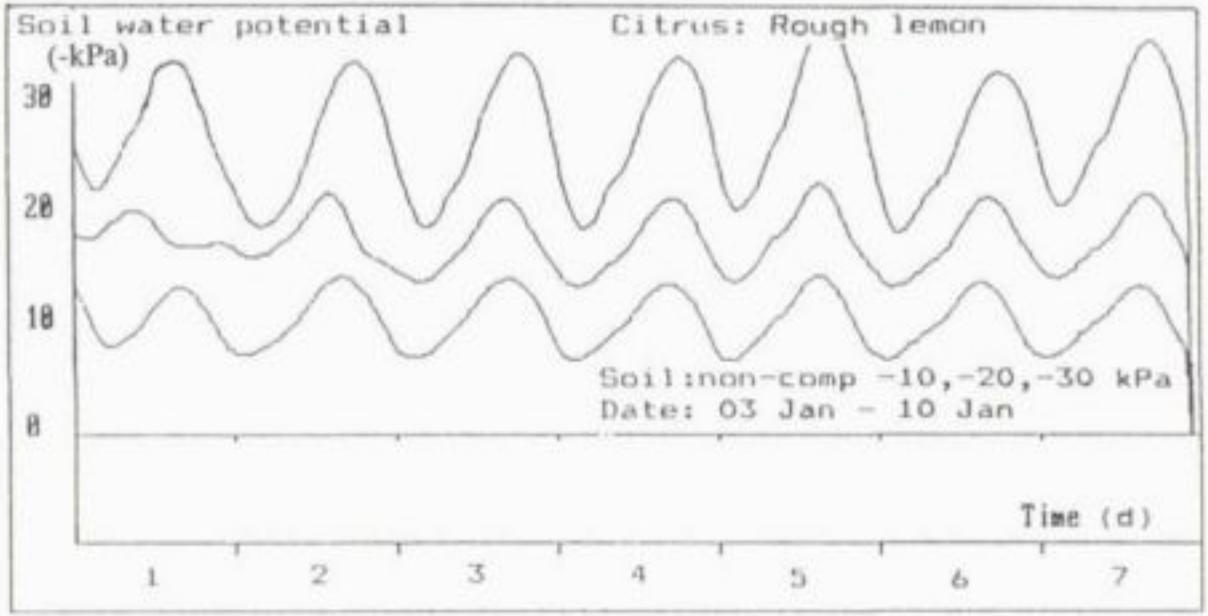


Fig. 6.16. Soil water potential in non-compacted soil at -10, -20, and -30 kPa.

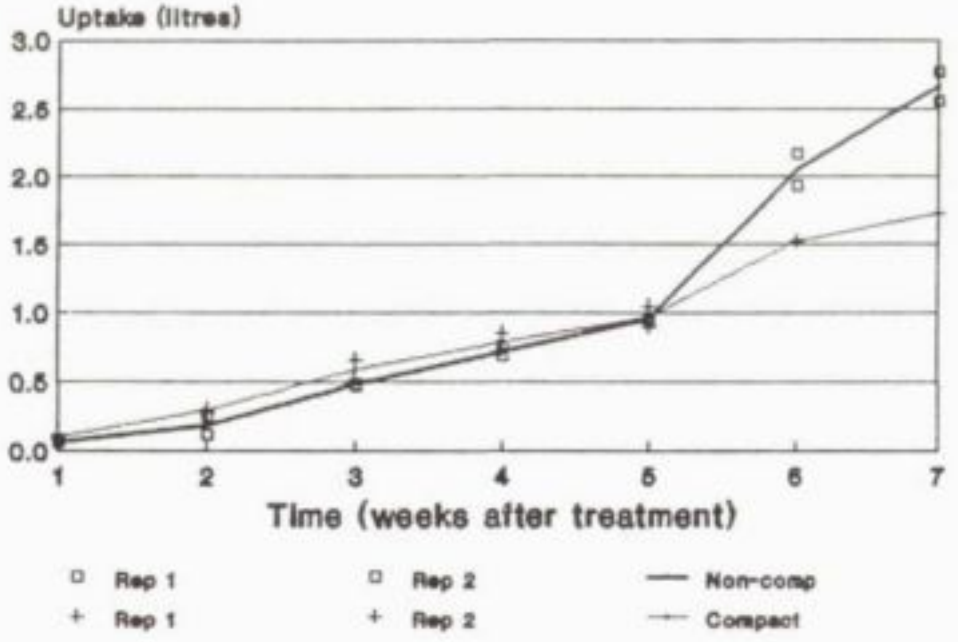


Fig. 6.17. Cumulative water consumption by RL in compacted and non-compacted soil at -10 kPa.

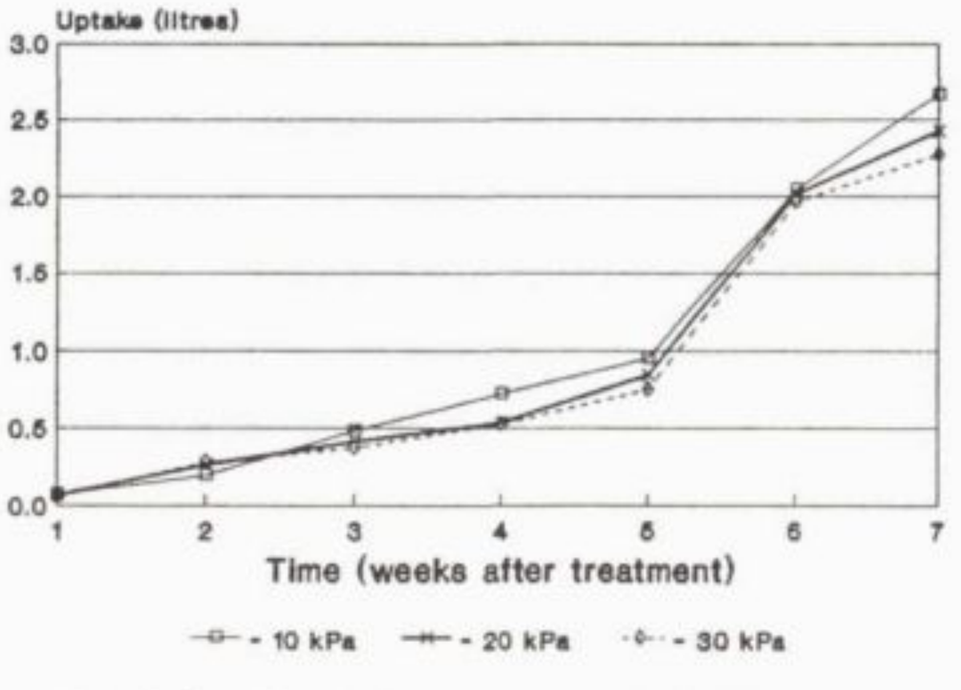


Fig. 6.18. Cumulative water consumption by RL in non-compacted soil at -10, -20, and -30 kPa.

treatment had used 2.7 dm^3 while those in compacted soil used 1.7 dm^3.

At -20 kPa, the seedlings in compacted and non-compacted soil used the same amount of water in the first two weeks after treatment (Appendix 6.14). From the third week onwards, the seedlings in non-compacted soil started to use more water than those in compacted soil. A similar situation was also found at -30 kPa where the seedlings in compacted soil used more water in the first three weeks after-which those in non-compacted soil started to use more water (Appendix 6.15). This may indicate that in the first few weeks the seedlings in non-compacted soil at both -20 and -30 kPa were not in good contact with the soil and as a result used less water compared to those in compacted soil. Moreover, the seedlings in non-compacted soil were severely wilted in the first few weeks after treatment. As the soil-root contact improved over time, these seedlings started to use more water than those in compacted soil. This could also mean that compaction reduced the availability of water at both -20 and -30 kPa. Needless to say, this led to a drought stress and ultimate death of the seedlings at -30 kPa in compacted soil at the end of the experimental period.

In non-compacted soil, the seedlings at -10 kPa used more water than those at -20 and -30 kPa (Figure 6.18). Similar results were found in compacted soil (Figure 6.19). This is due in part to a relative availability of water which declines with a decrease in soil water potential. In non-compacted soil, the seedlings at -20 kPa had used 91% as much water as those at -10 kPa while those at -30 kPa had used 85% of that used by plants at -10 kPa at the end of the growing season.

6.4.2.3 Plant Growth and Development

At -10 kPa, the seedlings in non-compacted soil were growing faster than in compacted soil (Figure 6.20). Similar results were also found at -20 kPa (Figure 6.21). Figure 6.22 illustrates the effects of soil water potential on plant height in non-compacted soil. At the end of the experimental period, the seedlings at -10 kPa in non-compacted soil were 24 cm while those at -20 and -30 kPa were 21 cm tall. In compacted soil, the seedlings at -10 kPa were more stressed than at -20 kPa, reaching 16 cm at the end of the season while those at -20 kPa reached 19 cm (Figure 6.23). These data show that maintaining the soil water potential at -10 kPa negatively affects the development of seedlings in compacted soil, probably due to poor aeration. According to Shalhevet & Levy (1990), citrus can tolerate waterlogging better during winter than during periods of high soil temperatures. Smajstrla et al. (1985) also reported that citrus seedlings at -10 kPa were visibly stressed on days where there was a high evaporative demand compared to -20 or -40 kPa. When the soil was not compacted, better plant growth occurred at relatively higher (e.g. -10 kPa) soil water potential levels. Moreover, the results indicate that when compacted, this soil is less suitable for plant growth and development at any of the soil water levels studied.

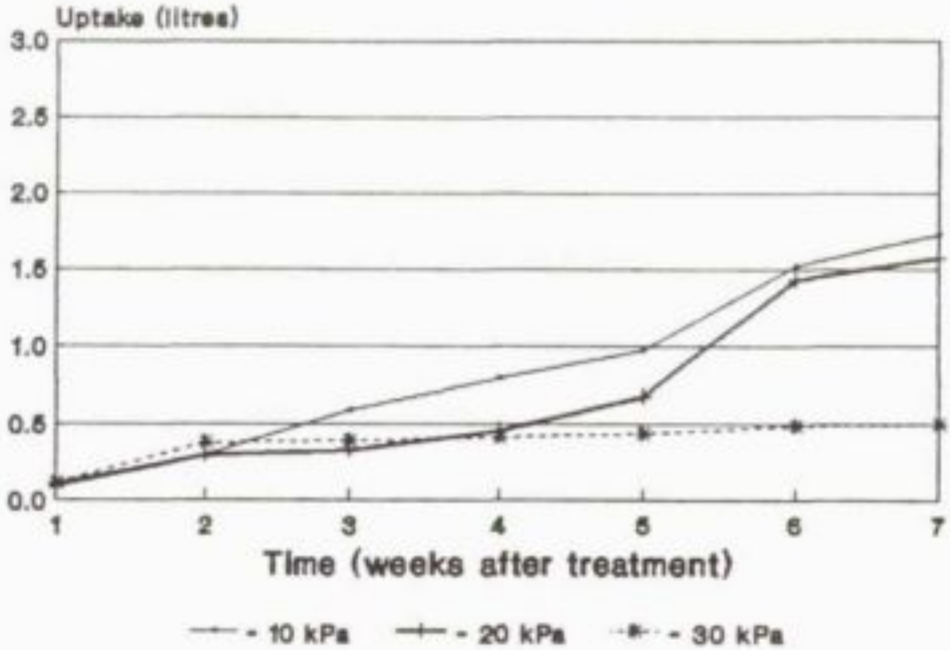


Fig. 6.19. Cumulative water consumption by RL in compacted soil at -10, -20, and -30 kPa.

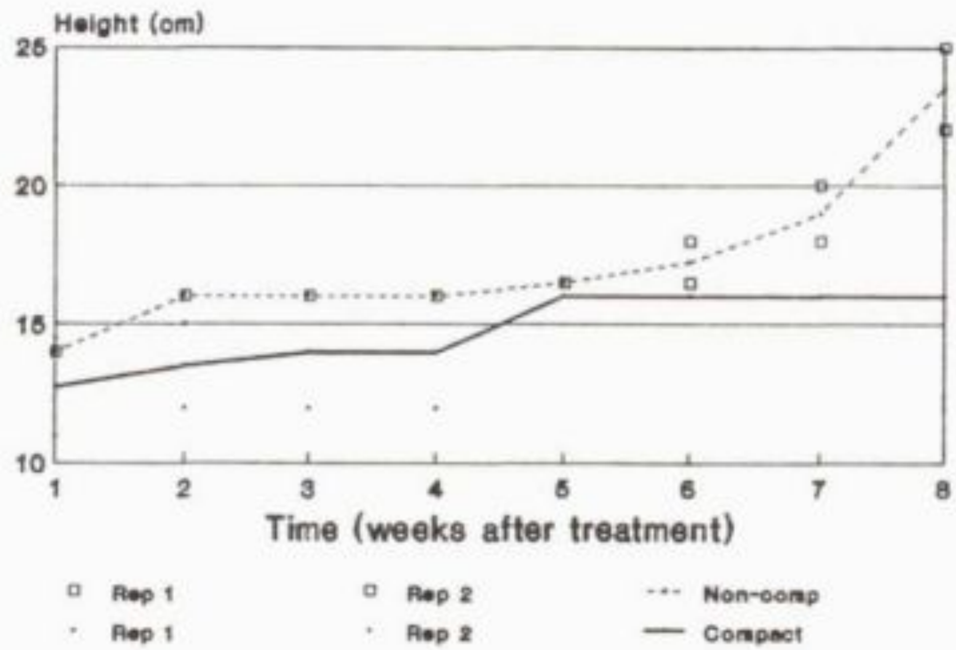


Fig. 6.20. Height of RL in compacted and non-compacted soil at -10 kPa.

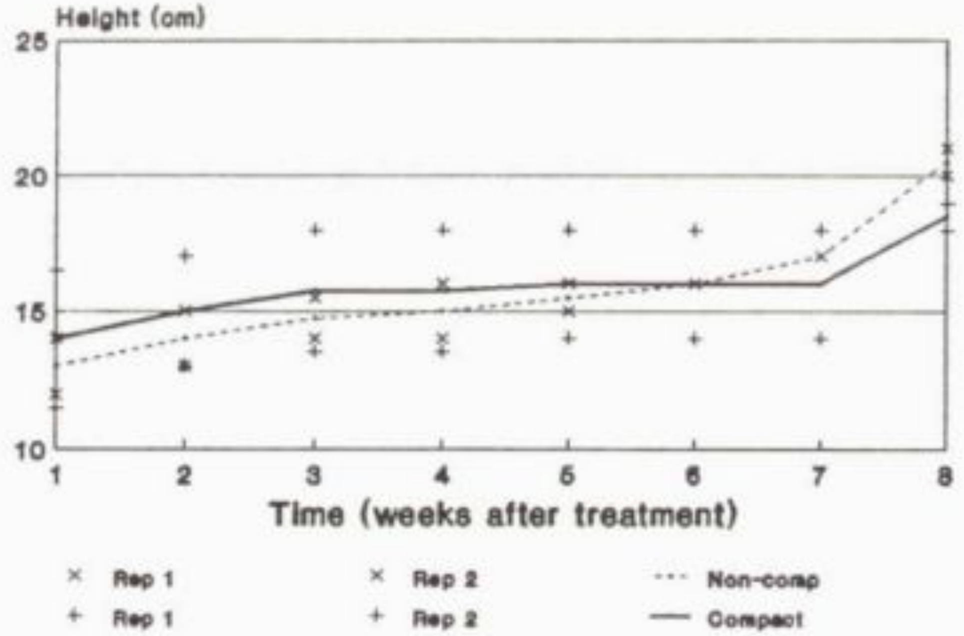


Fig. 6.21. Height of RL in compacted and non-compacted soil at -20 kPa.

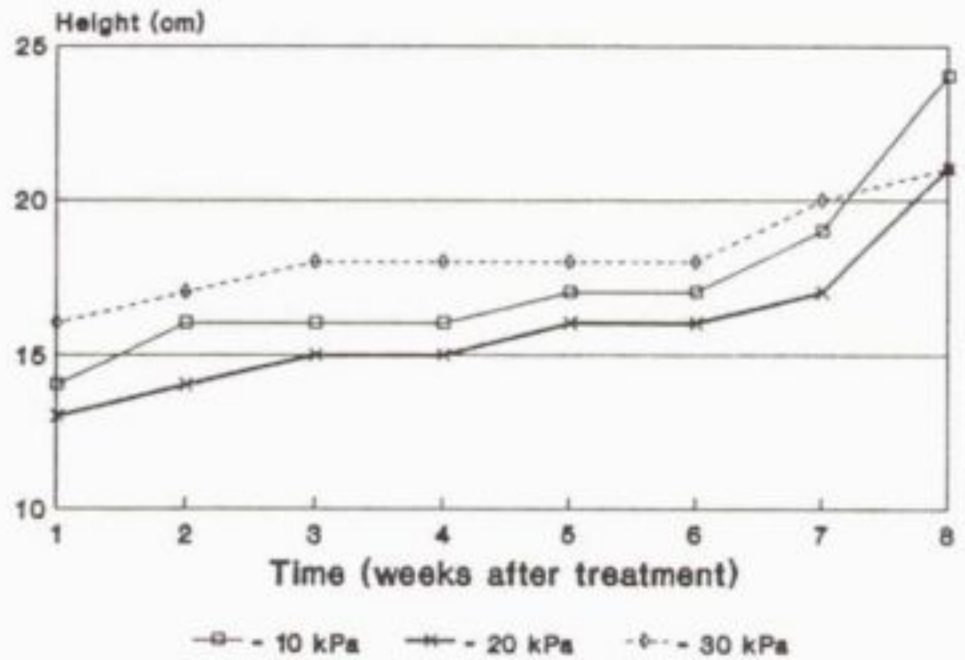


Fig. 6.22. Height of RL in non-compacted soil at -10, -20, and -30 kPa.

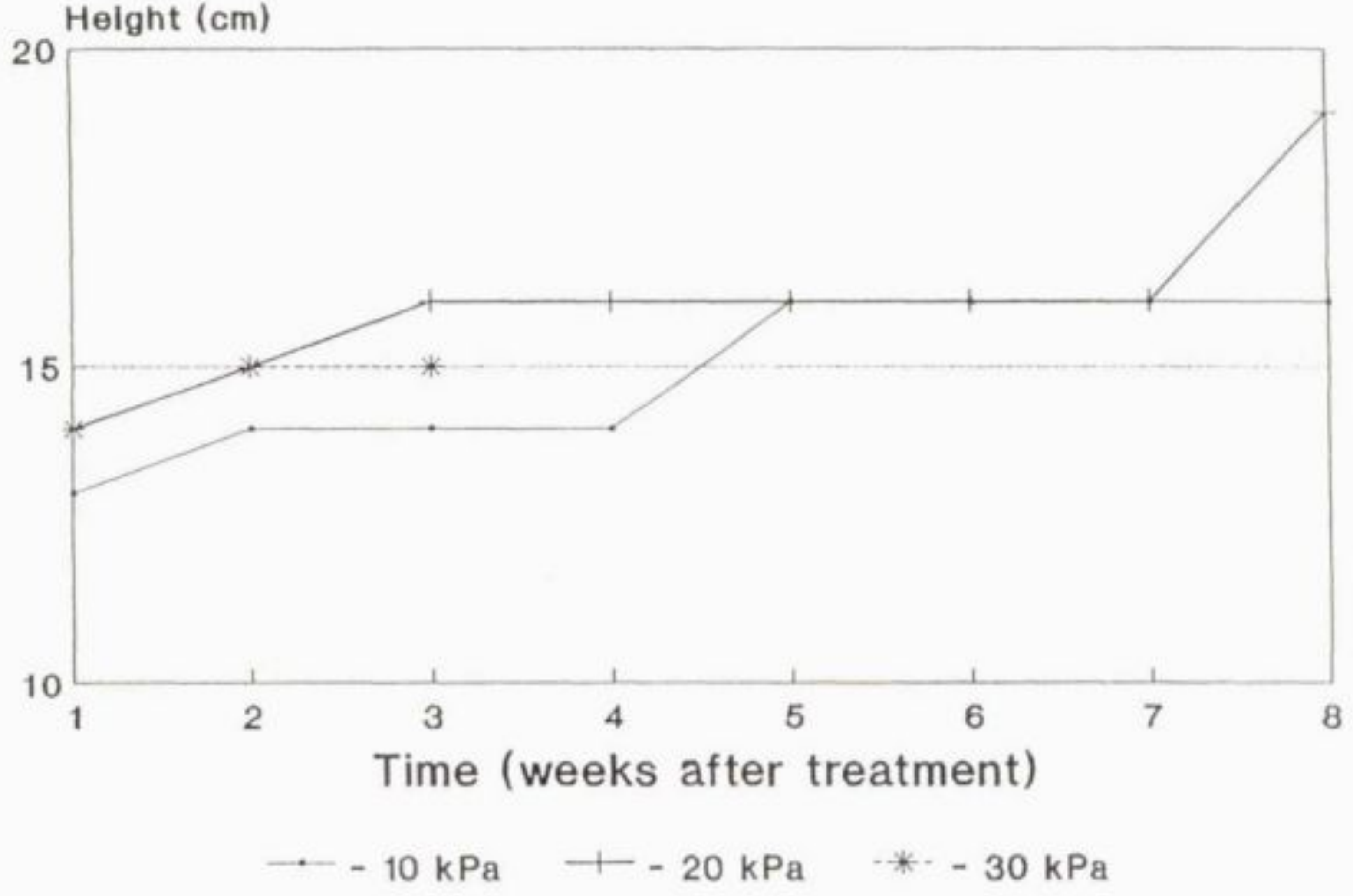


Fig. 6.23. Height of RL in compacted soil at -10, -20, and -30 kPa.

6.4.2.4 Morphological and Physiological Plant Responses

At -10 kPa, the compaction of soil resulted in reduced total dry mass, top dry mass, top:root ratio and water consumption (Table 6.6). However, the root dry mass was statistically significantly higher in seedlings grown in compacted soil (For statistical analyses, refer to Appendices 6.16-6.28).

At -20 kPa, there was no significant difference in total dry mass, top dry mass and root dry mass between seedlings in compacted and non-compacted soil. However, the water consumption was statistically significantly higher for seedlings in non-compacted soil while the water use efficiency and top:root ratio were statistically significantly higher for seedlings in compacted soil. At -30 kPa, the seedlings in compacted soil were stressed, resulting in low dry mass accumulation and water consumption.

In non-compacted soil, the seedlings at -10 kPa had a statistically significantly higher total dry mass, top dry mass, cumulative water consumption, and water use efficiency compared to those at -20 and -30 kPa. On the other hand, in compacted soil, the seedlings at -10 kPa had statistically significantly higher total dry mass and root dry mass even though they showed some symptoms of stress later in the season.

Table 6.7 illustrates the effects of soil compaction and soil water potential on leaf area, projected root surface area, soil water content and air-filled pore space. At -10 kPa, the seedlings in non-compacted soil had statistically significantly higher leaf area while the water consumption per leaf area was higher for seedlings in compacted soil. The soil water content and the air-filled pore space were higher in non-compacted soil. Similar results were found at -20 kPa. At -30 kPa, the seedlings in non-compacted soil had a statistically significantly higher leaf area and root surface area. The soil water content and the air-filled pore space were also statistically significantly higher in this treatment.

The soil water potential had a significant effect on seedlings in both compacted and non-compacted soil. In non-compacted soil, the seedlings at -10 kPa produced statistically significantly higher leaf area and somewhat lower water consumption per unit leaf area than those at -20 and -30 kPa. The soil water content was higher in this treatment while the air-filled pore space was much lower, but not close to the critical level of 10% (Table 6.7). Seedlings at -30 kPa produced lower leaf area and higher water consumption per leaf area. In compacted soil, the seedlings at -20 kPa produced a relatively but insignificantly higher leaf and projected root surface area. These results indicate that -20 kPa was somewhat better for compacted soil compared to -10 and -30 kPa.

Table 6.6. Effects of soil compaction and soil water potential on dry mass accumulation, water consumption, and water use efficiency by RL seedlings

Soil treatment	Total dry mass (g)	Top dry mass (g)	Root dry mass (g)	Top: root ratio	RA:RM (cm^2/g)	Water cons. (dm^3)	WUE ($g.dm^3$)
			-10 kPa soil water potential				
Non-comp	1.33	1.01	0.32	3.16	291	2.55	0.50
Non-comp	1.57	1.12	0.45	2.49	217	2.76	0.55
mean	**1.45**	**1.07**	**0.39**	**2.74**	**254**	**2.66**	**0.53**
Compact	1.00	0.31	0.69	0.45	62	1.73	0.55
Compact	1.15	0.31	0.84	0.37	114	1.73	0.64
mean	**1.08**	**0.31**	**0.77**	**0.40**	**88**	**1.73**	**0.60**
			-20 kPa soil water potential				
Non-comp	0.51	0.28	0.23	1.22	-	2.50	0.18
Non-comp	0.40	0.20	0.20	1.00	348	2.34	0.15
mean	**0.46**	**0.24**	**0.22**	**1.10**	**348**	**2.42**	**0.17**
Compact	0.32	0.19	0.13	1.46	469	1.57	0.17
Compact	1.04	0.79	0.25	3.16	435	1.58	0.63
mean	**0.68**	**0.49**	**0.19**	**2.58**	**452**	**1.58**	**0.40**
			-30 kPa soil water potential				
Non-comp	0.90	0.62	0.28	2.21	347	2.14	0.40
Non-comp	1.23	0.79	0.44	1.80	181	2.41	0.49
mean	**1.07**	**0.71**	**0.36**	**1.97**	**246**	**2.28**	**0.45**
Compact	0.51	0.25	0.26	0.96	37	0.48	0.92
Compact	0.43	0.21	0.22	0.95	113	0.50	0.79
mean	**0.47**	**0.23**	**0.24**	**0.96**	**75**	**0.49**	**0.86**
LSD	0.29	0.28	0.14	0.51	84	0.15	0.20

RA:RM - root area to root mass ratio.
WUE - water use efficiency.

Table 6.7. Effects of soil compaction and soil water potential on leaf area, root area, RA:LA ratio, and water consumption per leaf area

	Leaf area (cm^2)	Root area (cm^2)	RA:LA ratio	Water cons. per LA ($cm^3.cm^{-2}$)	Soil H_2O content (cm^3/cm^3)	Air-filled pore (%)
			-10 kPa soil water potential			
Non-comp	230	93.2	0.40	11.09	27.2	14.4
Non-comp	274	97.6	0.36	10.07	26.9	14.7
mean	**252**	**95.4**	**0.38**	**10.58**	**27.1**	**14.6**
Compact	48	42.8	0.89	36.04	23.1	12.9
Compact	90	95.4	1.06	19.21	24.7	11.3
mean	**69**	**69.1**	**0.98**	**27.63**	**23.9**	**12.1**
			-20 kPa soil water potential			
Non-comp	182	70.7	0.39	13.74	19.9	21.7
Non-comp	155	69.5	0.45	15.13	21.2	20.4
mean	**168**	**70.1**	**0.42**	**14.44**	**20.6**	**21.1**
Compact	74	61.0	0.83	21.23	17.7	18.3
Compact	121	108.7	0.90	13.11	18.4	17.6
mean	**97**	**84.9**	**0.87**	**17.17**	**18.1**	**18.0**
			-30 kPa soil water potential			
Non-comp	120	97.1	0.81	17.88	17.9	23.7
Non-comp	128	79.6	0.62	18.87	17.0	24.6
mean	**124**	**88.4**	**0.72**	**18.38**	**17.5**	**24.2**
Compact	20	9.6	0.48	-	14.5	21.5
Compact	38	24.8	0.66	-	14.0	22.0
mean	**29**	**17.2**	**0.57**	-	**14.3**	**21.8**
LSD	54	50.4	0.13	7.6	1.0	1.0

RA:LA - root area to leaf area ratio.

6.5 Conclusions

The compacted soil at -10 kPa resulted in a decline in total dry mass, top dry mass and water consumption as a result of inadequate supply of oxygen in the rhizosphere. At -20 kPa, the compaction of soil did not have negative effects on plant growth and development. This probably indicates that -20 kPa is the optimum soil water potential for RL seedlings in this soil when it is compacted. However, the total water consumption was lower for the seedlings in compacted soil, which resulted in an improved water use efficiency in these seedlings.

In non-compacted soil, a -10 kPa resulted in bigger seedlings than -20 and -30 kPa. The total dry mass, top dry mass and water consumption were significantly higher at -10 kPa probably due to the availability of water.

The results of the first, second, and third experiments indicate that it is not only the soil water content and dry bulk density that limit the development of seedlings. Other environmental conditions such as temperature, relative humidity, and light intensity may add to the effects caused by soil compaction and high soil water potential. An increase or decrease in any of these production factors may lead to a shift in the optimum range of conditions for plant development. For example, -20 kPa in compacted soil was optimal for RL seedlings in summer. This indicates high sensitivity of RL seedlings to inadequate soil aeration at -10 kPa. It also indicates that the hydraulic conductivity of this soil at -30 kPa is low for RL seedlings during summer, especially when this soil is compacted. As a result of changes in environmental factors, seedling performance varies under similar conditions over a period of time.

In this study, a marginal soil of Sterkspruit form was used. In this soil form, a very serious problem is in the subsoil which has high clay and silt contents. The fact that fairly good results were obtained in these studies with topsoil even at -10 kPa therefore does not quite reflect what would happen in the grove if the trees are not planted on ridges. The study, however, shows that even the Sterkspruit soil can be successfully used for citrus production provided that only the topsoil is used for making the ridges. Usually, the topsoil is characterized by high coarse sand and moderate clay contents, as well as low fine and very fine sand and silt contents.

CHAPTER 7

EFFECTS OF AERATION AND NON-AERATION OF RHIZOSPHERE ON CITRUS SEEDLINGS

7.1 Introduction

7.1.1 General

Citrus rootstocks can influence tree size, wilting, transpiration rate, fruit quality, yield, and other factors of concern in fruit crop production. According to Syvertsen (1981), variations in citrus tree water relations that have been attributed to rootstocks are probably due to differences in root quantity, distribution, and efficiency in water uptake and transport. Root system deterioration during waterlogging is a major obstacle to scion performance (Yelenosky, 1991). A reduction in photosynthetic carbon dioxide assimilation of certain rootstocks and a decrease in rubisco activity as well as a higher rate of dark respiration in waterlogged citrus roots have been reported elsewhere (Vu & Yelenosky, 1989).

Field crops and fruit trees may experience poor aeration conditions under high irrigation frequencies and poor soil drainage. According to Wiegand & Lemon (1958), the requirement of plant roots for oxygen does not decline even though the rhizospherical conditions prohibit an adequate supply of air. The internal aeration and the ability of citrus to grow under waterlogged conditions may have considerable significance in gas exchange processes. The ability of RL to develop adventitious roots under water may indicate its capability, to a certain extent, of tolerating anoxic conditions (Syvertsen et al., 1983). Other types of citrus rootstocks, such as TC, are capable of increasing their gas space porosity when growing under waterlogged conditions (Luxmoore et al., 1971).

In order to determine the importance of air in the rhizosphere, and particularly its effects and different responses by different types of citrus rootstocks, a water culture experiment was conducted. The main objective was to try and understand the mechanisms of adaptability and tolerance possessed by different citrus rootstocks when growing under anaerobic rhizospherical conditions.

7.1.2 Difficulties with Soil Experiments

For the soil experiments reported in Chapters 4, 5 and 6, it was not possible to obtain platinum microelectrodes or any instrument (such as the recent waterproof zirconia oxygen sensor, developed by Ishii & Kadoya, 1991) to monitor the effects of air (oxygen in particular) on the performance of citrus rootstocks. It was therefore also not possible to monitor the effects of soil compaction and high soil water potentials on oxygen content and oxygen diffusion rate (O.D.R) and their ultimate effects on seedling growth and development.

When there is shortage of oxygen in the rhizosphere, chemical reduction processes that lead to a decline in the pH of a growing medium take place. In soil studies, however, it was difficult to adjust and maintain a constant pH of the soil without disturbing some of its physical characteristics which were under investigation.

Water culture experiments also make it possible to adjust and maintain the pH of the growing medium over time without major effects on the physical conditions of the rhizosphere. This could also enable an assessment of the effects of low pH of the rhizosphere on the performance of citrus rootstocks.

The effects of low aeration and low pH of the rhizosphere on RL and TC seedlings were therefore studied using water culture experiments. The studies reported here and in Chapters 8 and 9 were conducted in order to provide some additional information that could lead to better understanding of cause-effect relationships and thus the tailoring of irrigation techniques to specific combinations of soils, plants, water regime and climatic conditions which are the components of crop production.

7.1.3 Motivation for Water Culture Experiments

In the light of the difficulties experienced with the soil experiments, water culture experiments were therefore conducted (as a supplement) concurrently with them in order to monitor and control some of the factors which could not be regulated or monitored in the soil.

7.2 Materials and Treatments

Water culture experiments were conducted in 10 dm^3 metal pots. The temperature in the glasshouse was kept between 25 and 28 °C during daytime.

Rough lemon and Troyer citrange seedlings were obtained from a citrus nursery at Brits. The seedlings were transplanted into full-strength Hoagland's solution on May 7, 1992 and the aeration of pots was started on May 9, 1992. At this stage both RL and TC seedlings were 20 cm tall.

There were three replications for both aerated and non-aerated solutions. This gave a total of twelve pots (i.e. two types of citrus x two treatments x three replications). The pH of the Hoagland's solution was not adjusted during the experimental period and ranged between 3.87 and 4.63. The plants were harvested on September 28, 1992, 145 days after the experiment started.

7.3 Results and Discussion

7.3.1 Plant Growth and Development

7.3.1.1 Plant Height

There was no difference in plant height between aerated and non-aerated RL during the first seven weeks of the experiment (Figure 7.1). From the eighth to 12th week, non-aerated RL outgrew the aerated seedlings (Appendix 7.1). However, this vigorous growth soon declined, and the aerated seedlings started growing faster than the non-aerated plants. Twenty-one weeks after starting to subject the seedlings to aeration or non-aeration, the aerated seedlings had reached an average height of 91 cm while the non-aerated seedlings had reached 84 cm. Although this difference in plant height was not statistically significant probably due to the short growing period, it shows some trend and the response which most seedlings have to such conditions. Another reason that can account for small differences was the ability of non-aerated RL to develop many adventitious roots in the topmost layer of solution, thus probably alleviating the shortage of oxygen in water. Non-aerated seedlings were pale green in colour, showing some symptoms of stress which are common in plants growing under waterlogged conditions.

In TC, a significant increase in height of aerated seedlings, relative to the non-aerated ones, was observed in the fifth week of the experiment (Figure 7.2). This resulted from the higher growth rate of the aerated seedlings from the second to the seventh week after transplanting (Appendix 7.2). The difference in height between aerated and non-aerated seedlings remained constant until the last two weeks, when the aerated seedlings started to grow even faster, reaching a height of 116 cm in the 21st week while non-aerated seedlings reached 87 cm.

There was no statistically significant difference in plant height between both aerated RL and TC seedlings over time (Figure 7.3). However, TC started to grow faster during the last eight weeks, with the aerated RL seedlings reaching 91 cm while TC reached 116 cm at the end of the experiment. The growth rate of both aerated RL and TC seedlings had similar oscillating curves early in the season, which was not the case for non-aerated plants (Appendices 7.3 and 7.4). In non-aerated solution, both RL and TC did not show oscillating growth rate curves. However, towards the end of the experimental period, the RL seedlings started to show some oscillations in the growth rate curve. The differences in growth rate curves between RL and TC in non-aerated solution may indicate some interaction between the rhizospherical environmental effects and citrus species and the tolerance of TC to waterlogging.

In non-aerated seedlings, there was no significant difference in height between RL and TC at the end of the experiment (Figure 7.4). The RL seedlings reached 84 cm while TC reached 87 cm.

7.3.1.2 Number of Leaves

Both the aerated RL and TC seedlings had a higher number of leaves compared to non-aerated plants (Figures 7.5 and 7.6, respectively). Within the first seven weeks after treatment, the aerated RL seedlings had developed an average of nine new leaves while non-aerated plants had

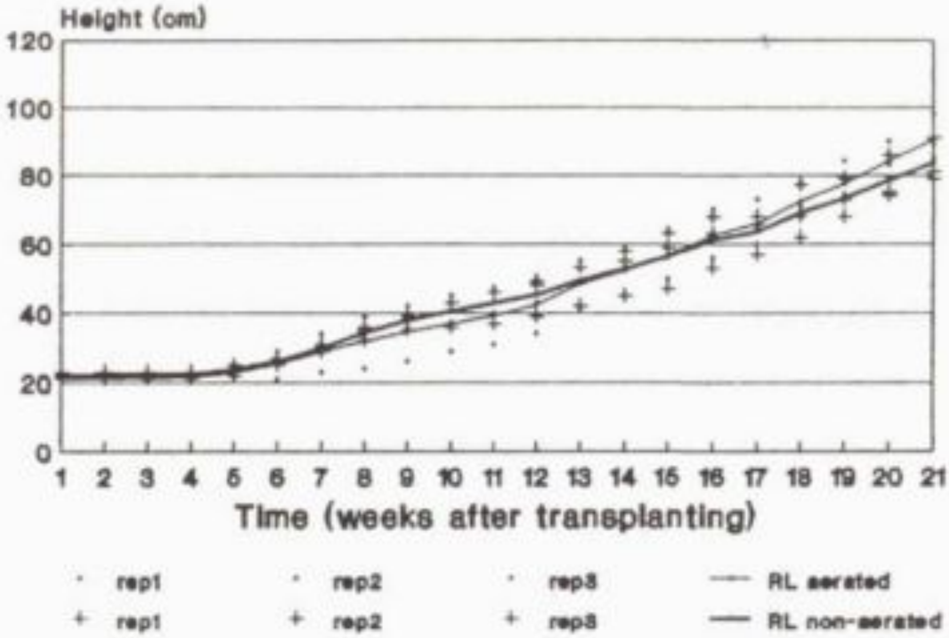


Fig. 7.1. Effect of aeration and non-aeration of nutrient solution on the height of RL.

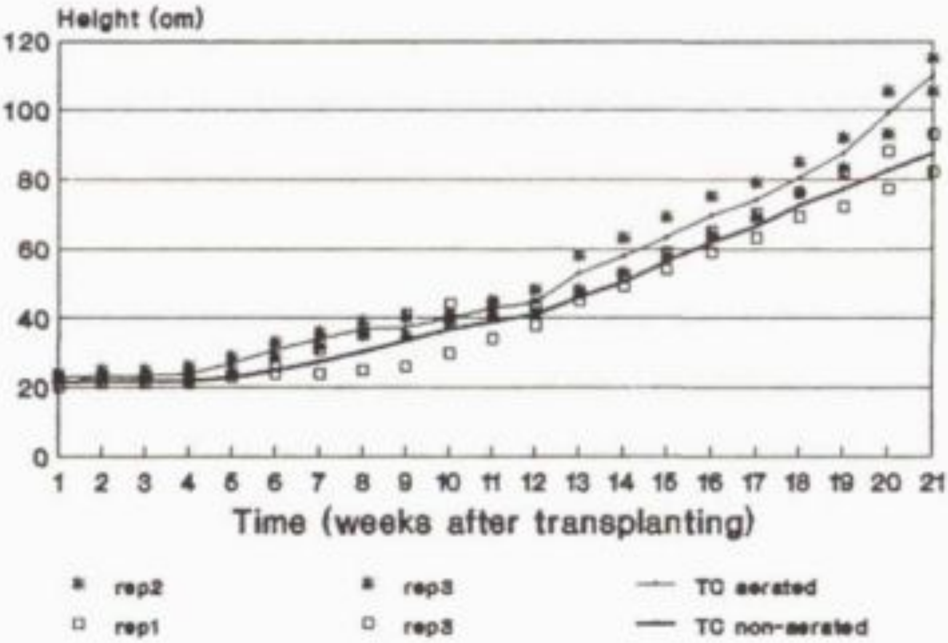


Fig. 7.2. Effect of aeration and non-aeration of nutrient solution on the height of TC.

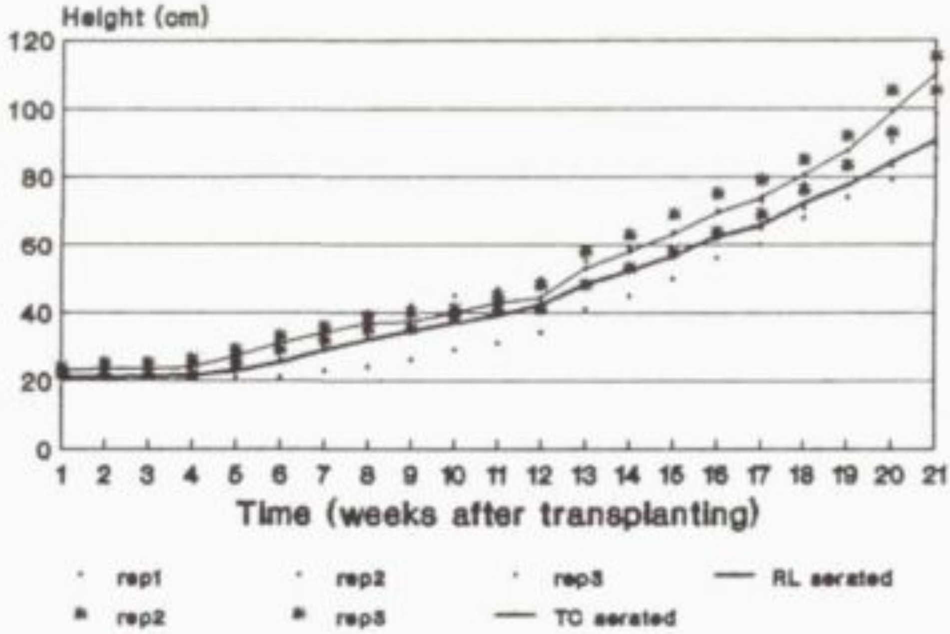


Fig. 7.3. Effect of aeration on growth of RL and TC seedlings. Each line shows the average of three values.

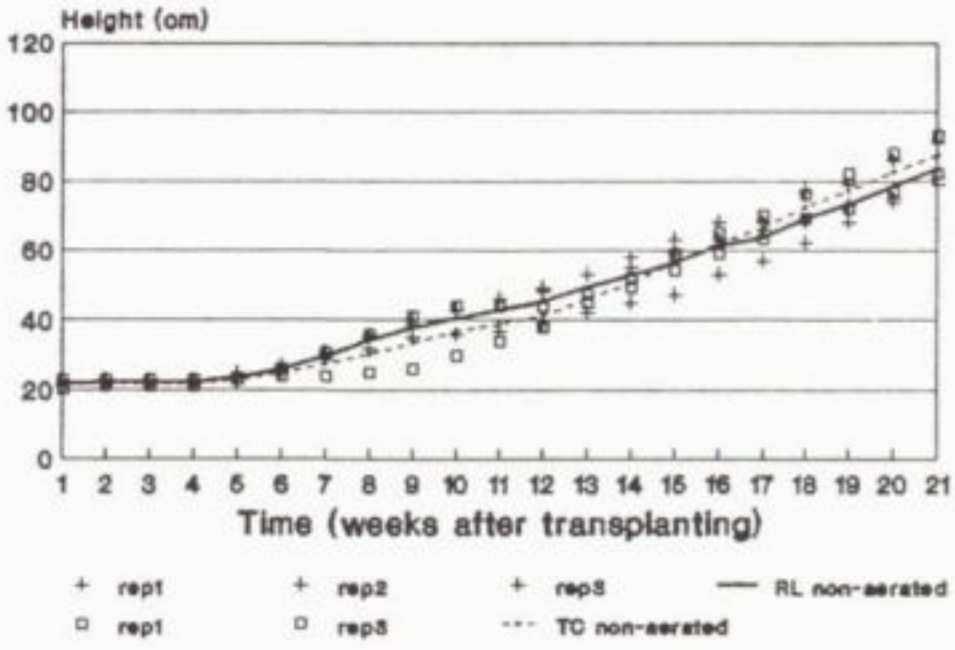


Fig. 7.4. Effect of non-aeration on growth of RL and TC seedlings. Each line shows the average of three values.

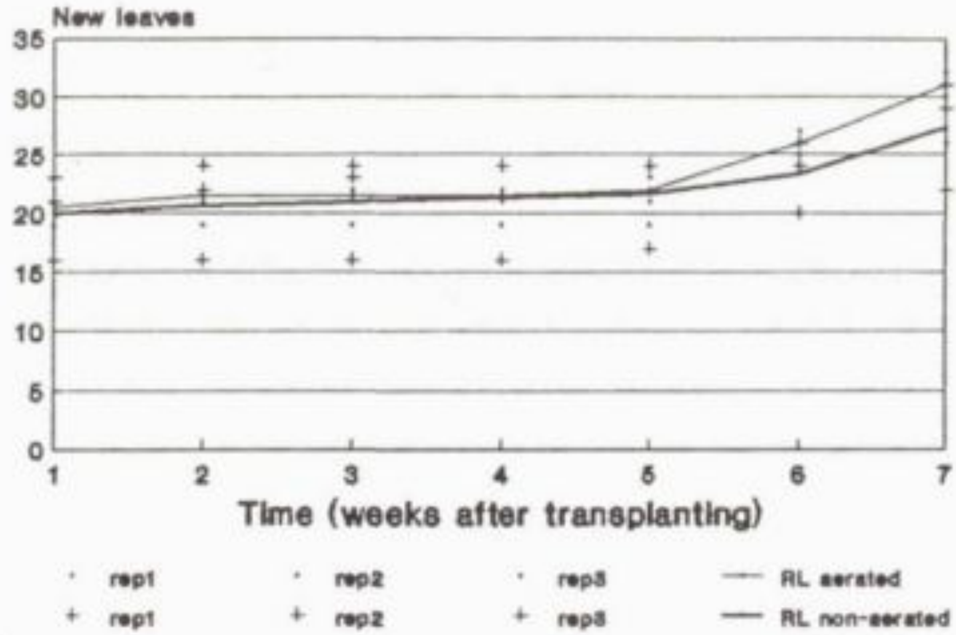


Fig. 7.5. The number of leaves of aerated and non-aerated RL in the first seven weeks after transplanting.

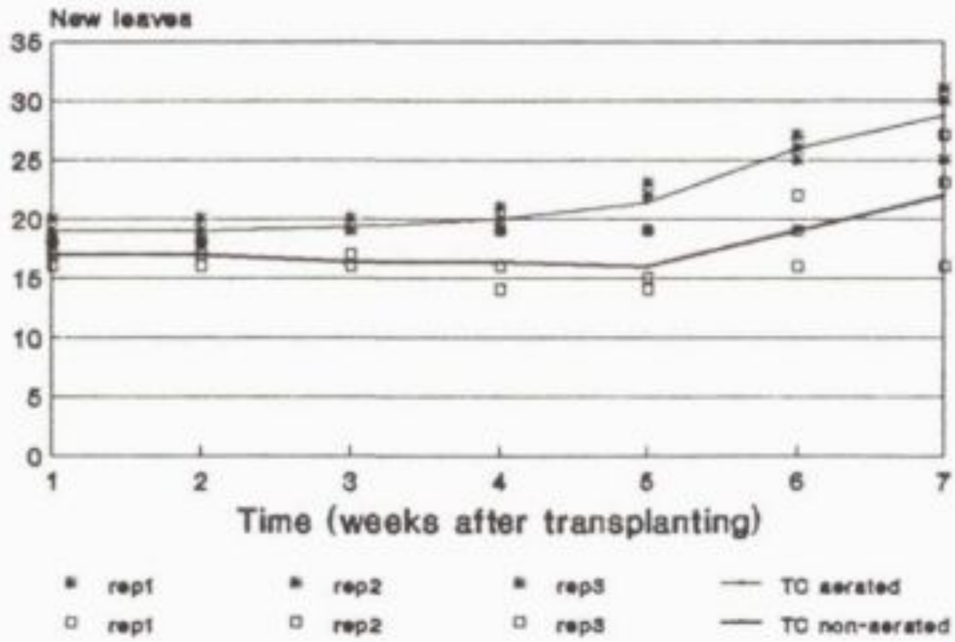


Fig. 7.6. The number of leaves of aerated and non-aerated TC in the first seven weeks after transplanting.

developed seven new leaves. The aerated TC, on the other hand, had developed 11 new leaves whilst the non-aerated plants had developed an average of only five new leaves. As a result of slow rate of formation of new leaves in non-aerated seedlings, the photosynthesizing capacity would have been limited, leading to a lower rate of dry matter accumulation. This resulted in a lower leaf area both in non-aerated RL and TC seedlings.

7.3.2 Morphological and Physiological Plant Responses

There was a statistically significant difference in dry mass accumulation between aerated and non-aerated RL seedlings (Table 7.1). Non-aeration reduced the total dry mass accumulation by 31% in RL, with aerated seedlings accumulating an average of 43.5 g while non-aerated plants accumulated 30 g (For statistical analyses, refer to Appendices 7.5 to 7.13). The top dry mass was also statistically significantly reduced by 27% in non-aerated RL seedlings, compared with aerated ones. The main effect of non-aeration was on the root dry mass which was statistically significantly reduced by 48.7%. This study also shows a statistically significant increase in top:root ratio between aerated and non-aerated RL, with the ratio of non-aerated seedlings 30% higher than that of aerated plants.

A similar situation was found with TC seedlings. A statistically significant difference was found in dry mass accumulation between aerated and non-aerated TC seedlings (Table 7.1). Non-aeration reduced the total dry mass accumulation by 23%. A statistically significant reduction of 17% and 37% in top and root dry mass, respectively, occurred in non-aerated seedlings. The top:root ratio was also statistically significantly increased by anoxic rhizospherical conditions into which the seedlings were exposed. An increase of 22% was found.

Klotz, Stolzy, Labanauskas & DeWolfe (1971) reported that low aeration of the rhizosphere reduced the rate of root production, height of stem, and water use in citrus seedlings. Hopkins et al. (1950) also reported that root growth in several crops is stopped by reducing oxygen content of the surrounding gas while the top growth continues.

In the soil studies (Chapters 4, 5 and 6), decreased top:root ratios were found as a result of soil compaction (i.e. increased root:top ratios), which means that roots became less efficient in producing top growth. Non-aeration in water culture, on the other hand, increased top:root ratio drastically, but decreased root:top ratios. This indicates high efficiency of the roots to produce top growth in the water culture. This is because nutrient elements are abundantly available in the Hoagland's solution and the small root system can still maintain quite reasonable top growth, which is not the case in soil.

Table 7.1. The effects of aeration and non-aeration on several plant parameters in RL and TC seedlings

Treatment	Total dry mass (g)	Top dry mass (g)	Root dry mass (g)	Top:root ratio	RA:RM (cm^2/g)
			Rough lemon		
	38.26	32.85	5.41	6.07	73.8
Aerated	43.32	36.30	7.02	5.17	123.9
	48.88	41.12	7.76	5.30	140.5
mean	**43.49**	**36.76**	**6.73**	**5.51**	**116.6**
S.E.	3.07	2.40	0.69	0.28	20.0
	30.99	27.67	3.33	8.31	121.6
Non-aerated	27.53	23.94	3.59	6.67	139.3
	32.08	28.65	3.43	8.35	116.3
mean	**30.20**	**26.75**	**3.45**	**7.78**	**126.1**
S.E.	1.37	1.43	0.09	0.55	6.9
			Troyer citrange		
	14.92	11.82	3.10	3.81	84.2
Aerated	18.18	14.07	4.11	3.42	93.2
	18.64	13.82	4.82	2.87	93.8
mean	**17.25**	**13.24**	**4.01**	**3.37**	**91.0**
S.E.	1.73	0.71	0.49	0.26	2.9
	13.97	11.74	2.23	5.26	87.4
Non-aerated	10.26	8.13	2.13	3.82	138.5
	16.32	13.05	3.27	3.99	126.9
mean	**13.52**	**10.97**	**2.54**	**4.36**	**118.9**
S.E.	1.76	1.47	0.38	0.47	15.5
LSD	3.23	2.64	0.76	1.06	21.6

RA:RM - root area to root mass ratio.

Table 7.2. The effects of aeration and non-aeration on leaf area, projected root area, root area:leaf area ratio, and root hydraulic conductivity of RL and TC seedlings

Treatment	Leaf area (cm^2)	Root area (cm^2)	RA:LA ratio	R.H.C* ($x10^{-5}$)
		Rough lemon		
	2371	399	0.17	1.01
Aerated	2488	870	0.35	0.58
	3276	1090	0.40	0.54
mean	**2712**	**785**	**0.31**	**0.71**
S.E.	284	204	0.07	0.15
	1841	405	0.22	0.47
Non-aerated	1492	500	0.34	0.43
	2060	399	0.22	0.41
mean	**1798**	**435**	**0.26**	**0.44**
S.E.	165	33	0.04	0.02
		Troyer citrange		
	780	261	0.33	0.62
Aerated	721	383	0.53	0.46
	795	452	0.57	0.30
mean	**765**	**365**	**0.48**	**0.46**
S.E.	23	56	0.07	0.09
	658	195	0.30	0.45
Non-aerated	572	295	0.52	0.35
	712	415	0.58	0.37
mean	**647**	**302**	**0.47**	**0.39**
S.E.	41	64	0.09	0.03
LSD	371	182	0.11	0.15

RA:LA - root area:leaf area ratio.
* R.H.C. - root hydraulic conductivity ($cm^3.cm^{-2}.Pa^{-1}.s^{-1}$).

Laker (unpublished data) also observed similar trends in studies on the effects of high Al on different wheat cultivars: In water culture high Al drastically reduced the root system of some cultivars, but had little effect on top growth. In soil experiments the top growth was drastically reduced where high Al restricted root development, however.

Table 7.2 shows the effect of non-aeration on leaf area and projected root surface area of RL and TC seedlings. The RL seedlings in non-aerated nutrient solution produced statistically significantly lower leaf area. A reduction of 34% in leaf area occurred as a result of non-aeration in RL seedlings while the projected root surface area was statistically significantly reduced by 45%. However, there was no significant difference in root area:leaf area ratio between aerated and non-aerated RL seedlings. The root hydraulic conductivity of the aerated RL seedlings was statistically significantly higher than that of non-aerated plants. This probably resulted from the higher root area in aerated compared to non-aerated plants. A reduction of 38% in root hydraulic conductivity occurred as a result of non-aeration in RL seedlings.

No statistically significant difference was found in leaf area between aerated and non-aerated TC seedlings. There was a 15% decline in leaf area as a result of non-aeration while the root area was reduced by 17%. Non-aeration did not have a significant negative effect on both root area:leaf area ratio and root hydraulic conductivity of TC. This probably indicates the degree and the mechanisms in which TC rootstock can tolerate waterlogged conditions.

7.3.3 Sensitivity of Seedlings to Non-aeration

Rough lemon seedlings were more severely affected by non-aeration than TC seedlings (Table 7.3). However, the root dry mass (1) was the most negatively affected plant parameter in both RL and TC. This leads to a high top:root ratio in non-aerated plants which is one of the main characteristics of the excess-water stressed plants. Similar results were reported by Stolzy et al. (1965a) who found that the roots of citrus seedlings were more affected by low oxygen diffusion rate than top growth.

In RL the projected root surface area was the second most affected parameter. Together with the third rated reduced root hydraulic conductivity, these two parameters can lead to a reduction in nutrient uptake by non-aerated RL seedlings. The reduction in leaf area (4) leads to a decline in photosynthesizing capacity of the plant. Consequently the total dry mass (5) and top dry mass accumulation (6) in non-aerated RL were reduced. All the plant parameters measured in RL seedlings were statistically significantly reduced (*) by non-aerated rhizospherical conditions.

Table 7.3. Relative decline of several citrus plant parameters as a result of non-aerated conditions in the rhizosphere

Parameter	Relative decline (%)	
	Rough lemon	Troyer citrange
Total dry mass (g)	30.6* (5)	21.6* (2)
Top dry mass (g)	27.2* (6)	17.1* (4)
Leaf area (cm^2)	33.7* (4)	15.4* (5)
Root dry mass (g)	48.7* (1)	36.7* (1)
Root area (cm^2)	44.6* (2)	17.1 (3)
Root H.C.**	38.1* (3)	14.6 (6)

* statistically significantly different from the aerated plants.
The number in parenthesis indicates the ranking of each parameter (1 = highest decline).
** Root hydraulic conductivity ($cm^3.cm^{-2}.Pa^{-1}.s^{-1}$).

The TC seedlings were also affected by non-aeration, but less than RL (Table 7.3). The rank order of the severity of TC also differed from that for RL. In TC the total dry mass was among the most affected parameters. This shows that the effect of stress conditions in the rhizosphere influenced the whole plant instead of the root system only. As indicated earlier, the initiation of new leaves and the increase in plant height of TC seedlings appeared to be more sensitive to anaerobic conditions compared to RL seedlings. It probably also illustrates the low efficiency of TC roots to support top growth. However, this type of rootstock was not as sensitive to anaerobic conditions as RL. Although the root dry mass accumulation was the most affected parameter, as in RL, the projected root surface area (3) and root hydraulic conductivity (6) in TC were not statistically significantly affected, in contrast to RL where these were severely affected.

CHAPTER 8

EFFECTS OF pH AND NON-AERATION OF THE RHIZOSPHERE ON CITRUS SEEDLINGS

8.1 Introduction

The pH of the rhizosphere has a large influence on the development of citrus. Ford (1964) found that various citrus rootstocks differ in their tolerance to the pH of the rhizosphere. Together with waterlogging, the low pH of the rhizosphere leads to poor feeder root growth. This is also common in the leached horizons where the pH is usually low.

Although citrus feeder roots are damaged by oxygen deficiency that results from waterlogging, studies by Ford (1964) have shown that root damage by sulfides is more rapid at low pH and in the leached horizon of the profile. Several studies have indicated that certain soils become acidic when waterlogged (Grable, 1966). The relatively poor feeder root growth by certain commercial citrus rootstocks together with the damage that usually occur at relatively low pH under waterlogged conditions should be evaluated before planting these rootstocks in the acid soils on a large scale. According to Tucker et al. (1992), a higher rhizospherical pH may help to delay the death of citrus roots under waterlogged conditions.

This study was conducted in order to determine the effects of low pH and non-aeration of the rhizosphere on growth and development of RL and TC seedlings. The pH of the nutrient solution was maintained at two specified levels with minimum disturbance on the aeration/non-aeration conditions.

8.2 Materials and Treatments

Rough lemon and Troyer citrange seed was germinated in vermiculite growth medium on May 11, 1993. The seedlings were fertigated with full-strength Hoagland's solution every day. On August 25, 1993 when the seedlings were 10 cm tall, they were transplanted into water culture in 10 dm^3 metal pots. Both RL and TC seedlings were grown in aerated and non-aerated nutrient solution at pH 4 and pH 7. The pH of the nutrient solution was adjusted using dilute NaOH and HCl solutions. There were four replications for each treatment. The seedlings were harvested after 90 days (RL) and 120 days (TC).

8.3 Results and Discussion

8.3.1 Plant Growth and Development

There was no difference in plant height as a result of pH on aerated TC seedlings for most part of the growing season (Figure 8.1). However, in the 16th week after different treatment started, the seedlings grown at pH 7 started to grow faster than those at pH 4. At the end of the experimental period, the seedlings at pH 7 were 70 cm tall while those at pH 4 were 57 cm. There was also no difference in plant height of non-aerated seedlings as a result of pH during the first five weeks after transplanting (Figure 8.2). However, the seedlings at pH 7 started to grow faster than those at pH 4 in the sixth week. In the 12th week the seedlings at pH 4 started to grow faster, reaching a height of 46 cm at the end of the experiment while those at pH 7 reached 40 cm. This difference, however, was not statistically significant.

Aerated TC seedlings at pH 4 grew faster than the non-aerated plants at the same pH (Figure 8.3). Although there was no difference in height during the first four weeks after treatment, the aerated seedlings thereafter started to grow faster than non-aerated plants, reaching 57 cm at the end of the experiment while the non-aerated seedlings reached 46 cm. Much bigger differences were found between aerated and non-aerated seedlings grown at pH 7 (Figure 8.4). The difference in plant height started to increase in the fifth week after treatment. At the end of the experimental period, the aerated seedlings had reached 70 cm while the non-aerated plants had reached only 40 cm. This means that non-aeration statistically significantly reduced the height of TC seedlings by 20% and 43% at pH 4 and 7, respectively, at the end of the experiment.

The pH did not have any major effect on the height of RL seedlings for the first 10 weeks after transplanting in aerated solution (Figure 8.5). From the 11th week onwards, the seedlings at pH 4 started to grow faster, reaching a height of 96 cm while those at pH 7 reached 83 cm at the end of the experimental period. This difference was, however, not statistically significant. Also in non-aerated solution no statistically significant difference was found in plant height as a result of pH (Figure 8.6). At the end of the season, the seedlings were 62 cm and 59 cm tall at pH 4 and pH 7, respectively.

Non-aeration of RL seedlings resulted in a slower increase in plant height. At pH 4 there was no difference in plant height between aerated and non-aerated plants for the first 10 weeks after treatment (Figure 8.7). In the 11th week the aerated seedlings started to grow faster than those in non-aerated nutrient solution. At the end of the season the height of seedlings was 96 cm and 62 cm in aerated and non-aerated solution, respectively. This difference was statistically significant. At pH 7 the aerated seedlings started to grow faster than non-aerated plants in the eighth week after treatment, reaching 83 cm while the non-aerated seedlings reached 59 cm at the end of the experimental period (Figure 8.8).

8.3.2 Morphological and Physiological Plant Responses

The top dry mass and the leaf area of TC seedlings were not significantly reduced by low pH in aerated nutrient solution (Table 8.1). On the other hand, the top:root ratio was significantly

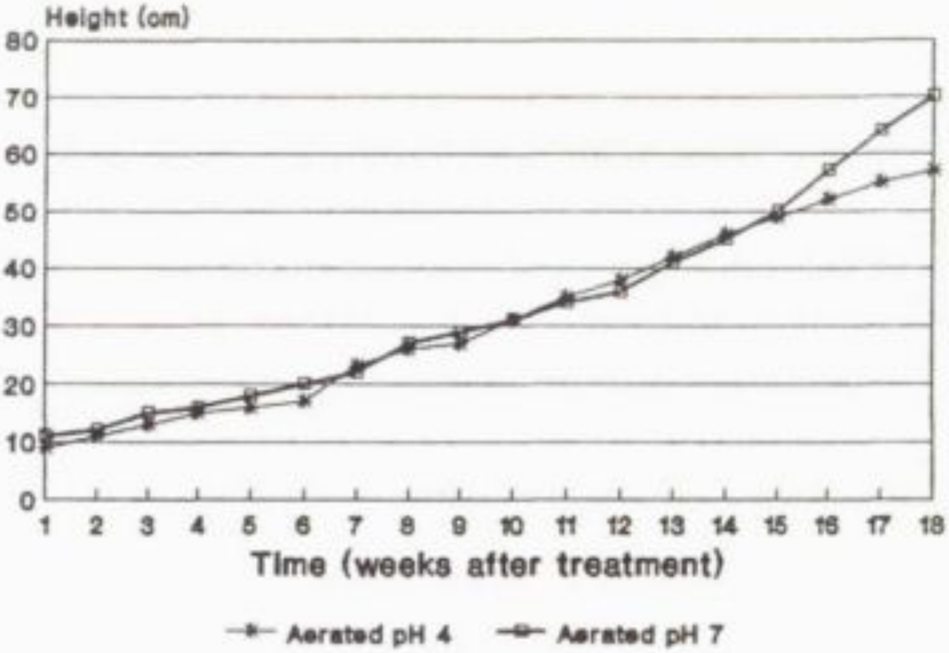


Fig. 8.1. Height of TC seedlings in aerated nutrient solution at pH 4 and pH 7.

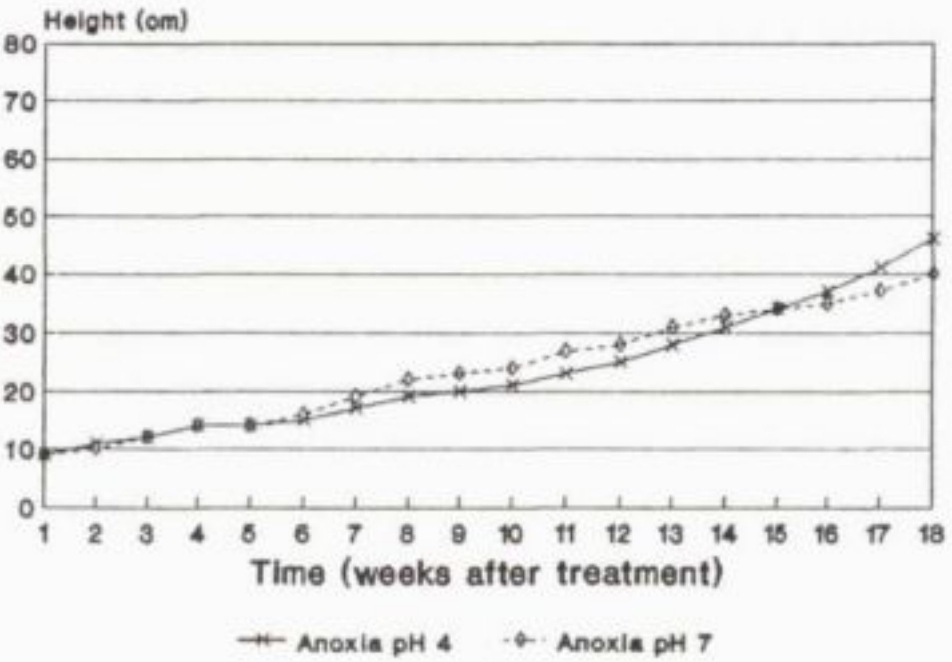


Fig. 8.2. Height of TC in non-aerated nutrient solution at pH 4 and pH 7.

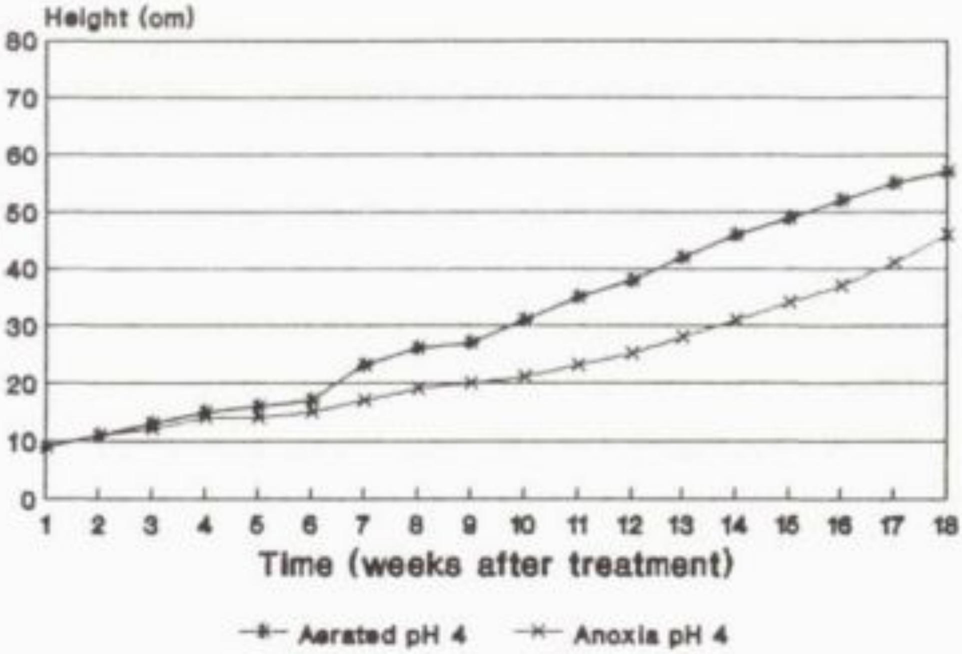


Fig. 8.3. Height of TC in aerated and non-aerated nutrient solution at pH 4.

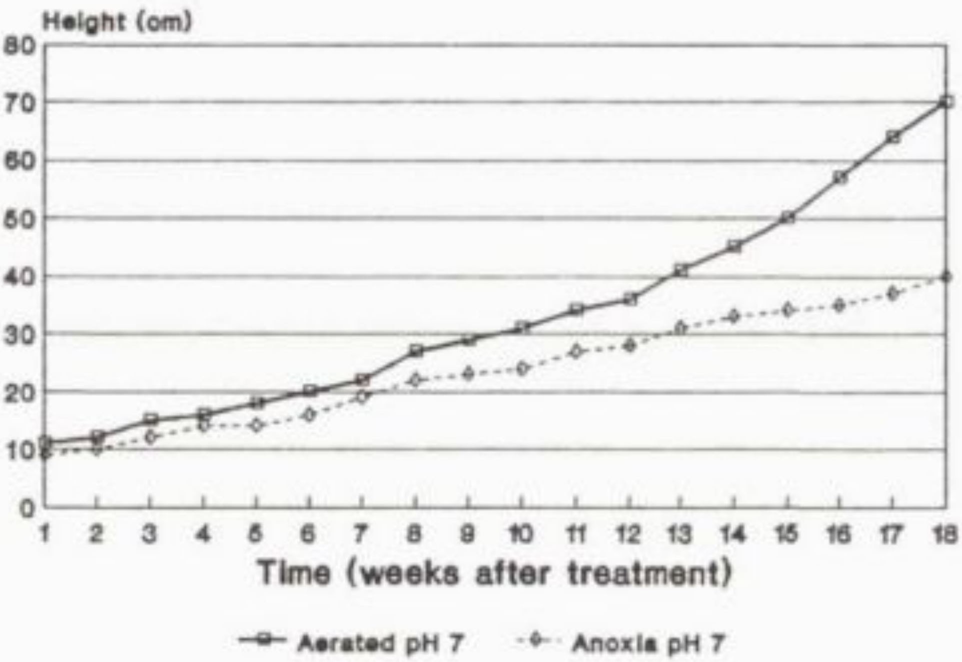


Fig. 8.4. Height of TC in aerated and non-aerated nutrient solution at pH 7.

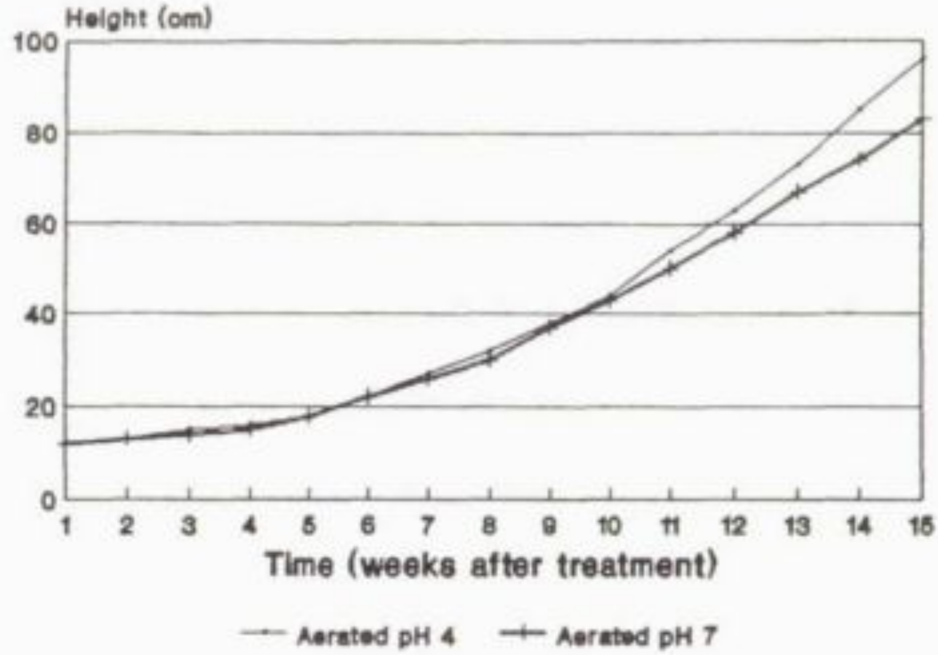


Fig. 8.5. Height of RL in aerated nutrient solution at pH 4 and pH 7.

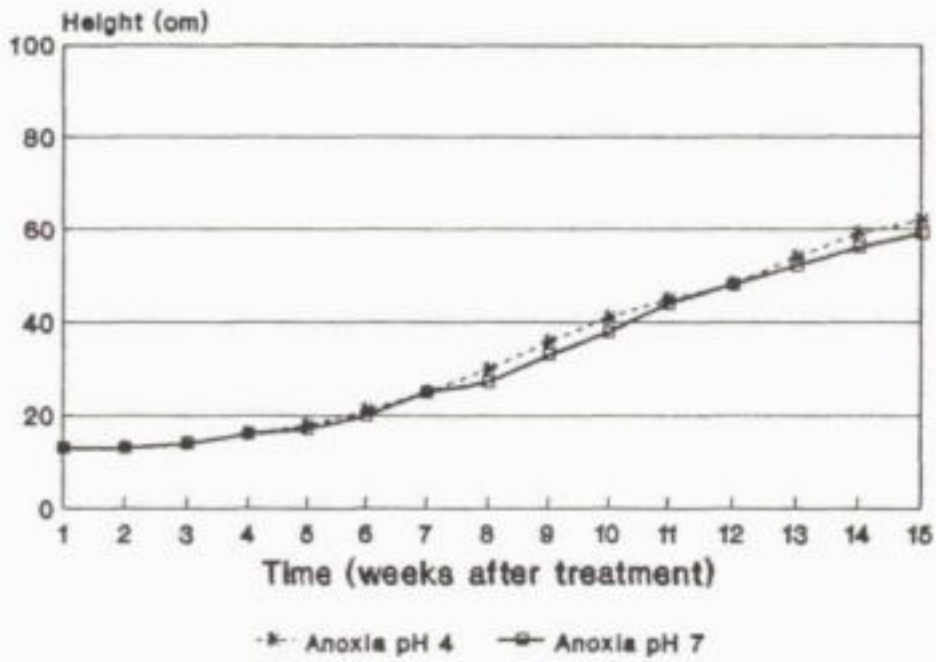


Fig. 8.6. Height of RL in non-aerated nutrient solution at pH 4 and pH 7.

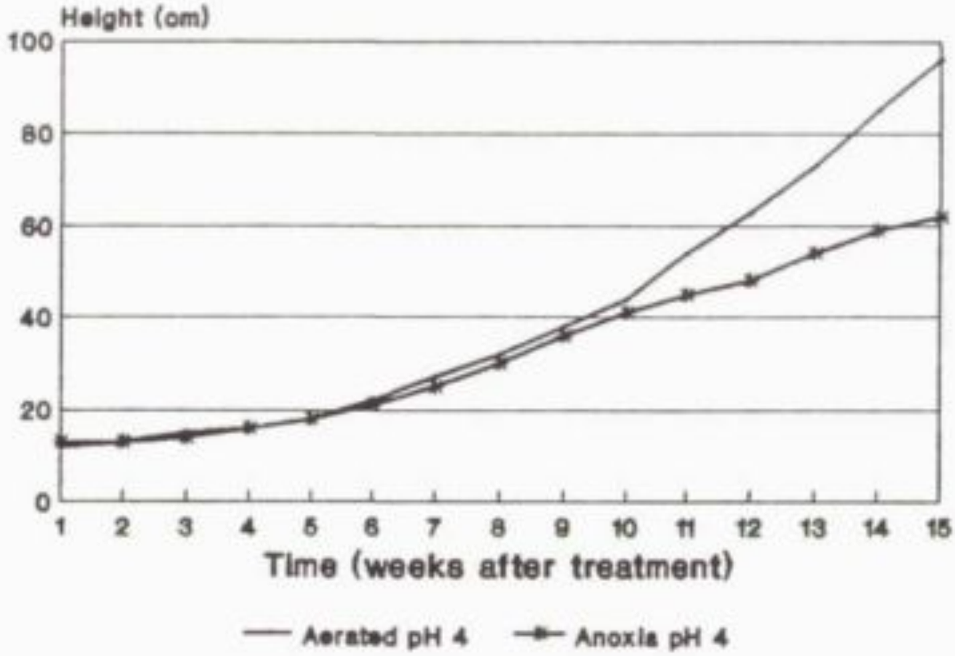


Fig. 8.7. Height of RL in aerated and non-aerated nutrient solution at pH 4.

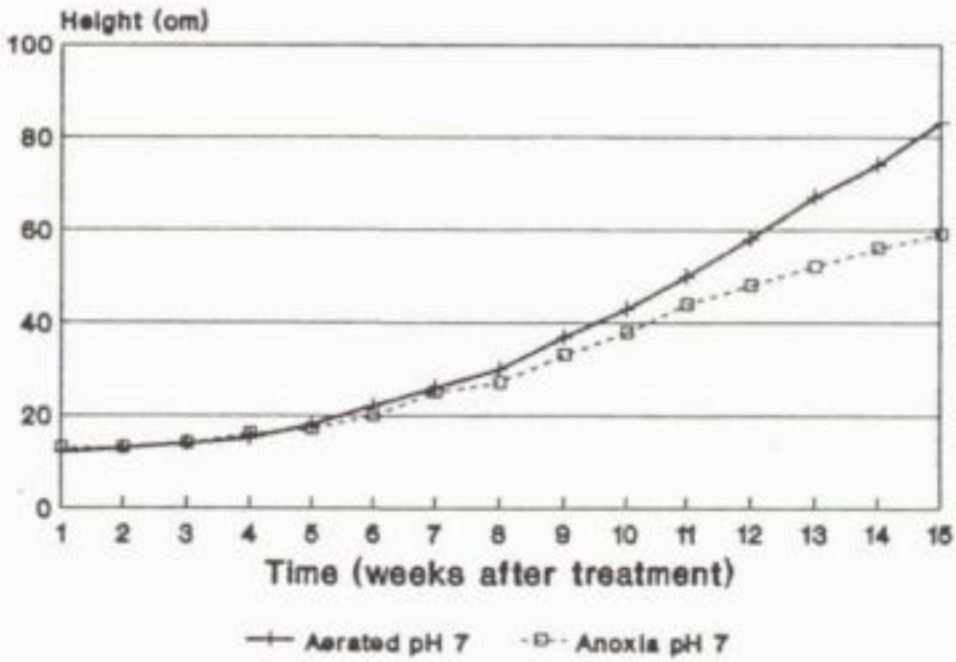


Fig. 8.8. Height of RL in aerated and non-aerated nutrient solution at pH 7.

lower in aerated seedlings at pH 4 than at pH 7. This means that the root system at pH 7 was more efficient than at pH 4. Although there were some differences in total dry mass, root dry mass and root area, these differences were not statistically significant (For statistical analyses, refer to Appendices 8.1 to 8.7). Ford (1964) found that the root system of Poncirus trifoliata was damaged at pH 5 but showed excellent tolerance to non-aeration at pH 6.5. This suggests that the TC rootstock should be carefully evaluated before planting on a large scale in relatively acidic soils.

In non-aerated nutrient solution, only the projected root surface area and the root area:leaf area ratio of TC seedlings were statistically significantly reduced at pH 4 compared to those at pH 7. For all other plant parameters measured, the differences were not statistically significant.

The aeration of TC seedlings at pH 7 resulted in statistically significantly higher total dry mass, top dry mass, root dry mass and leaf area than the non-aerated plants (Table 8.1). However, the ratio of root area:leaf area was statistically significantly higher in seedlings grown in non-aerated nutrient solution. At pH 4, the aeration of nutrient solution resulted in statistically significantly higher root dry mass, projected root surface area and root area:leaf area ratio and significantly lower top:root ratio. There was no difference in total dry mass, top dry mass, and leaf area between aerated and non-aerated seedlings at this pH level.

In aerated RL seedlings, the low pH resulted in statistically significantly higher total dry mass, root dry mass, root surface area, and root area:leaf area ratio compared to those at pH 7 (For statistical analyses, refer to Appendices 8.8 to 8.14). The leaf area was significantly higher in seedlings grown at pH 7 while there was no significant difference in top dry mass and top:root ratio between seedlings at pH 4 and pH 7.

In non-aerated RL seedlings the root surface area and root area:leaf area ratio were statistically significantly higher in seedlings grown at pH 4. No significant difference was found in total dry mass, top dry mass, root dry mass, top:root ratio, and leaf area between RL seedlings grown at pH 4 and pH 7. Non-aeration of RL seedlings resulted in statistically significant reduction of all the morphological parameters at both pH 4 and pH 7 (Table 8.2).

Table 8.1. Effects of pH and non-aeration of nutrient solution on growth and development of TC seedlings

	Total dry mass (g)	Top dry mass (g)	Root dry mass (g)	Top: root ratio	Leaf area (cm^2)	Root area (cm^2)	RA: LA ratio
			Aerated				
	7.02	5.85	1.17	5.00	291.1	182.6	0.63
	7.91	5.56	2.35	2.37	277.8	391.5	1.41
pH7	4.40	3.63	0.77	4.71	213.1	172.3	0.81
	6.14	3.99	2.15	1.85	175.1	171.3	0.98
mean	**6.37**	**4.76**	**1.61**	**3.48**	**239.3**	**229.4**	**0.96**
S.E.	0.75	0.56	0.38	0.80	27.4	54.1	0.17
	5.45	3.77	1.68	2.24	202.1	290.9	1.44
	6.26	3.99	2.27	1.76	187.1	384.9	2.06
pH4	6.10	4.39	1.71	2.57	229.6	249.6	1.09
	4.33	2.71	1.62	1.67	122.9	238.2	1.94
mean	**5.54**	**3.72**	**1.82**	**2.04**	**185.4**	**290.9**	**1.63**
S.E.	0.44	0.35	0.15	0.21	22.6	33.3	0.23
			Non-aerated				
	6.76	5.43	1.33	4.08	266.6	244.0	0.92
	3.87	2.72	1.15	2.36	137.2	237.2	1.73
pH7	4.27	2.83	1.44	1.97	149.8	200.6	1.34
	3.38	2.46	0.92	2.67	135.8	154.0	1.13
mean	**4.57**	**3.36**	**1.21**	**2.78**	**172.3**	**208.9**	**1.28**
S.E.	0.75	0.69	0.11	0.46	31.6	20.7	0.17
	4.46	3.06	1.40	2.19	177.2	176.7	1.00
	5.39	4.31	1.08	3.99	229.2	197.6	0.86
pH4	4.48	3.59	0.89	4.03	195.7	154.4	0.79
	3.11	2.52	0.59	4.27	138.1	124.5	0.90
mean	**4.36**	**3.37**	**0.99**	**3.40**	**185.1**	**163.3**	**0.89**
S.E.	0.47	0.38	0.17	0.48	19.0	15.7	0.04
LSD	1.35	1.13	0.49	1.00	55.8	74.9	0.36

RA:LA - root area to leaf area ratio.

Table 8.2. Effects of pH and non-aeration of nutrient solution on growth and development of RL seedlings

	Total dry mass (g)	Top dry mass (g)	Root dry mass (g)	Top: root ratio	Leaf area (cm²)	Root area (cm²)	RA:LA ratio
			Aerated				
	11.79	9.44	2.35	4.02	797.8	650.5	0.82
	10.21	7.78	2.43	3.20	613.7	591.7	0.96
pH 7	10.81	8.55	2.26	3.78	766.9	581.2	0.76
	10.20	7.54	2.66	2.83	683.4	623.1	0.91
mean	**10.65**	**8.33**	**2.42**	**3.46**	**715.4**	**611.6**	**0.86**
S.E.	0.43	0.43	0.09	0.27	41.6	15.7	0.04
	11.25	8.47	2.78	3.05	639.1	740.3	1.16
	11.23	8.57	2.66	3.22	641.1	740.0	1.15
pH 4	11.89	9.01	2.88	3.13	660.0	676.9	1.03
	11.45	8.24	3.21	2.57	624.0	802.7	1.29
mean	**11.47**	**8.57**	**2.88**	**2.99**	**641.1**	**740.0**	**1.16**
S.E.	0.15	0.16	0.12	0.15	7.4	25.7	0.05
			Non-aerated				
	9.19	7.80	1.39	5.61	663.5	367.7	0.55
	9.23	7.57	1.66	4.56	697.1	429.7	0.62
pH 7	8.60	6.71	1.89	3.55	584.1	454.2	0.78
	7.98	6.28	1.70	3.69	559.7	423.5	0.76
mean	**8.75**	**7.09**	**1.66**	**4.35**	**626.1**	**418.8**	**0.68**
S.E.	0.29	0.36	0.10	0.47	32.4	18.3	0.06
	9.06	7.09	1.97	3.60	562.9	529.8	0.94
	8.24	6.72	1.52	4.42	535.6	471.7	0.88
pH 4	9.34	7.76	1.58	4.91	651.4	450.5	0.69
	9.13	7.22	1.91	3.78	545.3	500.1	0.92
mean	**8.93**	**7.19**	**1.74**	**4.18**	**573.8**	**488.0**	**0.86**
S.E.	0.25	0.22	0.12	0.30	26.5	17.2	0.06
LSD	0.61	0.68	0.23	0.52	64.8	42.7	0.12

RA:LA - root area to leaf area ratio.

Table 8.3 shows a relative decline in plant parameters for both RL and TC as a result of non-aeration and low pH of the rhizosphere. Non-aeration had a statistically significant negative effect on most plant parameters both at pH 7 and pH 4. At pH 4, non-aeration had a relatively higher negative effect (large values) on most morphological parameters than at pH 7 on both RL and TC seedlings.

Table 8.3. Relative effects of non-aeration and low pH on the on morphological parameters of RL and TC seedlings

	Relative decline (%) due to:							
	Non-aeration on:				Low pH on:			
	RL		TC		RL		TC	
	pH7	**pH4**	**pH7**	**pH4**	**AE**	**NAE**	**AE**	**NAE**
Total mass*	18	22	28	21	8+	2+	13	5
Top mass	15	16	29	9	3+	1+	22	0
Root mass	31	40	25	46	19+	5+	13+	18
Top:root	21+	27+	15	40+	14	4	43	23+
Leaf area**	13	11	28	0	10	8	23	7+
Root area	32	34	9	44	21+	17+	27+	22
RA:LA ratio	21	26	33+	45	35+	27+	70+	31

AE - aerated solution.
NAE - non-aerated solution.
* mass (g), ** area (cm^2).
+ gain rather than decline.

The root dry mass, projected root surface area, root area:leaf area ratio, and the top:root ratio were the most reduced plant parameters in RL. In TC non-aeration resulted in a relatively higher negative impact on the root system only at pH 4.

The low pH (pH 4) had a positive effect on most plant parameters in both aerated and non-aerated RL seedlings. The leaf area, however, was reduced by low pH on both RL and TC seedlings. As seen on Table 8.3 the response of RL seedlings was consistent under all rhizospherical conditions. These data show that damage by non-aeration was more (high values) at low pH on RL seedlings. Similar results were reported by Ford (1964). The TC, on the other hand, showed some discrepancies in response to both non-aeration and low pH. For example, the low pH resulted in reduced leaf area in aerated seedlings while there was some gain in leaf area in non-aerated seedlings. On the other hand, the low pH resulted in reduced root dry mass, projected root surface area, and RA:LA ratio in non-aerated seedlings while there was some gain in these parameters in the aerated seedlings at the same pH. Moreover, it was found that an excess decline of plant parameters in non-aerated seedlings coincided with some higher gains in aerated seedlings. The various response shown by these two types of citrus rootstocks probably reflects different defence mechanisms of RL and TC growing under unfavourable rhizospherical conditions.

The negative effects of non-aeration on plant growth and development necessitated some further investigation into the possible causes of poor performance of seedlings under such conditions. The investigation on the possibility of poor nutrient uptake as a result of anaerobic conditions was the main aim in the next experiment.

CHAPTER 9

EFFECTS OF AERATION AND NON-AERATION ON NUTRIENT STATUS OF TROYER CITRANGE SEEDLINGS

9.1 Introduction

Anaerobic conditions in the rhizosphere with the associated changes in pH and redox potential cause an alteration to the mineral constituents and chemical processes (Rowe & Beardsell, 1973). The decline in growth of fruit trees under waterlogged conditions is undoubtedly largely due to the reduction of nutrient and water uptake by roots subjected to oxygen deficiency.

Concentration of nutrients, alone, in various parts of plants does not always present a precise evaluation of the nutrient status in plants (Labanauskas, et al., 1971). Reduction or increase in nutrient concentrations in plant tissues may be positively or negatively correlated with total dry mass produced. Labanauskas et al. (1971) found that inadequate aeration of the soil reduces the rate of passive water movement through a root system. They further concluded that as a result of slower water movement into the plant, the uptake of certain nutrients may diminish. This study was undertaken in order to determine the effects of poor aeration of the rhizosphere on growth of young TC, uptake of nutrient elements, the possibility of a dilution factor on plant nutrient status, and on the morphological and physiological changes in plant parameters.

9.2 Materials and Treatments

Troyer citrange seed was germinated in vermiculite growing medium on August 7, 1992. Seedlings were irrigated with deionized water every morning and fertigated with Hoagland's solution once a week. The seedlings were transplanted into aerated and non-aerated nutrient solution on November 2, 1992 and harvested on February 24, 1993 after 135 days. The Hoagland's solution was changed every two weeks. The pH of the nutrient solution was adjusted to pH 6 with dilute NaOH or HCl solutions every week. There were 21 replications for each treatment. Only five representative replications were randomly selected from each treatment for post harvest observations, and three replications for leaf tissue analysis.

9.3 Results and Discussion

9.3.1 Plant Growth and Development

The height of both aerated and non-aerated TC seedlings was the same during the first six weeks after transplanting (Figure 9.1). From the fourth week onwards, the aerated seedlings started growing faster than the non-aerated ones, reaching a height of 83 cm at the end of the growing season while the non-aerated seedlings reached 57 cm. Anoxic conditions had reduced the plant height by 31% at the end of the growing season.

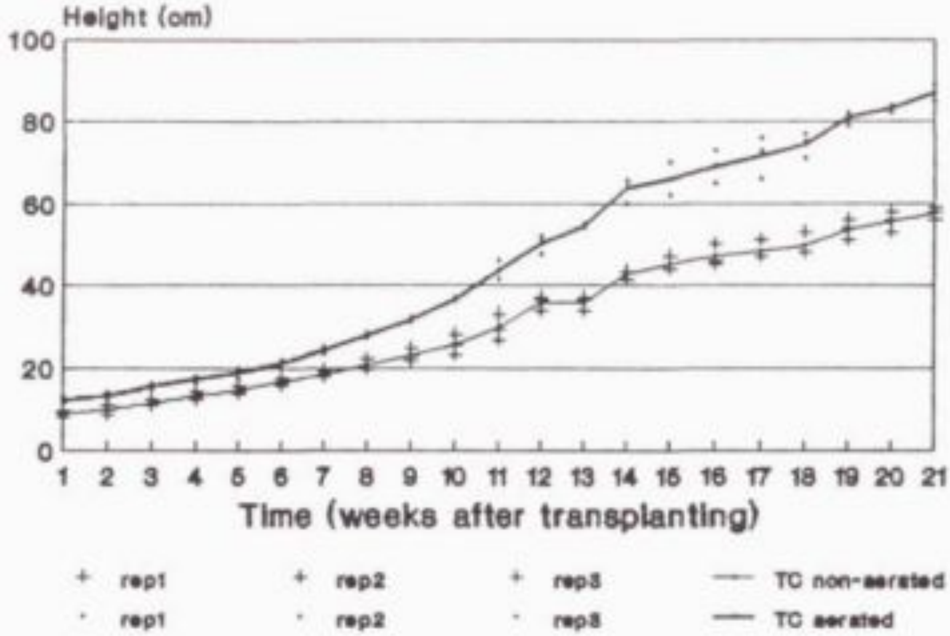


Fig. 9.1. Height of TC in aerated and non-aerated nutrient solution at pH 6.

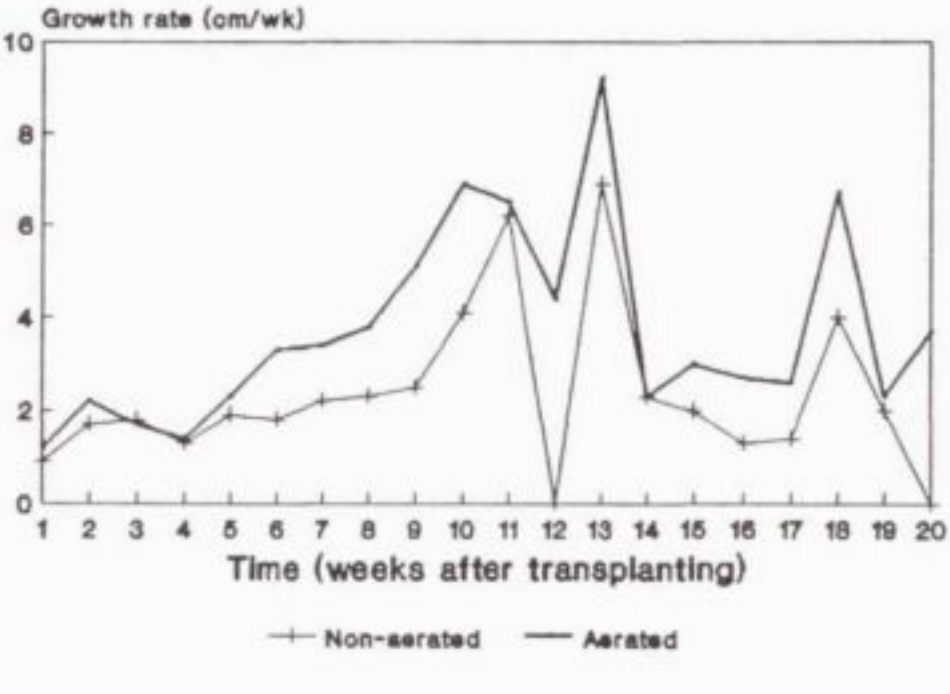


Fig. 9.2. Growth rate of TC in aerated and non-aerated nutrient solution.

9.3.2 Morphological and Physiological Plant Responses

The total dry mass of non-aerated TC seedlings was statistically significantly reduced by 44% compared to aerated plants (Table 9.1)(For statistical analyses, refer to Appendices 9.1 to 9.9). Both the top and the root dry mass accumulation in non-aerated nutrient solution were statistically significantly reduced by 43 and 47%, respectively. This was due, in part, to excess defoliation that occurred in non-aerated seedlings which may have led to less accumulation of photosynthates. The top:root ratio was not significantly different between aerated and non-aerated TC seedlings.

Table 9.1. Effects of aeration and non-aeration of nutrient solution on dry mass accumulation of young TC rootstock

Treatment	Total dry mass (g)	Top dry mass (g)	Root dry mass (g)	Top:root ratio
	11.95	8.41	3.54	2.38
	11.28	7.89	3.39	2.33
Aerated	15.39	12.08	3.31	3.65
	13.22	8.03	5.19	1.55
	14.52	9.96	4.56	2.18
mean	**13.27**	**9.27**	**4.00**	**2.42**
S.E.	0.77	0.79	0.37	0.34
	9.27	6.59	2.68	2.46
	7.58	5.89	1.69	3.49
Non-aerated	8.04	5.77	2.27	2.54
	6.19	4.00	2.19	1.83
	6.01	4.17	1.84	2.27
mean	**7.42**	**5.28**	**2.13**	**2.52**
S.E.	0.61	0.51	0.17	0.27
LSD	1.59	1.54	0.67	1.01

Table 9.2. Effects of aeration and non-aeration of nutrient solution on morphological and physiological parameters of young TC rootstock

Treatment	Leaf area (cm^2)	Root area (calculated)*	RA:RM (cm^2/g)	RA:LA ratio	R.H.C ($x10^{-5}$)**
	363.4	237.2	66.9	0.653	0.812
	341.1	303.7	85.6	0.889	0.194
Aerated	313.3	242.0	73.1	0.772	0.812
	548.7	367.0	70.7	0.669	0.516
	485.4	299.2	65.6	0.616	0.274
mean	**410.4**	**289.8**	**72.5**	**0.720**	**0.522**
S.E.	45.4	23.7	3.6	0.050	0.130
	285.2	212.9	79.4	0.748	0.162
	358.8	191.6	113.4	0.534	0.169
Non-aerated	287.7	185.3	81.6	0.644	0.280
	176.1	186.6	85.2	1.059	0.251
	185.4	172.0	93.5	0.927	0.236
mean	**258.6**	**189.7**	**89.1**	**0.782**	**0.220**
S.E.	34.5	6.7	6.2	0.095	0.023
LSD	92.9	40.2	11.6	0.174	0.210

* the projected root area was measured with area meter and multiplied by pi (3.141593) to correct for surface area.

RA:RM - root area to root mass ratio.

RA:LA - root area to leaf area ratio.

** root hydraulic conductivity ($cm^3.cm^{-2}.Pa^{-1}s^{-1}$).

The leaf area and projected root surface area were statistically significantly reduced by non-aeration treatment (Table 9.2). No significant difference was found in root area:leaf area ratio between the aerated and non-aerated seedlings. Non-aeration of young TC resulted in a statistically significant reduction of root hydraulic conductivity by more than 50%. Several factors, such as the reduced root system in anaerobic conditions, reduced number of root hairs, and a possible collapse of root water-conducting tissue may have led to a decline in root hydraulic conductivity of non-aerated plants.

Table 9.3 shows a relative decline of some morphological and physiological plant parameters as a result of anaerobic conditions in the rhizosphere of TC seedlings. The root hydraulic conductivity was the most negatively affected plant parameter. Both the root mass and the root volume were also among the most negatively affected plant parameters. The total plant mass, top mass, and the leaf area were the least affected. This indicates that aeration and non-aeration of the rhizosphere have a greater effect on the root system of TC seedlings than on the top growth.

Table 9.3. Relative decline of the morphological and physiological plant parameters in young TC plants as a result of non-aeration of nutrient solution

Plant parameter	Relative decline (%)
Total mass (g)	34.8 (4)
Top mass (g)	34.5 (5)
Leaf area (cm^2)	31.1 (6)
Root area (cm^2)	34.5 (5)
Root mass (g)	35.6 (2)
Root volume (cm^3)	35.1 (3)
Root H.C. ($cm^3.cm^{-2}.Pa^{-1}.s^{-1}$)	57.9 (1)

The number in parenthesis indicates the ranking of each parameter as a result of the non-aeration effect.

9.3.3 Nutrient Status of Leaves

The concentration of most nutrient elements was not significantly affected by aeration and non-aeration of the nutrient solution (Table 9.4). For example, the N, P, K, Na, Fe, Mn, and Ca concentration and K:Ca ratio were not significantly affected by the treatments (For statistical analyses, refer to Appendices 9.10 to 9.33). This differs from the results of Hopkins et al. (1950) where the accumulation of major nutrient elements was dependent upon oxygen supply to roots. In this study, however, Mg concentration and K:(Ca+Mg) ratio were statistically significantly higher in seedlings grown in non-aerated nutrient solution. On the other hand, Ca:Mg ratio and Zn concentration were statistically significantly higher in seedlings grown in aerated nutrient solution. The data indicate the possibility of the occurrence of a dilution factor which led to low concentration of nutrient elements in relatively bigger than in smaller seedlings. This was confirmed by the data for nutrient uptake (Table 9.5).

Table 9.4. Nutrient status of young TC seedlings sampled 140 days after aeration (AE) and non-aeration (NAE) treatments

Treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)	Ca:Mg ratio	K:Mg ratio
AE	3.96	0.34	3.16	2.65	0.24	11.04	13.17
AE	2.23	0.28	3.19	3.08	0.23	13.39	13.87
AE	3.77	0.36	2.81	2.97	0.23	12.91	12.22
mean	**3.32**	**0.33**	**3.05**	**2.90**	**0.23**	**12.45**	**13.09**
S.E.	0.55	0.02	0.12	0.13	0.003	0.72	0.48
NAE	3.74	0.35	3.04	2.68	0.24	11.17	12.67
NAE	3.50	0.32	3.44	2.86	0.26	11.00	13.23
NAE	3.29	0.35	3.00	2.58	0.28	9.21	10.71
mean	**3.51**	**0.34**	**3.16**	**2.71**	**0.26**	**10.46**	**12.20**
S.E.	0.13	0.01	0.14	0.08	0.01	0.63	0.76
LSD	1.11	0.05	0.37	0.30	0.02	1.87	6.77

	Na (%)	K:Ca ratio	K:(Ca+Mg) ratio	Fe (ppm)	Mn (ppm)	Cu (ppm)	Zn (ppm)
AE	0.06	1.19	1.09	159	1035	10.0	33.0
AE	0.04	1.04	0.96	201	1244	0.0	22.5
AE	0.04	0.95	0.88	180	1346	0.0	12.0
mean	**0.05**	**1.06**	**0.98**	**180**	**1208**	**3.3**	**22.5**
S.E.	0.01	0.07	0.06	12	92	3.3	6.1
NAE	0.08	1.13	1.04	244	1274	1.5	7.5
NAE	0.05	1.20	1.10	328	1604	6.0	0.0
NAE	0.05	1.16	1.05	234	1311	3.0	1.5
mean	**0.06**	**1.16**	**1.06**	**269**	**1396**	**3.5**	**3.0**
S.E.	0.01	0.02	0.02	30	104	1.3	2.3
LSD	0.02	0.14	0.13	63	273	7.0	12.7

The aeration of young TC seedlings did not only increase the dry mass accumulation but also the uptake of nutrient elements. For example, the content of all the nutrient elements except Cu and Fe was statistically significantly higher in aerated than in non-aerated seedlings when expressed on a shoot basis (Table 9.5). According to Schaffer, Andersen & Ploets (1992), reduced nutrient uptake under anaerobic conditions could be attributed to several factors including mortality, reduction in root respiration, water uptake and root hydraulic conductivity. As Rowe & Beardsell (1973) concluded, high carbon dioxide, which is common in poorly aerated rhizospherical conditions, does not have a direct toxic effect on root growth but possibly reduce the translocation of both nutrients and metabolites in the plant. This, together with the dilution factor concept, explains the disagreement often encountered in nutrient studies and the effect of environmental conditions on the nutrient status of plants.

Table 9.5. Nutrient content per top of TC seedlings grown in aerated (AE) and non-aerated (NAE) nutrient solution for 140 days

Treatment	N (mg)	P (mg)	K (mg)	Ca (mg)	Mg (mg)	Na (mg)	Fe (mg)	Mn (mg)	Zn (mg)
AE	333	28.6	266	223	20.2	5.0	1.3	8.7	0.28
AE	269	33.8	385	372	27.8	4.8	2.4	15.0	0.27
AE	376	35.9	280	296	22.9	4.0	1.8	13.4	0.12
mean	**326**	**32.8**	**310**	**297**	**23.6**	**4.6**	**1.8**	**12.4**	**0.22**
S.E.	31	2.2	38	43	2.2	0.3	0.3	1.9	0.05
NAE	247	23.1	200	177	15.8	5.3	1.6	8.4	0.05
NAE	206	18.8	203	169	15.3	2.9	1.9	9.4	0.00
NAE	190	20.2	173	149	16.2	2.9	1.4	7.6	0.01
mean	**214**	**20.7**	**192**	**165**	**15.8**	**3.7**	**1.6**	**8.5**	**0.02**
S.E.	17	1.3	10	8	0.3	0.8	0.1	0.5	0.02
LSD	70	4.9	76	86	4.4	1.7	0.7	4.4	0.11

CHAPTER 10

PRELIMINARY FIELD STUDIES INTO THE EFFECTS OF SOIL WATER CONTENT AND SOIL BULK DENSITY ON THE LEAF WATER POTENTIAL OF CITRUS AND INTO PRACTICAL IRRIGATION SCHEDULING

10.1 Introduction

The vegetative development of citrus is closely dependent on the irrigation regime of the trees. As trees reach full size, excessive growth induced by intensive irrigation and fertilization can lead to decreased yields (Shalhevet & Levy, 1990). Scheduling irrigation using the water balance method is widely accepted and practised by irrigation researchers. Although this has been practised for some time, it is not widely used by farmers.

Knowledge of when irrigation is needed and of the likely response of crops to irrigation is desirable for irrigation planners. This helps to estimate the demand for water and to carry out economic analyses of the irrigation process.

Soil physical properties are among the factors that influence the decision-making process in determining when to irrigate. When compacted, certain soils tend to have a low relative water saturation and undergo waterlogging easily. According to Nel & Bennie (1984), the occurrence of areas of irregular and poor growth in citrus orchards in South Africa is commonly a consequence of poorly drained soils.

Recognition of the fact that the soil water system is dynamic is of fundamental importance, especially when scheduling irrigation. It is often the rate of water movement within the system that determines whether or not irrigation is necessary. According to Campbell & Campbell (1982), any measure of soil water content is useful mainly as an index of the rate at which water is taken up by plants or lost from the root zone. Nel & Bennie (1984) found that poor growth is not always associated with the occurrence of poorly permeable soil layers. A given soil water content is therefore most useful in conjunction with other information about the soil-water-plant-atmosphere system.

According to Reginato & Howe (1985), the purpose of irrigation is to maximize the leaf water potential. Irrigation increases leaf water potential by increasing soil water potential or by decreasing the resistance to the flow of water from the soil to the plant. Neither the soil water status nor the atmospheric demand accurately represents the plant water status, for the plant integrates its total environment. Only by measuring appropriate plant parameters can one evaluate a plant general condition and, using that information, decide when to irrigation.

The purpose of the first study was to determine the effect of soil physical properties and excess soil water content on citrus. The leaf water potential was used as an indicator of the adequate/optimum and excess water in the wet range of profile available water (PAW) in the soil. The second study was an evaluation of a practical irrigation scheduling programme which was designed by members of the project team.

10.2 Field Study on the Effects of Soil Physical Properties and Water Content

10.2.1 Materials and Method

The experiment was conducted at Moosrivier citrus farm during January and February 1993. Two types of soil, Hutton and Sterkspruit forms (Soil Classification Working Group, 1991), were selected on the basis of their different physical characteristics. The dry bulk densities of the soils (undisturbed), measured at 30 cm depth, were 1510 and 1680 $kg.m^{-3}$ for the Hutton and Sterkspruit soils, respectively. Washington Navels on RL rootstock is grown on both soils and the trees were 33 years old.

The field-determined field capacity was measured for each soil, using a double ring method (Boedt & Laker, 1985). A neutron hydroprobe access-tube was installed in the centre of the irrigation basin. The basin was then flooded with water and covered with plastic in order to prevent the drying of the soil surface. A tensiometer was also placed close to the access-tube to a depth of 30 cm. Soil water measurements were taken over three days. The soil water content 72 hours after flooding the basin was considered to represent field capacity since there was minimal change in soil water content thereafter.

Each irrigation plot consisted of three carefully selected healthy trees in a row, with the middle tree representing the sample and the two other trees used as borders. An irrigation basin was constructed with soil around each plot. A watering tank and tractor were used to supply water to experimental plots.

In each soil type the water level was maintained at either field capacity (adequate water) or above field capacity (excess water) during the experimental period. The levels of water treatment were aimed at keeping the air-filled porosity of the soil at or below 10% and 23% for the Sterkspruit and Hutton soils, respectively. Each treatment was replicated three times.

A Scholander-type pressure chamber (Vanassche & Laker, 1989) was used for leaf water potential (LWP) measurements. The leaf samples were covered with aluminium foil 24 hours before sampling and the first LWP measurements started about three days after irrigation (All the plots were irrigated on a Friday and the first pre-dawn leaf water potential measurements were taken the following Monday). Three leaves (inside the canopy) were sampled from each plot four times a day: at pre-dawn, 09H00, 13H00, and 15H30. During sampling, the leaves were placed in polyethylene bags to minimize transpiration while bringing them to the laboratory.

The aluminium foil was removed just before the LWP was measured. The stem-end of the leaf was cut and exposed above the pressure chamber. The pressure was gradually increased in the chamber until the midrib started to exude some small bubbles. The reading on the pressure gauge was then recorded.

10.2.2 Results and Discussion

10.2.2.1 Soil Water Content

The field capacities of the Sterkspruit and Hutton soils were found to be 28 and 20%, respectively, at soil water potentials of -34 and -18 kPa respectively for the two soils (Figure 10.1). Figures 10.2 and 10.3 illustrate the water content of Sterkspruit and Hutton soils (respectively) at moderate and excess-water treatment levels. Eight millimetres of water was applied to reduce the air-filled porosity of Sterkspruit soil profile to 5% in the excess-water treatment. At field capacity the air-filled porosity of this soil was 10%. On the other hand, 19 mm water was applied to Hutton soil to saturate the soil profile. As a result of the high drainage capacity of this soil profile, the water drained through the soil and it was impossible to keep the air-filled porosity below 10% in this soil. The air-filled porosity of the Hutton soil at field capacity was 23%, while that of excess-water treatment was 20%. Aeration was, therefore, never a problem in this soil.

10.2.2.2 Soil Water Potential

The soil water potentials of both adequately and excessively watered Sterkspruit soil was lower than those for the Hutton soil. This indicates that the trees on the Sterkspruit soil may have difficulties to absorb water even at relatively high water saturation levels. Also the magnitude of the difference of soil water potential between adequately and excessively watered Sterkspruit soil was bigger than that of Hutton soil. Nel & Bennie (1984) also found big differences in volumetric water content and air-capacity between soils of the Bontberg and Msinga series at field capacity, even though the dry bulk densities of the soils did not differ. Air-filled porosity has been identified as the primary factor that can be used to explain much of the variation between plants on different soils (Nel & Bennie, 1984). These authors also found that in the Doveton soil series, where the air-filled porosity was continuously less than 15% throughout the profile, the trees were small and root growth was apparently restricted. On the other hand, unrestricted root growth was found on soil of the Bontberg series where the air-filled porosity in the subsoil was above 15%.

10.2.2.3 Leaf Water Potential

Figures 10.4 and 10.5 show the pre-dawn leaf water potential of trees on the Sterkspruit and Hutton soils, respectively. In both soils the leaf water potential of trees on the adequate and excess water treatments on the first day of measurements (three days after treatments were imposed) was equal. This illustrates that it takes several days for mature citrus trees to respond to changes in soil water regime.

From the second day onwards the pre-dawn leaf water potentials differed between the two treatments, with the trees on excess water treatments showing a higher leaf water potential than those on adequate water treatments. This was true for trees on both Sterkspruit and Hutton soils. There were no major differences in leaf water potential between trees on Sterkspruit and Hutton soils at the same level of watering despite the differences in soil water potentials of the two soils. The differences between adequate and excess water treatments were similar for the two soils. For Hutton soil, the difference in pre-dawn LWP values was

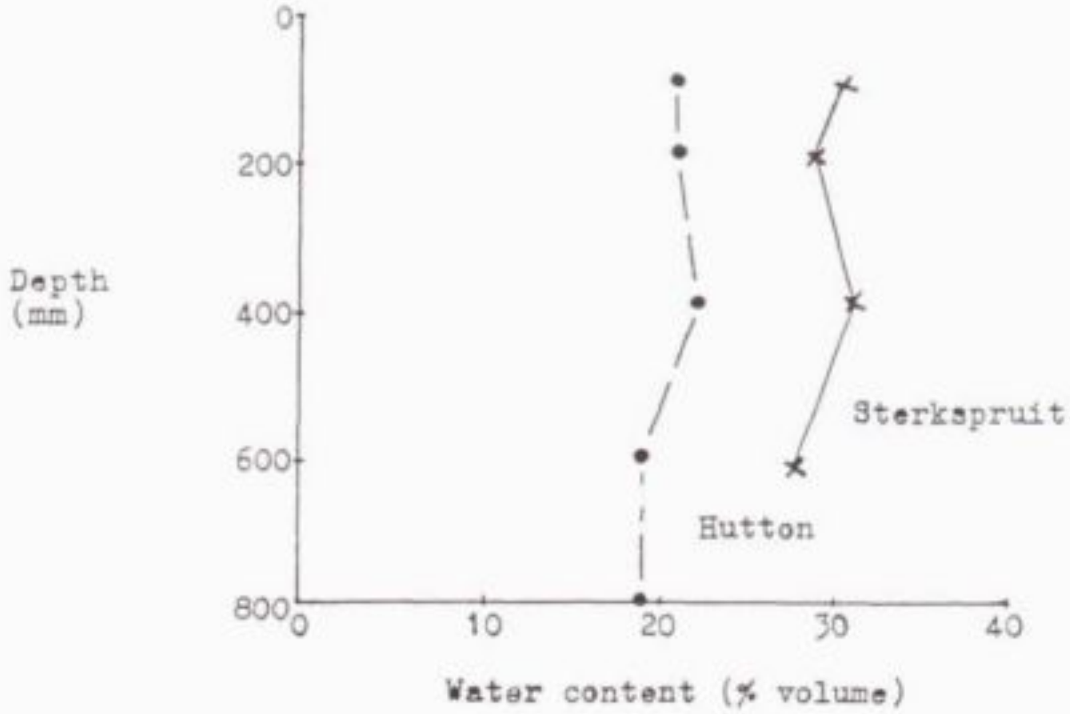


Fig. 10.1. Soil water content of Hutton and Sterkspruit soil profiles at field -determined field capacity.

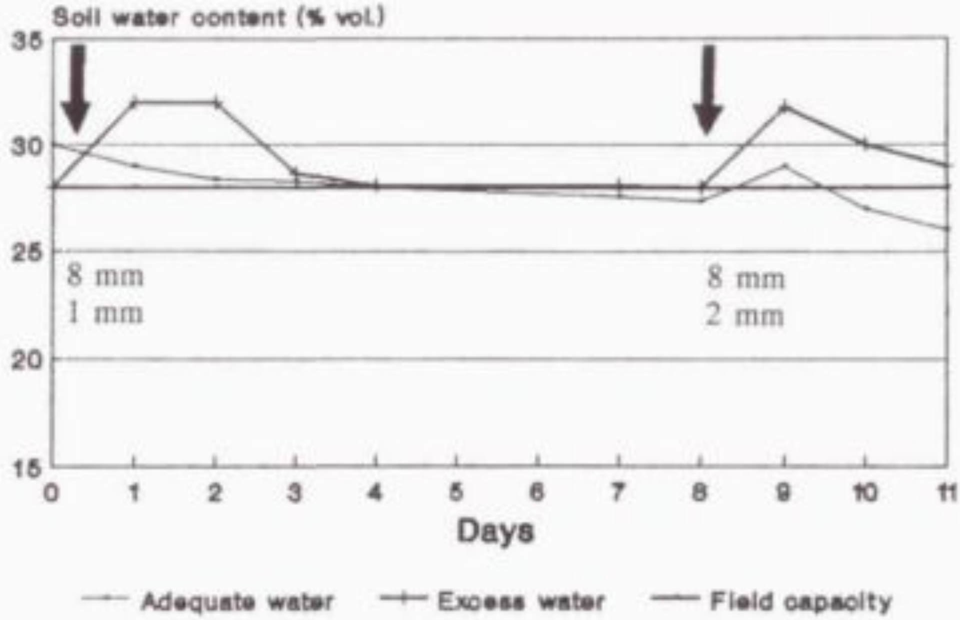


Fig. 10.2. Water content of Sterkspruit soil profile during experimental period.

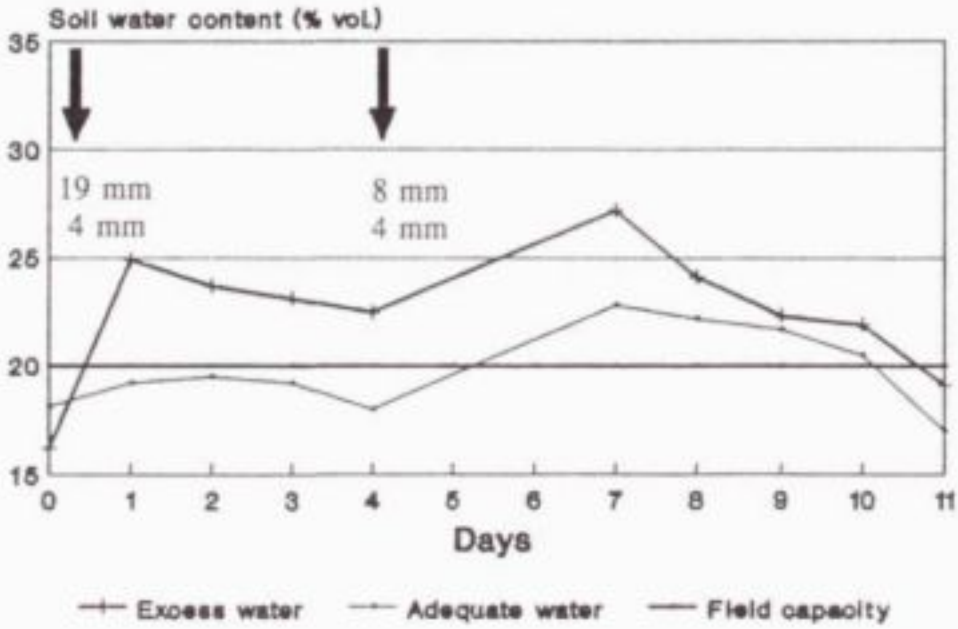


Fig. 10.3. Water content of Hutton soil profile during experimental period.

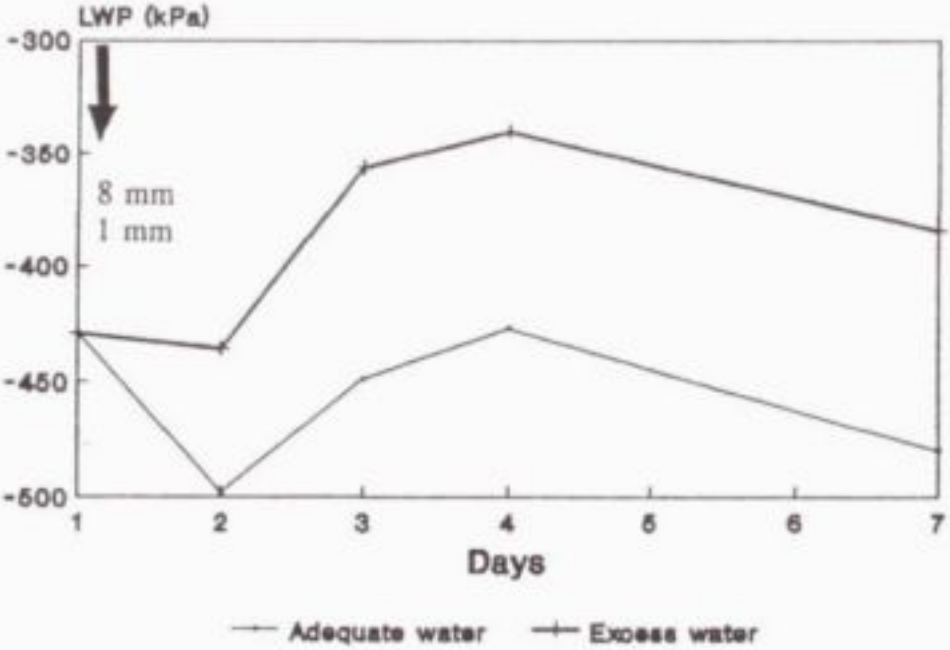


Fig. 10.4. Pre-dawn leaf water potential of citrus in excessively and adequately watered Sterkspruit soil profile.

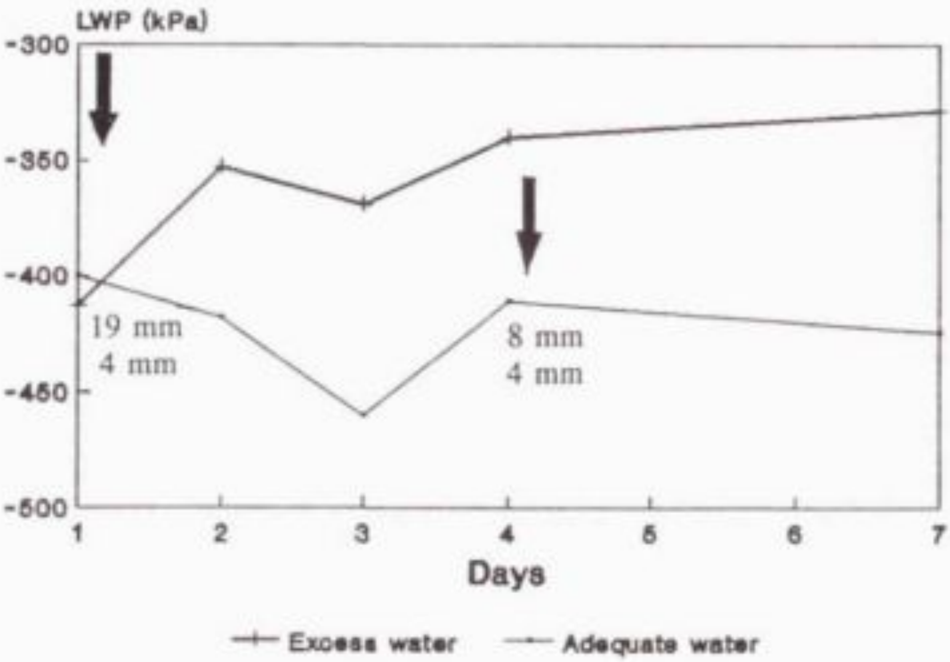


Fig. 10.5. Pre-dawn leaf water potential of citrus in excessively and adequately watered Hutton soil profile.

relatively constant from day 2 onwards. LWP in adequate water treatment may be decreasing after day 4. In Sterkspruit soil, there was a rise in LWP until day 4 and then it dropped gradually.

The magnitude of the difference in LWP between adequate and excess water treatments was constant in both Sterkspruit and Hutton soils at 09H00 (Figures 10.6 and 10.7). The leaves from the excess water treatment had a higher LWP compared to those from the adequate water treatment. When the water was applied in Hutton soil after the fourth day, there was an increase in LWP for both treatments. This was also true for trees on Sterkspruit soil after the eighth day. A similar situation was found on LWP measurements at 13H00 (Figures 10.8 and 10.9). Figure 10.8 shows that the LWP was equal for adequately and excessively watered trees on Sterkspruit soil on the fourth day. This coincided with the time when there was a very strong wind during leaf sampling.

The magnitude of the difference in LWP between adequately and excessively watered trees remained constant even at 15H30 (Appendices 10.1 and 10.2). However, it was not clear whether the trees under excess water conditions had started to respond to waterlogging. Two factors can account for this tree response to water treatments. Firstly, as a result of poor maintenance of excess water in the soil profile (due to practical problems) the duration of anaerobic (low oxygen diffusion rate) stress was probably too short to cause any significant effect on trees and thus leaf water potential. Secondly, the big citrus trees may have a buffering effect on soil water availability such that the duration of waterlogging must be even longer to cause any negative effect on plant condition. This is in agreement with the results of Stolzy et al. (1965a) who found that it is the duration of waterlogging that has a negative impact on citrus development compared to several short waterlogging episodes.

10.3 Practical Irrigation Scheduling Evaluation

10.3.1 General

The ultimate test for any research on irrigation scheduling is whether it can be applied successfully under practical farming circumstances. Due to the relatively long time needed to sort out the newly developed Pero system and to conduct the subsequent pot and preliminary field experiments, there was insufficient time left to conduct a comprehensive, statistically designed practical irrigation scheduling evaluation.

Fortunately, the management at Moosrivier estate approached the project team to advise them in regard to the purchasing of a neutron hydroprobe and its implementation in irrigation scheduling in their citrus orchards. Up to that time, irrigation scheduling at Moosrivier was fixed, with specific volumes of water being applied at fixed time intervals.

Irrigation scheduling based on soil water monitoring is a well-established technology. This is especially the case with field crops (agronomic crops), where water is often extracted to soil water potentials which are far too low for tensiometers to handle. In the case of horticultural crops, such as fruit, soil water contents are usually managed within narrow high soil water potential limits and tensiometers are predominantly used for irrigation scheduling.

The big difference between the neutron hydroprobe and other methods used for irrigation

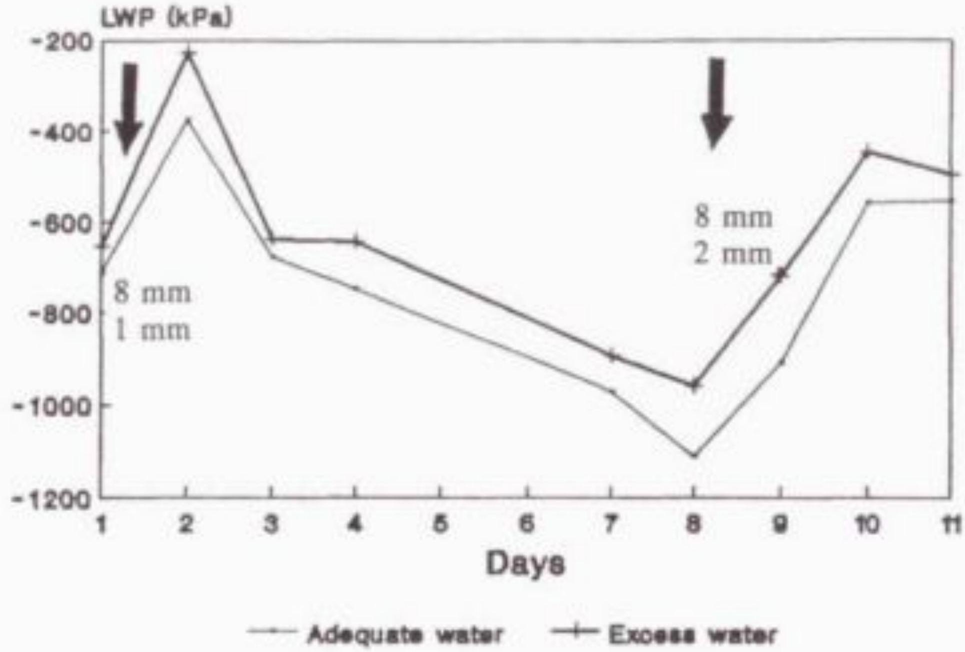


Fig. 10.6. Leaf water potential of citrus in excessively and adequately watered Sterkspruit soil profile at 09H00.

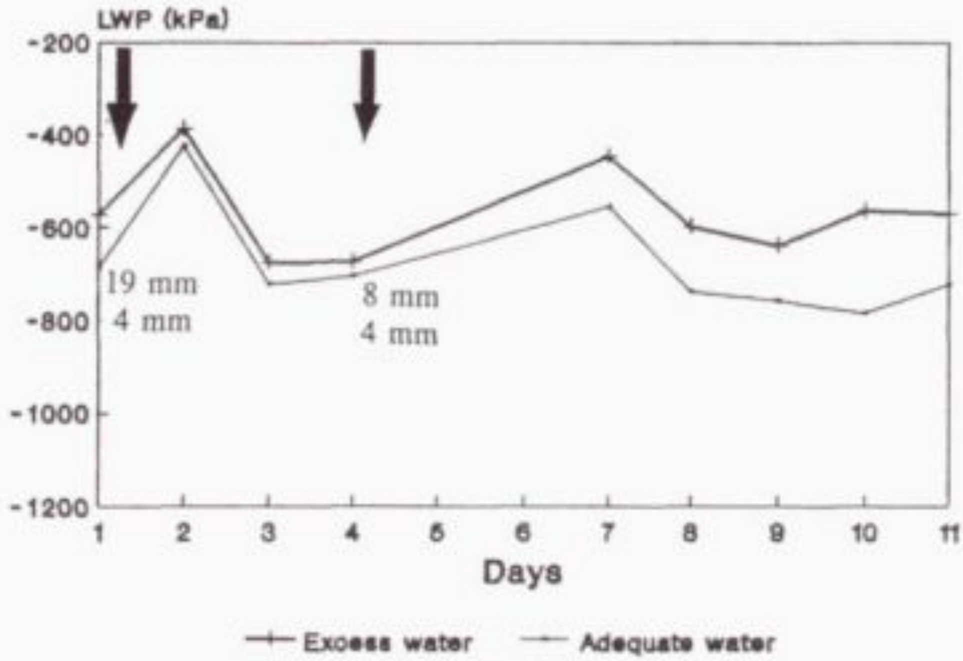


Fig. 10.7. Leaf water potential of citrus in excessively and adequately watered Hutton soil profile at 09H00.

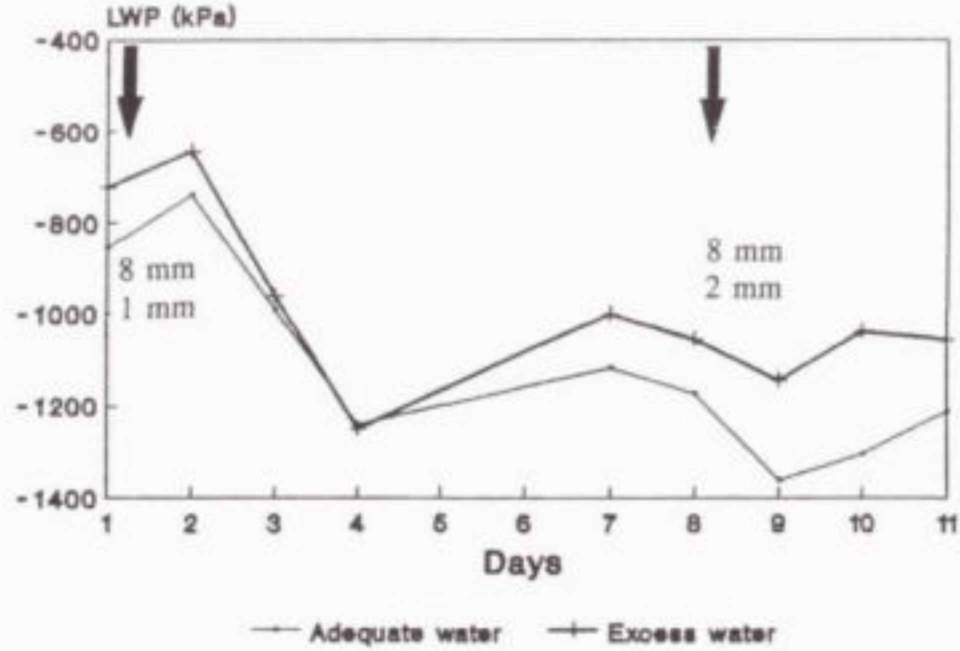


Fig. 10.8. Leaf water potential of citrus in excessively and adequately watered Sterkspruit soil profile at 13H00.

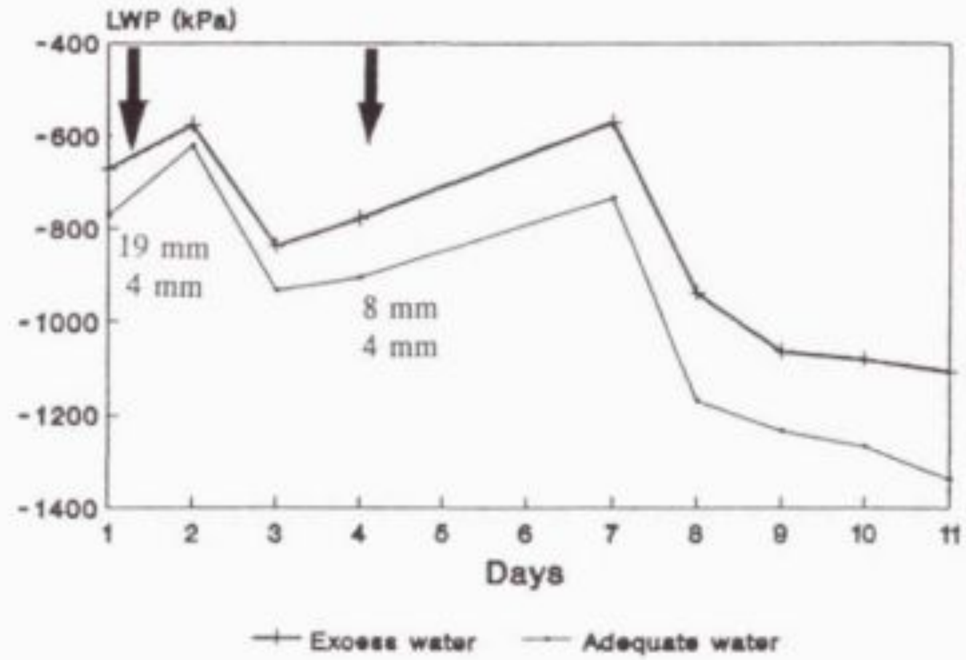


Fig. 10.9. Leaf water potential of citrus in excessively and adequately watered Hutton soil profile at 13H00.

scheduling is that with the neutron hydroprobe the actual amount of water that is extracted from the **whole root zone** is always measured, while with other methods, e.g. tensiometers or climate based crop factors, this is not the case.

The critical parameters for successful application of scheduling by means of neutron hydroprobes are the upper and lower limits that are used to indicate plant-available water in the soil profile. The previous chapters in this report aimed at determining these, especially suitable upper limits, for citrus. The work reported here would hopefully give some preliminary indication of the practical applicability of these.

It is, furthermore, important to record the data in such a way that it is easy for the irrigation farmer/manager to decide when to irrigate (and how much water to apply). Both Utah State University (USU) at Logan and the United States Bureau of Reclamation (USBR) developed simple graphical methods for this (Laker, 1983). The upper and the lower limits of plant-available water in the soil profile are indicated by horizontal lines on these graphs, which have date on the x-axis and water content on the y-axis. Figure 10.10 is a real example of one such graph for a field on a farm in Utah that followed the programme of Hill (Laker, 1983). In this programme the university provides the expertise (determining the upper and lower limits of soil water to be used) and neutron hydroprobe, the Soil Conservation Services (SCS) provides a technician (who records the soil water content readings) and a vehicle, and the farmer pays a certain amount per year per neutron hydroprobe access tube. All the farmer has to do, is to ensure that the recorded soil water content line does not go below the horizontal lower limit line and applies just enough water to bring the water content to the upper limit line. Instead of plotting the information manually on a graph, it could be fed into a computer. Carter and Conway at the USBR pointed out that plotting soil moisture content versus time on a graph provides a visual means for forecasting the date of the next irrigation (Laker, 1983). Rasmussen at USU in Logan indicated that the success of this type of system can be ascribed to the fact that farmers believe it because they see the readings (Laker, 1983).

It was decided to use such graphic display of soil water content versus time as indication to the managers at Moosrivier of when to irrigate and how much water to apply.

10.3.2 Field Data

The neutron hydroprobe scheduling was introduced in a number of citrus orchards at Moosrivier citrus estate. Soil water contents at field capacity, permanent wilting point and -20 and -50 kPa soil water potentials were determined by members of the project team. Based on the results of the previous work, it was decided to use the water content at -20 kPa soil water potential as upper limit and a value somewhat higher than that at -50 kPa as lower limit. (Since the results of the basic studies showed that -50 kPa was somewhat too dry).

The irrigation managers could not apply the irrigation scheduling before members of the project team calibrated the neutron hydroprobe for the different soils used. It is very important to note that the factory calibrations cannot be simply used, as was indicated by Boedt & Laker (1985) and Vanassche & Laker (1989).

After the upper and lower limits for soil water were determined and the neutron hydroprobe

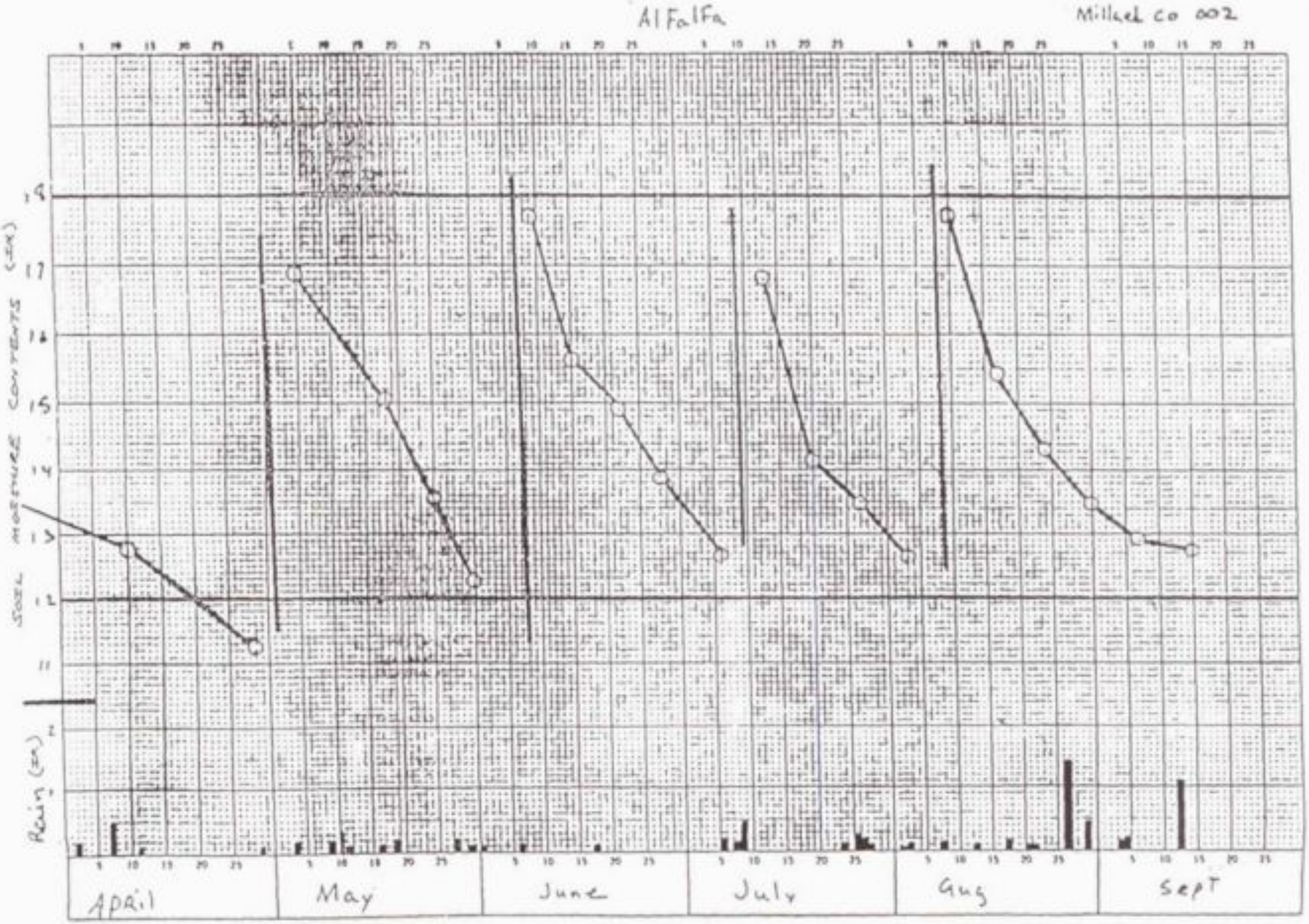


Fig. 10.10. Example of an irrigation scheduling graph, based on neutron hydroprobe monitoring, from the programme of Hill at USU, Logan (From Laker, 1983).

was calibrated for the soils, the irrigation managers successfully implemented the scheduling programme. They also kept accurate records, which enabled analysis of the results of the programme. Members of the project team were at no stage involved in the management of the programme or the recording of field data.

The records of soil water content for one orchard are given in Figures 10.11 and 10.12 in order to indicate how the soil water content was regulated during the irrigation scheduling. Figure 10.11 indicates the various soil water content lines that were determined beforehand, whereas Figure 10.12 indicates only the upper and lower limits between which the irrigation managers had to keep the soil water content.

The dry bulk density of this soil profile was 1646 $kg.m^{-3}$ for the top 30 cm, 1589 $kg.m^{-3}$ for the 30 - 60 cm layer and 1626 $kg.m^{-3}$ for the layers below 60 cm. This soil profile had less clay than the Sterkspruit soil but more than the Hutton soil used in the previous experiment. Both Washington Navels and Valencias growing on this soil were 30 years old (i.e. mature trees in full bearing).

It should be noted that the soil was initially too dry and that it took about 18 days to bring the soil water content to the desired level (Figure 10.12).

The scheduling programme started at the beginning of February 1993. At the end of August 1993 (i.e. after seven months) the following statistics were provided to the project team by the irrigation managers at the estate:

* Previously the relatively clayey soils were irrigated at fixed 7-day intervals and sandy soils at 3-day intervals. Since the introduction of the soil water monitoring, the intervals between irrigations became longer, even up to as long as 14 days at times.

* The irrigation scheduling programme resulted in a saving of 24% on water and pumping costs. The water saving over the 7-month period was 1.8 million m^3. Moreover, a saving of 12% on labour costs was attained. This was mainly due to the fact that since March 1993 no irrigations were applied during weekends, whereas before the programme was introduced irrigations were applied every weekend. The total saving on pumping and labour costs over the 7-month period amounted to R600 000.

* Although a yield decrease was expected as a result of the hot, dry conditions prevailing during the specific season, the yield of Washington Navels increased by 12% over the previous season and that of Valencias by 38%. The quality of the fruit was also better. All other farms in the area recorded yield decreases during this season.

* The condition of the trees improved visibly during the period and indications were that the following season would be an excellent one.

It should be kept in mind that these results were not obtained with statistically designed comparative experiments. Yield reactions are never expected so soon after introduction of new treatments in a perennial orchard crop. All that could be stated with certainty

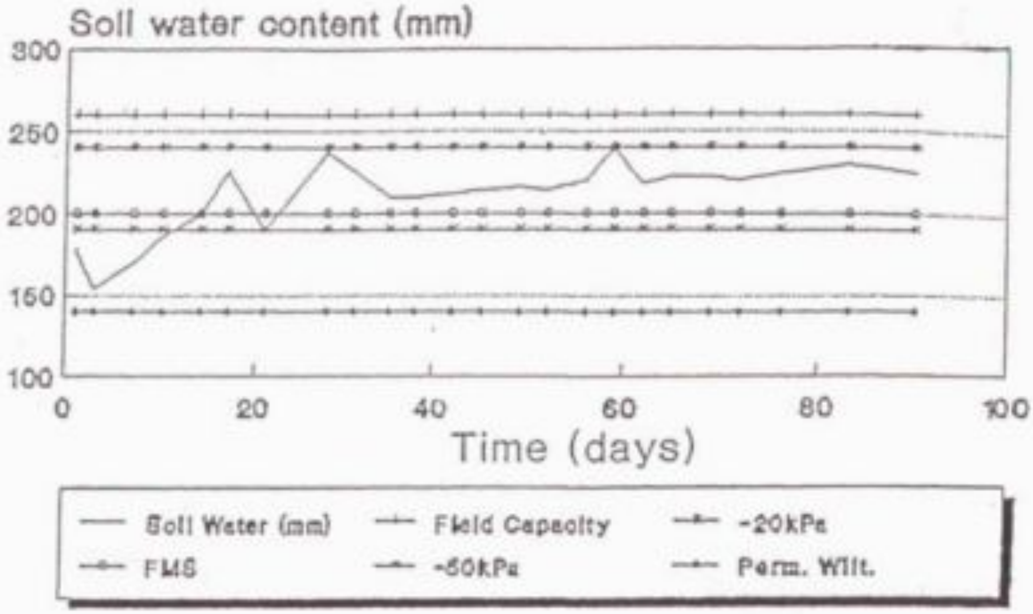


Fig. 10.11. Soil water contents at different soil water constants and soil water potentials for a citrus orchard soil at Moosrivier.

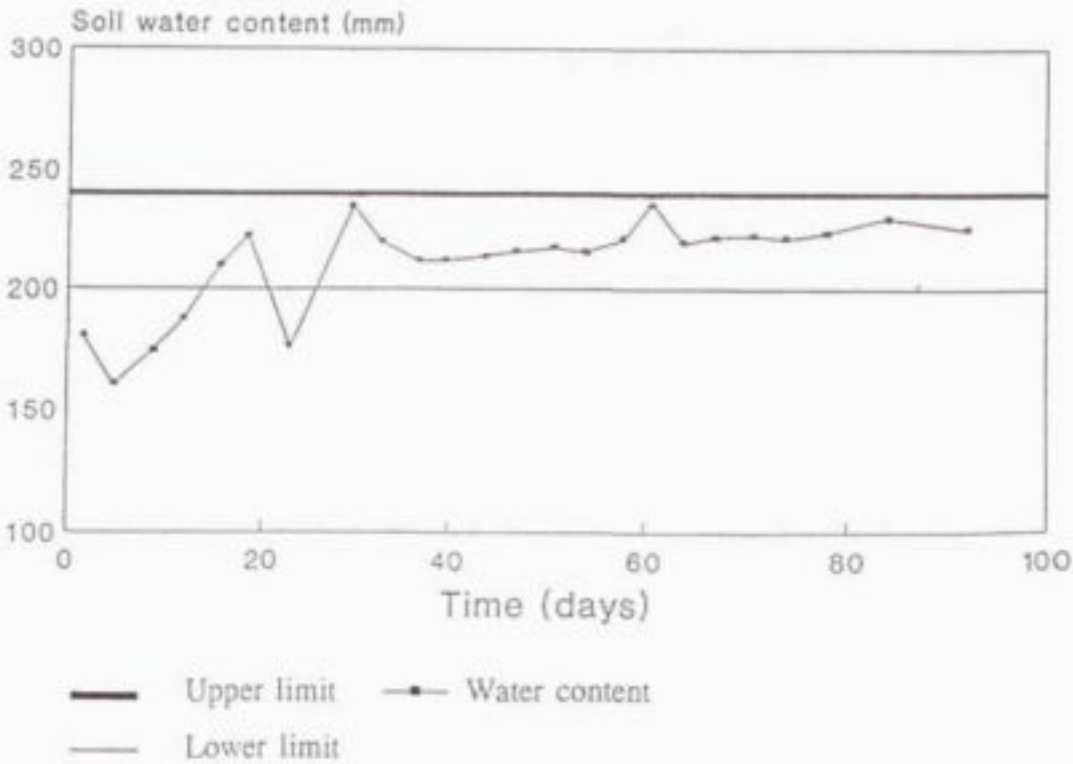


Fig. 10.12. Water status of a soil profile in a Moosrivier citrus orchard relative to the recommended upper and lower limits.

at that stage was that significant savings in terms of water and in pumping and labour costs were achieved.

After a visit to Moosrivier at the end of September 1994 and discussions with the estate managers and local extension officer, Annandale (1994) reported the following:

> During 1994 the savings on pumping and labour costs, and on water, persisted. Citrus yields were higher by 50% and fruit quality was much higher, much better prices consequently being fetched for the fruit.

Again, it must be emphasized that these results were not verified by controlled comparative experiments. The indications are so promising that such experimentation would seem justified in future.

10.3.3 Opportunities

On an estate like Moosrivier where additional land is apparently available and water is the limiting factor, the possibility to irrigate additional areas with the water that is saved is an even much greater opportunity benefit than the additional income from existing groves (Annandale, 1994).

In other areas of South Africa where limited water supplies may lead to conflicts between irrigation estates and rural communities, such water savings may help to avoid/resolve conflicts and have large socio-economic benefits. Rasmussen (Laker, 1983) indicated that because water is so cheap in the USA the experience has shown that it is impossible to convince farmers to save water simply for the sake of saving water. He pointed out that experience has shown that where farmers can see the financial benefits from saving water (e.g. reduced pumping costs, increased yields, improved crop quality, additional production opportunities) they will respond positively and in the process save water because of that.

10.3.4 Problems and Threats

Successful implementation of neutron-probe based irrigation scheduling is dependent on a sound knowledge of how to do it and its correct application. In the trial run it was, for example, necessary for the project team to do the calibration of the neutron probe for each soil. The team also drafted the basic graphs on which the data had to be plotted. This is also the way that Hill operated in Utah (Laker, 1983).

Furthermore, experts have to remain continuously and more closely involved to supervise the correct running of such a system. In the Moosrivier case this could not be maintained since the project team was disbanded when the research project ended at the end of 1993. Moreover, the manager at Moosrivier who was involved with the original implementation of the system together with the project team, has also left the estate. There is serious concern that lack of understanding of the system and especially lack of expert support may impact negatively on its success in future (Annandale, 1994). This will not only have negative economic impacts for such an estate, but may hamper further implementation of such system - with its concomitant benefits - elsewhere.

10.4 Conclusions

The results illustrate that different soils should be treated differently in regard to optimum soil water content/potential for irrigation scheduling. For example, at field capacity, the tensiometer reading for the Sterkspruit soil was -34 kPa while that of the Hutton soil was -18 kPa. If, for instance, -18 kPa was used to represent a "constant" lower limit (at which irrigation water is applied everytime the soil water potential drops below this level) for both soils irrespective of their different physical properties, it would lead to waterlogging in the Sterkspruit soil.

At field capacity, the air-filled porosity of the Sterkspruit soil was 10.5%, which is less than half that of the Hutton soil (23%). This indicates the significance of relative water saturation of the soil as a component in irrigation scheduling. Soil compaction, being the main cause of a "shift" in relative water saturation of the soil, deserves more attention than in the past where the approach was "when" and "how much" water to apply. With new irrigation techniques being used in irrigated agriculture, especially in South Africa, the approach has to be shifted to "specific soil-plant-water-air-disease relationships". This is partly due to the fact that most of these new irrigation techniques maintain high levels of soil water potential and constant air-filled porosity, which was not the case in the past.

Irrigation scheduling based on crop water requirements and water availability in the soil profile may not only result in water savings but also improve the yield and quality of the crop, giving major economic and socio-economic benefits.

CHAPTER 11

CONCLUSIONS AND RECOMMENDATIONS

11.1 Conclusions

The overall objective of this study was to examine the relative effects of soil compaction, high soil water potential, and the availability of air to the roots on the development of young citrus rootstocks. An understanding of the relationships between these production components helps to determine the most appropriate irrigation practices to be followed. Moreover, the improvements in irrigation technology have necessitated a shift in our approach to irrigation requirements of plants. The crucial issue is to identify an appropriate upper limit of soil water content/potential for a specific soil-plant combination.

In order to achieve our objective, different soil dry bulk densities and soil water potentials for sub-optimal and marginal soils were superimposed and their effects on growth and development of Rough lemon (RL) and Troyer citrange (TC) rootstocks were investigated.

In this series of experiments, RL rootstock was found to be very sensitive to soil compaction even at usually recommended soil water potential levels, due to oxygen stress in the rhizosphere. However, this rootstock had an ability to maintain fair top growth under stressful rhizospherical conditions, indicating a high efficiency of its root system. The TC rootstock, on the other hand, did not show stress symptoms in compacted soil, probably due to its slow growth habit. Actually, the seedlings in compacted soil had better root and top growth than those in non-compacted soil. This indicates that TC is suitable for relatively wet and compacted soils while RL is suitable for non-compacted soils. Joubert (1993) found that the greatest negative response to soil compaction occurred at bulk densities between 1500 and 1600 $kg.m^{-3}$ for RL while that of TC occurred at 1400 to 1500 $kg.m^{-3}$. This is in agreement to the poor response of RL in compacted soil and poor response of TC in non-compacted soil at a soil water potential of -6 kPa reported in this study.

It was also found that there are major differences in the severity of compaction-induced stress among various soils and soil water potential levels between different seasons, being more severe during hot periods. Interactions between soil bulk density and soil water potential levels have a great influence on plant development. Moreover, these interactions do not only affect plant growth but also the water use efficiency and the accumulation of nutrient elements in plants. This implies that for every soil-water-plant combination there is no fixed "optimum" level of soil water. Nel & Bennie (1984) arrived at similar conclusions.

In this study, it was found that for most soils when compacted, a -10 kPa soil water potential was stressful. Citrus roots at this soil water potential could not grow well, probably because of the sub-optimal levels of oxygen or as a result of the difficulty in penetrating the compacted soil or both. According to Nel & Bennie (1984), the air capacity was the main factor that led to variation in tree and root growth. However, if the soil was not compacted, relatively high levels of soil water potential, such as -10 kPa, could be maintained with no or minimum negative effects on plant growth and development. There were exceptions to this, especially for TC seedlings in non-compacted soils with low relative water saturation. This was due, in part, to the fact that TC rootstock does not have a vigorous root system which makes it difficult for the roots to satisfy plant water demands, especially shortly after transplanting.

Both RL and TC seedlings are negatively affected by oxygen deficiency in the rhizosphere. In water culture experiments, both the leaf area and the root hydraulic conductivity of these rootstocks were negatively affected by anaerobic conditions. According to Marler & Davies (1990), the shortage of air in the rhizosphere of citrus leads to excess defoliation which results in a reduction of photosynthesizing capacity of the plants. Consequently the plant growth declines. In this study, a reduction in root hydraulic conductivity in non-aerated plants may have resulted in poor uptake of both water and nutrient elements.

The growth pattern of RL rootstock was also affected by soil compaction and soil water potential. When the soil was not compacted, the rootstocks developed gradually and continuously whereas in compacted soil there was an irregular increase in plant height. The stress to which the plants were exposed in compacted soil may have led to poor photosynthesizing ability of the seedlings such that they could only grow once enough photosynthetic reserves were available. Besides irregular growth of seedlings in compacted soil, they tended to form many branches and small-sized leaves which is one of the characteristics of waterlogging stress in many plant species.

The water use efficiency of RL and TC seedlings is largely influenced by both soil compaction and soil water potential. In this study, it was found that although RL seedlings in non-compacted soils were always bigger with increased soil water potential, there is a point beyond which the water use efficiency (WUE) declines. At a given soil water potential, the compaction of soil resulted in a reduction in water use efficiency by RL rootstock compared to non-compacted soil. If a stable clayloam soil was compacted, such as the Hutton soil, an increase or decrease in soil water potential did not change the water use efficiency of citrus seedlings.

The performance of RL rootstock in compacted and non-compacted stable clayloam soil over a range of soil water potential followed a specific trend. As the soil water potential decreased from -10 to -30 kPa, there was a gradual decline in plant performance in non-compacted soil. On the other hand, there was an improvement in plant performance in compacted soil with a decrease in soil water potential from -10 kPa to the point (-30 kPa) where the soil water reached a level that did not allow plant growth. At excessively high soil water potential, the compacted soil undergoes waterlogging due to its high relative water saturation thus limiting the oxygen supply to plant roots. This shows the significance of relative saturation of the soil, which is greatly influenced by soil compaction and macropore volume. The highest tolerable levels of soil water potential (i.e. -10 kPa for non-compacted soil and -20 kPa for most compacted soils) for RL rootstock represent air-filled porosity comparable to the 15% air capacity at field water capacity (FWC) and 10% air-filled porosity reported by Nel & Bennie (1984) and Patt et al. (1966), respectively, as minimum values for citrus growth.

The effects of soil compaction were very similar to those of anaerobic rhizospherical conditions for both RL and TC. In both cases the root system was more negatively affected than top growth

{Compare Table 5.3 (for soil compaction) with Tables 7.3, 8.3 and 9.3 (for non-aeration)}. The data indicate that the root system of citrus was more sensitive to anaerobic conditions which resulted from soil compaction while the top growth was more sensitive to soil water potential.

The results of the field experiment at Moosrivier are not reflective of what would be expected under excessively wet soil conditions. This was partly due to practical problems such as the availability of water on site for recharging the soil profile, a relatively long time that is needed to waterlog (stress) large citrus trees, the possible luxury consumption of water by citrus trees, etc. The highly successful irrigation scheduling trial holds much promise, however.

11.2 Recommendations

The results of this study indicate the necessity that each soil should be characterized carefully and dealt with separately for irrigation scheduling purposes. For light sandy soils that are relatively well-drained, RL is probably the most suitable rootstock while the TC is good for heavy clayey soils which are relatively poorly aerated. When dealing with various orchard soils with different physical characteristics, the following recommendations can minimize the inefficient use of irrigation water under drip and micro-sprinkler irrigation systems.

* When a drip irrigation system is used for water supply, it is necessary to determine the bulk density of the soil and its influence on hydraulic conductivity and distribution pattern of water. When the dry bulk density of the soil exceeds 1700 $kg.m^{-3}$, TC rootstock is recommended especially when the soil is wet and poorly aerated.

* Irrigation scheduling using a conventional method that employs the crop factor and evaporation data from the Weather Bureau Class A pan may not be very useful, especially in clayey soils, since the drip irrigation system does not wet the whole surface area under the drip zone of the tree. It is, therefore, necessary to develop a more reliable method of irrigation scheduling taking into account the hydraulic conductivity and the relative water saturation of the soil, and use these factors as components for the estimation of crop water demand. In their conclusion, Nel & Bennie (1984) stated that when irrigation scheduling is done using Class A pan data, a different crop factor should be used for different soils. An alternative can be the use of tensiometers with a view of keeping the soil water potential lower than the value corresponding to 15% air-filled porosity.

* The argument that trees under drips rely on a very stable water supply and that they can be stressed easily during drought and the fact that trees are prone to wind damage due to poor anchorage resulting from shallow root system has not been tested. Further research that compares both the root distribution under different irrigation systems, relatively light and heavy soils, and the ultimate effect of these on plant performance would be necessary.

Soil compaction resulting from traffic in the orchard (especially during harvest) is likely to cause a "shift" in relative water saturation of the subsoil. Moreover, the use of "constant" values (which is a common practice) such as tensiometer readings for irrigation scheduling on soils with different bulk densities may lead to root disease problems especially when these constant values were developed for relatively light soils. This leads to high incidence of waterlogging in relatively heavy soils. The adjustments on the optimum quantities of irrigation water then become necessary in situations where it is not possible to break the compacted soil layers mechanically. When the soil undergoes compaction as a result of traffic in the grove, it may be necessary to "shift" (lower) the optimum level of soil water content for irrigation purposes. This will allow maintenance of an air-filled porosity that will be optimal for root growth and plant development. According to De Lange, Mohajane, Crosby & Laker (1994), there is a great need to look urgently at real crop water requirements (and supply) under very hot, dry conditions with high evaporative demand. The FAO's CROPWAT (computerized programme for irrigation scheduling) shows that the crop factor (coefficient, f) for citrus is much lower under "hot and dry" conditions than under normal conditions. Failure to take this into account will lead to waterlogging, poor water use efficiency and excessive irrigation system costs. Severe waterlogging of citrus under drip irrigation was also observed during a hot, dry period at an estate in Swaziland as a result of a failure to adjust a crop factor. In the light of the results of the study reported here, this downward adjustment of the crop factor is also necessary under conditions where soil compaction occurs.

The results of this study and those from the work by Joubert (1993)(Appendices AB 1 - AB 5) give a comprehensive picture of what could happen in the citrus grove as a result of soil compaction and relatively high soil water potential. While Joubert (1993) was investigating the relationship between soil compaction and disease (Phytophthora root rot in particular) problems in citrus seedlings, the present study reports on the negative effects of soil compaction and high soil water potential on air-filled porosity and relative water saturation of the soil and their ultimate effects on citrus rootstocks. The water culture experiments also provided additional information on the importance of aeration and pH of the rhizosphere on the development of citrus rootstocks. The data from the present study and those from studies by Bennie (1972), Drew (1992), Joubert (1993), Nel (1981) and Nel & Bennie (1984) indicate that soil compaction and excessively high soil water potential:

1. reduce air-filled porosity of the soil.
2. lead to waterlogging by increasing relative saturation of the soil.

3. impede root growth, physically.
4. predispose root system by reducing root surface area (thick roots).
5. lead to poor uptake of water and nutrient elements.
6. lead to low assimilation and photosynthetic rates.
7. lead to poor energy conversion rate by plants.
8. result in the breakdown of root cell components.
9. increase exudation of sugars by root system.
10. lead to wet soil conditions that are conducive to pathogen activities.
11. result in disease occurrence.

Since anoxic rhizospherical conditions also prohibit initiation of new roots, a decline of citrus in compacted soil results from both a poor root system and root rot diseases. Different citrus types will undergo different morphological and physiological changes in order to tolerate and adapt (defence mechanisms) to stressful rhizospherical conditions.

Further research that will address the problem of soil compaction and a shift in relative water saturation of the soil (Carter & Johnston, 1989) in a real field situation is necessary. This, together with the findings of other related studies, will help to develop irrigation models for adjustments in order to overcome waterlogging problems that result from "shifts" in the optimum levels of irrigation water due to soil compaction. This, in turn, will lead to savings in irrigation water, minimize root rot diseases in citrus, and thus increase net profit.

More field studies, as well as the establishment of expert support systems for practical in-field irrigation scheduling, are required to improve the economics and water use efficiency in citrus production.

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APPENDIX

Summaries from

RELATIONSHIP BETWEEN SOIL COMPACTION AND PHYTOPHTHORA ROOT ROT OF CITRUS

by D. Joubert

(M.Sc dissertation, Department of
Microbiology and Plant Pathology,
University of Pretoria, 1993)

This study by Deon Joubert was conducted concurrently with the research reported here. The project leader of the research reported here (Laker) and one of the team members (Vanassche) played a key role in the technical/scientific planning of the study by Joubert as well as in an advisory capacity throughout his research.

Since the two studies complement each other, the summaries given by Joubert for each of the five chapters in his dissertation are given here verbatim.

It should be noted that Joubert used the suction method of water regulation which was developed for the master's research of A.T.P. Bennie, which was also conducted under the guidance of the project leader of the WRC sponsored project reported here (Laker).

App AB 1

Effect of Phytophthora nicotianae on growth of Rough lemon and Troyer citrange seedlings at different soil bulk densities

The effect of Phytophthora nicotianae on the growth of Rough lemon and Troyer citrange citrus seedlings at increasing levels of soil bulk density (SBD), viz. 1400, 1500, 1600 and 1700 $kg.m^{-3}$ was studied in the greenhouse. At each SBD seedlings were inoculated with P. nicotianae or left uninoculated. Constant moisture levels were maintained in all the treatments. With Rough lemon, the greatest effect on shoot growth was observed between 1500 and 1600 $kg.m^{-3}$ whereas Troyer citrange showed the greatest effect between 1400 and 1500 $kg.m^{-3}$. Similarly, a decrease in root growth occurred with increased SBD with the most marked effect (more than 40% reduction in feeder root length) between 1400 and 1500 $kg.m^{-3}$ for both rootstocks. An increase in SBD also resulted in thicker and shorter feeder roots. P. nicotianae did not have a significant effect on shoot growth of seedlings at any SBD. In comparison with the uninoculated control treatments, P. nicotianae caused an average reduction in feeder root length of 14.6%, 24.5%, 32.5%, and 42.5% at SBD's of 1400, 1500, 1600 and 1700 $kg.m^{-3}$, respectively, for both rootstocks. Despite the reduction in length very little root rot was observed in feeder roots. This can be ascribed to the fact that soil moisture was maintained at a relatively low level. Fresh mass of primary roots were unaffected by P. nicotianae. The data indicate that increasing SBD aggravates the effect of P. nicotianae on citrus roots at constant soil moisture levels even though little root rot was visible. The data furthermore indicate the optimum SBD to be 1400 $kg.m^{-3}$ or less and the optimum penetrometer soil strength (PSS) to be 500 kPa or less.

App AB 2

Effect of subsoil compaction on growth of Rough lemon and Troyer citrange seedlings and on development of Phytophthora root rot

The effect of subsoil compaction on growth and Phytophthora root rot of Rough lemon and Troyer citrange seedlings was studied in a greenhouse experiment. The seedlings were established in 5 dm^3 pots containing soil that was either sterilized or inoculated with Phytophthora nicotianae. Soil in the bottom 7 cm of each pot was compacted to a soil bulk density (SBD) of 1700 $kg.m^{-3}$, while the remaining volume in each pot was filled at SBD of 1400 $kg.m^{-3}$. For controls, pots were filled at 1400 $kg.m^{-3}$ without compacted subsoil. One day after irrigation, moisture contents of 18% (m/m) and 21% (m/m) were measured in treatments with non-compacted and compacted subsoil, respectively. No significant differences in seedling height of Rough lemon occurred between the various treatments, whereas a significant decrease in seedling height of Troyer citrange seedlings occurred in treatments with compacted subsoil and inoculated with P. nicotianae. In pots with uninoculated subsoil, roots were evenly distributed throughout the entire soil volume. In pots with the compacted subsoil, roots were growing horizontally above the compacted layer, with only a few roots penetrating the subsoil. P. nicotianae caused feeder root losses of less than 15% in the non-compacted subsoil treatment, and more than 33% in the compacted subsoil treatment, for both rootstocks. The data indicate that the compacted subsoil changed the root growth patterns of both rootstocks and aggravated the effect of P. nicotianae on citrus roots, probably because of slower drainage.

App AB 3

Relationship between soil compaction, soil moisture and Phytophthora root rot of Rough lemon seedlings

The effect of Phytophthora nicotianae on the growth of Rough lemon seedlings at a soil bulk density (SBD) of 1400 $kg.m^{-3}$ (non-compacted) and 1700 $kg.m^{-3}$ (compacted) and soil moisture levels (SML) of 7 to 11% (m/m)(dry), 12 to 16% (m/m)(moist) and 17 to 28% (m/m)(wet) was studied in the greenhouse. Each treatment (SBD x SML) was duplicated so that one half of the seedlings could be inoculated with P. nicotianae and the other half left uninoculated. Penetrometer soil strength varied by varying SBD and SML. At SBD of 1400 kg.m^{-3}, an increase in seedling growth occurred with increase in soil moisture. At SBD 1700 kg.m^{-3}, seedling growth increased as soil moisture increased from dry to moist, but showed a decrease with the wet treatment. Shoot growth of seedlings (height as well as leaf size) in soil at bulk density of 1700 kg.m^{-3} was significantly smaller compared with seedlings grown in soil at bulk density of 1400 kg.m^{-3}, while total feeder root length was decreased by more than 60% at the different moisture levels. P. nicotianae did not have any significant effect on shoot growth at dry and moist treatments, but caused significant decrease in shoot growth in the wet treatment at both SBD's. At SBD of 1400 kg.m^{-3}, the fungus did not cause any significant root losses in the dry and moist treatments, but caused feeder root loss of 61.28% in the wet treatment, while at SBD of 1700 kg.m^{-3}, it caused feeder root losses of 15.64%, 34.21% and 90.91% in the dry, moist and wet treatments, respectively. Feeder roots of seedlings grown in soil at bulk density of 1700 kg.m^{-3} showed a greater attraction for zoospores of P. nicotianae than feeder roots of seedlings grown in soil at bulk density of 1400 kg.m^{-3}.

App AB 4

Predisposing effect of soil compaction on root disease caused by Phytophthora nicotianae on six citrus rootstocks

The effect of soil compaction on growth and Phytophthora root rot of six citrus rootstocks were studied in the greenhouse. The rootstocks tested were Rough lemon, Volckameriana, Troyer citrange, Carrizo citrange, Swingle citrumelo and Empress mandarin. Root and shoot growth as well as the development of root rot was determined in seedlings grown at soil bulk density (SBD) of 1400 kg.m^{-3} (non-compacted) or SBD of 1700 kg.m^{-3} (compacted) respectively, inoculated or uninoculated with P. nicotianae. For all the rootstocks tested there was a significant decrease in seedling shoot growth in compacted soil compared to non-compacted soil. Soil compaction caused a decrease of between 71% and 92% in total lengths of feeder roots of different rootstocks. Feeder roots of seedlings grown in compacted soil were significantly thicker than those of plants grown in non-compacted soil, while specific lengths of feeder roots were significantly less in compacted soil. In non-compacted soil, P. nicotianae caused feeder root loss of less than 20%, while in compacted soil the fungus caused losses of between 33 and 55% for the different rootstocks. Data indicate that Rough lemon and Volckameriana were most tolerant, while Troyer citrange, Carrizo citrange, Swingle citrumelo and Empress mandarin were the most sensitive to compaction. Data furthermore indicate that soil compaction aggravated root losses caused by P. nicotianae.

App AB 5

General discussion and conclusions

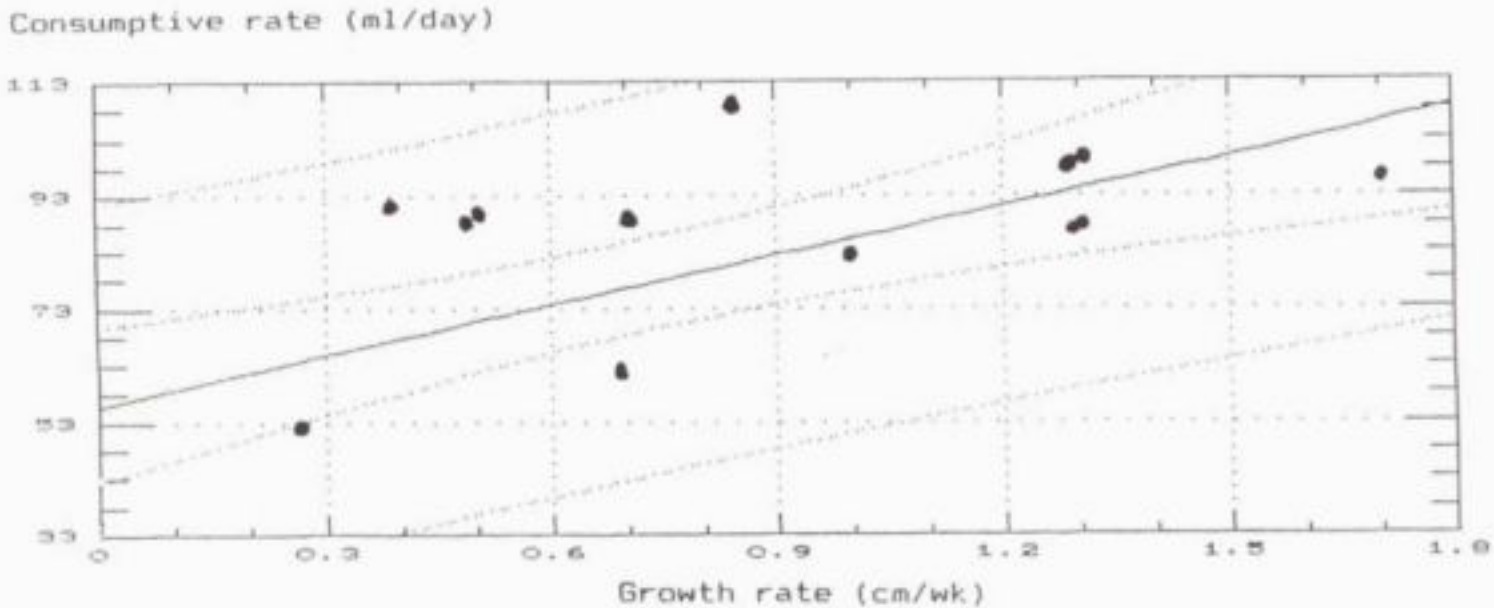
Throughout the experiment, a decrease in root growth occurred with increase in SBD and support previous findings for other crops. Where compacted subsoil layers existed, seedlings were able to compensate by forming more roots in non-compacted topsoil. A difference between rootstocks in ability to grow in compacted soil was also observed. The more vigorous rootstocks such as Rough lemon and Volckameriana were able to develop most roots, while the slower growing rootstocks like Troyer citrange, Swingle citrumelo, Carrizo citrange and Empress mandarin were most sensitive to compaction.

Not only was root growth inhibited, but feeder roots of seedlings growing in compacted soil were shortened, thickened and deformed with cracks and holes on the root surface. This can be attributed to certain morphological changes, such as increase in cross-section of cortex and endodermal cells, that took place in roots due to compaction.

Even though the decrease in root growth was not reflected to the same degree in reduced shoot growth, there was a decrease in seedling height, leaf size, as well as total nutrients in leaves of these seedlings, except for Na and Cl which showed elevated concentrations. The decrease in root growth will eventually result in smaller trees with smaller and most probably less leaves. This will have a negative effect on photosynthesis and ultimately lead to an energy deficit in the tree. These factors will result in a suppression of root development.

Soil compaction not only affected plant growth, but also changed the soil structure, thereby creating conditions conducive to Phytophthora. Due to inhibition of root growth and deformation of feeder roots, the assumption was that seedlings were predisposed to Phytophthora by compaction. The subsequent decrease in nutrient uptake could also affect the tolerance of the plant because of the poorer nutritional status of the plant.

The cracks and holes on root surfaces most probably resulted in an increase in root exudation which caused an increase in chemotactic response of zoospores to roots and also acted as infection sites for zoospores. Therefore, by reducing the rate of root growth and increasing exudation, the probability of successful host-pathogen contact and the dynamics of root-pathogen interactions is enhanced due to compaction. Compensation of root losses due to root rot was also hampered in the compacted soil because of the slow rate of root growth.



App. 4.1. Regression line showing a relationship between growth rate and **water** consumptive rate of RL in compacted soil at -6 kPa.

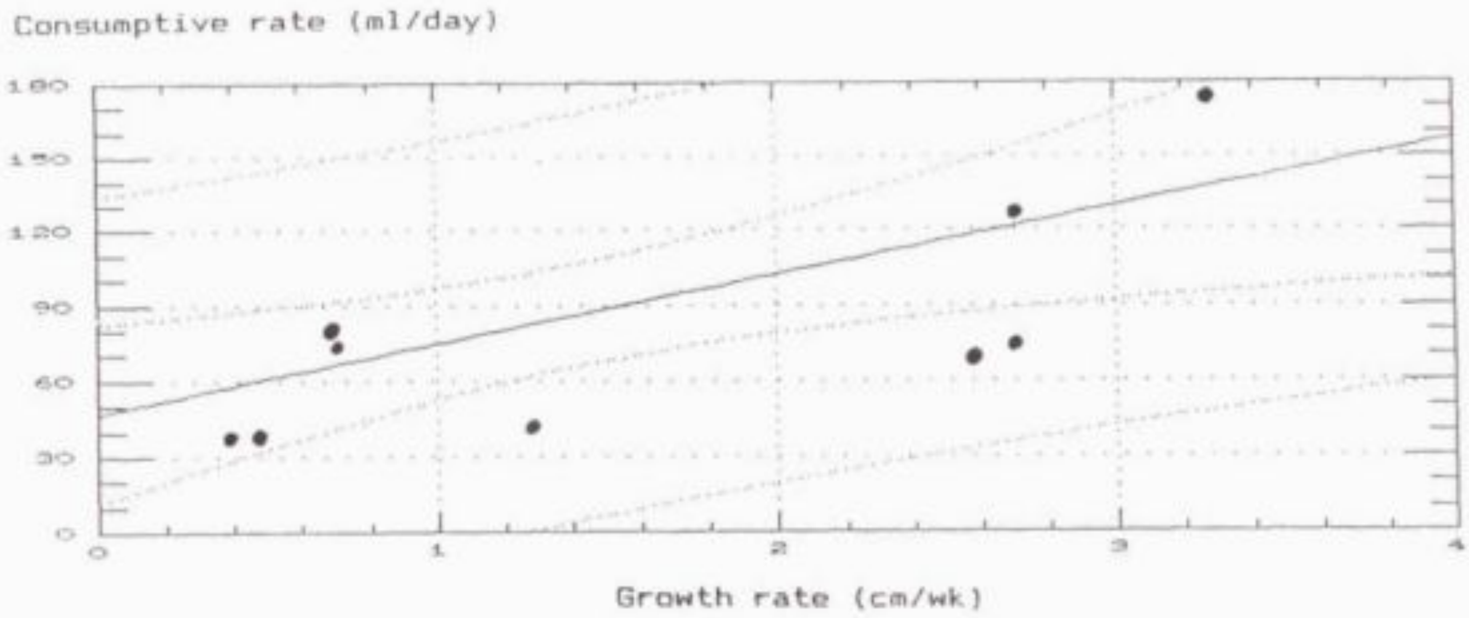
Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	55.9598	6.39043	8.7568	4.70939E-7
Slope	29.2733	7.13081	4.10519	1.07122E-3

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	3928.4832	1	3928.4832	16.8526	.00107
Error	3263.5168	14	233.1083		
Total (Corr.)	7192.0000	15			

Correlation Coefficient = 0.739073　　R-squared = 54.62 percent

Stnd. Error of Est. = 15.2679



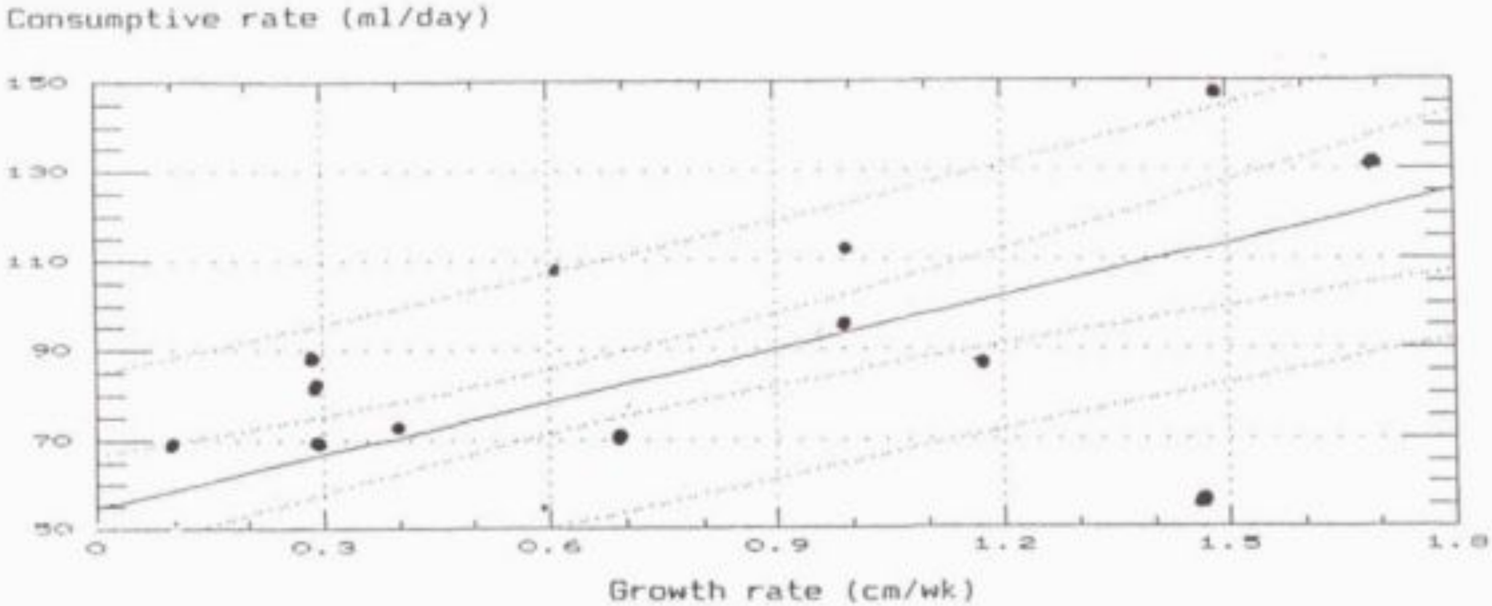
App. 4.2. Regression line showing a relationship between growth rate and water consumptive rate of TC in non-compacted soil at -6 kPa.

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	46.9976	16.415	2.86308	0.0133187
Slope	27.583	9.36652	2.94485	0.0113841

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	11605.105	1	11605.105	8.672	.01138
Error	17396.628	13	1338.202		
Total (Corr.)	29001.733	14			

Correlation Coefficient = 0.632576 R-squared = 40.02 percent
Stnd. Error of Est. = 36.5814



App. 4.3. Regression line showing a relationship between growth rate and water consumptive rate of TC in compacted soil at -6 kPa.

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	54.9219	5.44684	10.0832	1.6341E-7
Slope	39.0992	6.62478	5.90196	5.21931E-5

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	5713.4328	1	5713.4328	34.8331	.00005
Error	2132.3006	13	164.0231		
Total (Corr.)	7845.7333	14			

Correlation Coefficient = 0.853359 R-squared = 72.82 percent
Stnd. Error of Est. = 12.8072

App. 4.4. Stat. anal.

One-Way Analysis of Variance

Data: 27.0 27.3 16.0 10.8 8.9 12.7 3.2 6.1 2.4 5.6 8.5 8.7

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: Total mass: 1=RL loose; 2=RL compact; 3=TC loose; 4=TC compact

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	647.54000	3	215.84667	16.644	.0008
Within groups	103.74667	8	12.96833		
Total (corrected)	751.28667	11			

0 missing value(s) have been excluded.

App. 4.5. Stat. anal.

One-Way Analysis of Variance

Data: 19.7 18.9 10.7 7.12 5.63 8.60 2.06 3.71 1.53 2.82 5.25 5.36

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: Shoot mass: 1=RL loose; 2=RL compact; 3=TC loose; 4=TC compact

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	344.13043	3	114.71014	15.107	.0012
Within groups	60.74527	8	7.59316		
Total (corrected)	404.87570	11			

0 missing value(s) have been excluded.

App. 4.6. Stat. anal.

One-Way Analysis of Variance

Data: 7.37 8.43 5.26 3.67 5.22 4.11 1.14 2.38 0.84 2.75 3.20 3.36

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: Root mass: 1=RL loose; 2=RL compact; 3=TC loose; 4=TC compact

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	49.133692	3	16.377897	18.357	.0006
Within groups	7.137400	8	.892175		
Total (corrected)	56.271092	11			

0 missing value(s) have been excluded.

App. 4.7. Stat. anal.

One-Way Analysis of Variance

Data: 2.67 2.24 2.04 1.94 1.75 2.09 1.81 1.56 1.82 1.03 1.64 1.60

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: Top:root ratio: 1=RL loose; 2=RL compact; 3=TC loose; 4=TC compact

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	1.2602917	3	.4200972	6.205	.0175
Within groups	.5416000	8	.0677000		
Total (corrected)	1.8018917	11			

0 missing value(s) have been excluded.

App. 4.8. Stat. anal.

One-Way Analysis of Variance

Data: 1449 1324 1013 786 403 806 129 239 99 96 289 269

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: Leaf area: 1=RL loose; 2=RL compact; 3=TC loose; 4=TC compact

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	2350075.0	3	783358.33	26.401	.0002
Within groups	237372.7	8	29671.58		
Total (corrected)	2587447.7	11			

0 missing value(s) have been excluded.

App. 4.9. Stat. anal.

One-Way Analysis of Variance

Data: 543 545 495 250 132 232 112 215 68 119 209 180

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: Root area: 1=RL loose; 2=RL compact; 3=TC loose; 4=TC compact

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	298158.00	3	99386.000	31.438	.0001
Within groups	25290.67	8	3161.333		
Total (corrected)	323448.67	11			

0 missing value(s) have been excluded.

App. 4.10. Stat. anal.

One-Way Analysis of Variance

Data: 0.37 0.41 0.49 0.34 0.33 0.29 0.87 0.90 0.68 1.24 0.72 0.67

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: RA:LA ratio: 1=RL loose; 2=RL compact; 3=TC loose; 4=TC compact

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.6982917	3	.2327639	7.870	.0090
Within groups	.2366000	8	.0295750		
Total (corrected)	.9348917	11			

0 missing value(s) have been excluded.

App. 4.11. Stat. anal.

One-Way Analysis of Variance

Data: 1.37 1.18 1.02 1.46 1.47 1.47

Level codes: 1 1 1 2 2 2

Labels: Root hydraulic conductivity: 1=RL loose; 2=RL compact

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.1148167	1	.1148167	7.472	.0523
Within groups	.0614667	4	.0153667		
Total (corrected)	.1762833	5			

0 missing value(s) have been excluded.

App. 4.12. Stat. anal.

One-Way Analysis of Variance

Data: 1.90 1.89 1.23 0.91 0.77 1.08 0.43 0.91 0.35 0.64 0.99 0.95

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: Water use efficiency: 1=RL loose; 2=RL compact; 3=TC loose; 4=TC compact

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	2.0099583	3	.6699861	8.934	.0062
Within groups	.5999333	8	.0749917		
Total (corrected)	2.6098917	11			

0 missing value(s) have been excluded.

App. 4.13. Stat. anal.

One-Way Analysis of Variance

Data: 14.25 14.46 13.0 11.88 11.46 11.79 7.52 6.71 6.76 8.69 8.57 9.15

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: Water uptake: 1=RL loose; 2=RL compact; 3=TC loose; 4=TC compact

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	84.338267	3	28.112756	115.726	.0000
Within groups	1.943400	8	.242925		
Total (corrected)	86.281667	11			

0 missing value(s) have been excluded.

App. 4.14. Stat. anal.

One-Way Analysis of Variance

Data: 27.6 28.9 46.2 35.1 23.4 27.0 54.4 58.0 44.4 42.2 29.8 33.6

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

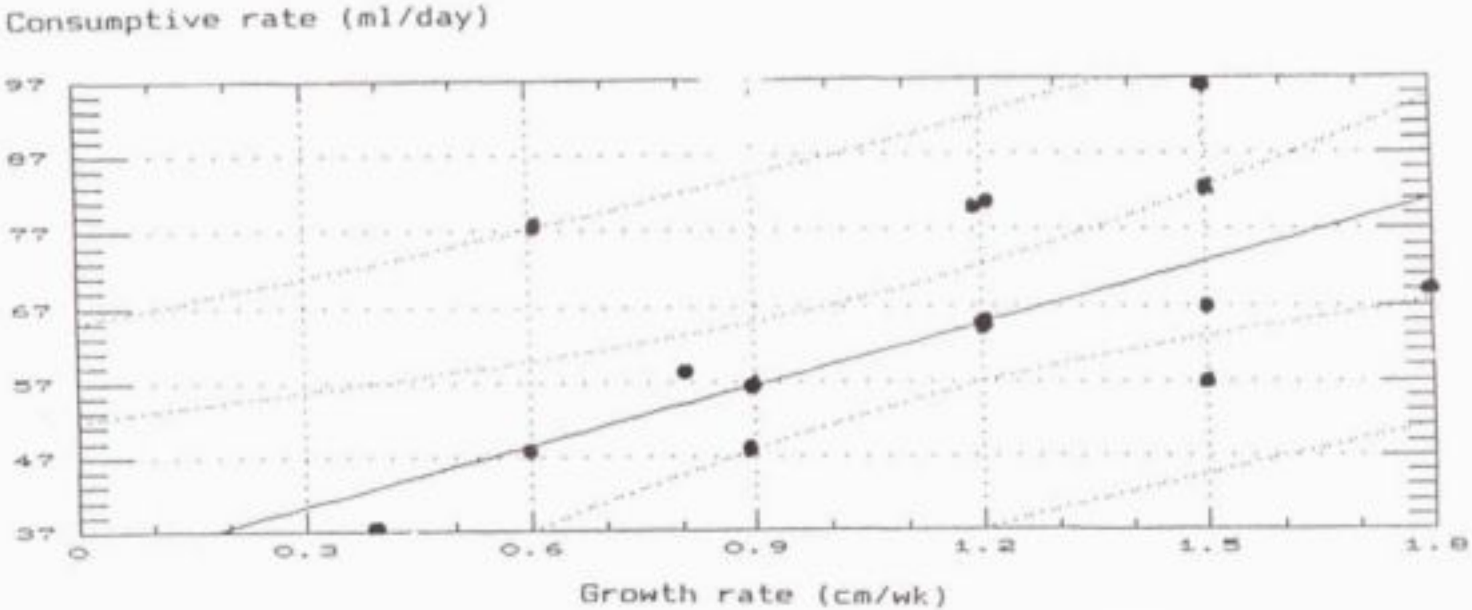
Labels: RA:root mass: 1=6kPa L RL; 2=6kPa C RL; 3=6kPa L TC; 4=6kPa C TC

Range test: LSD Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	923.01667	3	307.67222	5.776	.0212
Within groups	426.16000	8	53.27000		
Total (corrected)	1349.1767	11			

0 missing value(s) have been excluded.



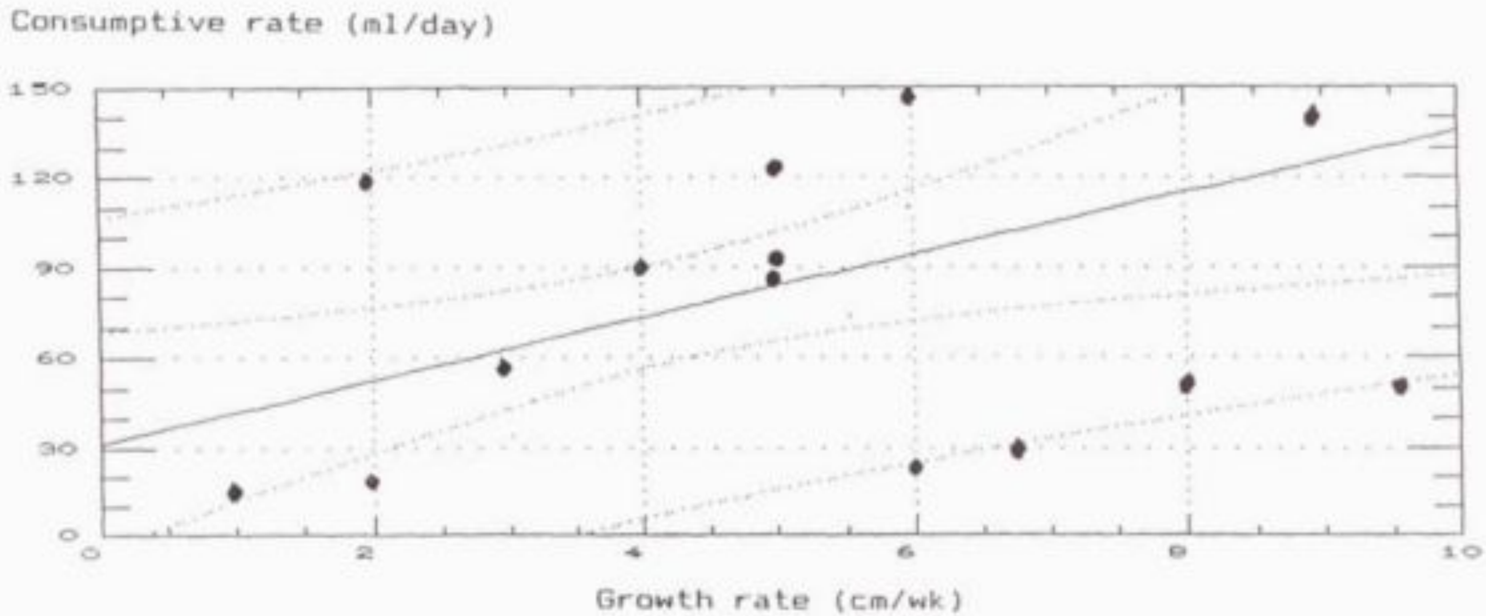
App. 5.1. Regression line showing a relationship between growth rate and water consumptive rate of RL in compacted soil at -10 kPa.

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	32.1383	8.89512	3.61303	4.74422E-3
Slope	27.1024	7.30812	3.70853	4.05109E-3

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	1935.5640	1	1935.5640	13.7532	.00405
Error	1407.3526	10	140.7353		
Total (Corr.)	3342.9167	11			

Correlation Coefficient = 0.760924 R-squared = 57.90 percent
Stnd. Error of Est. = 11.8632



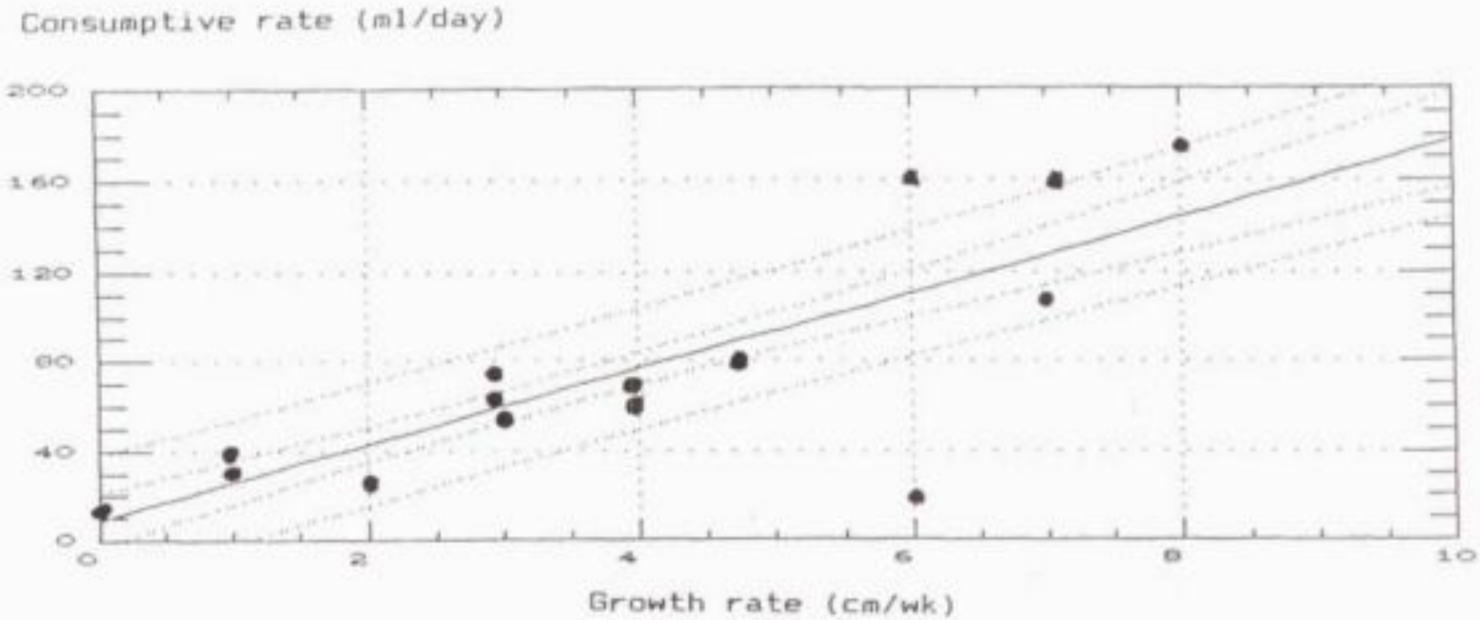
App. 5.2. Regression line showing a relationship between growth rate and water consumptive rate of RL in non-compacted soil at −10 kPa.

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	31.5625	17.081	1.84781	0.087504
Slope	10.4375	3.61441	2.88775	0.0127033

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	7669.4750	1	7669.4750	8.3391	.01270
Error	11956.125	13	919.702		
Total (Corr.)	19625.600	14			

Correlation Coefficient = 0.625131 R-squared = 39.08 percent
Stnd. Error of Est. = 30.3266



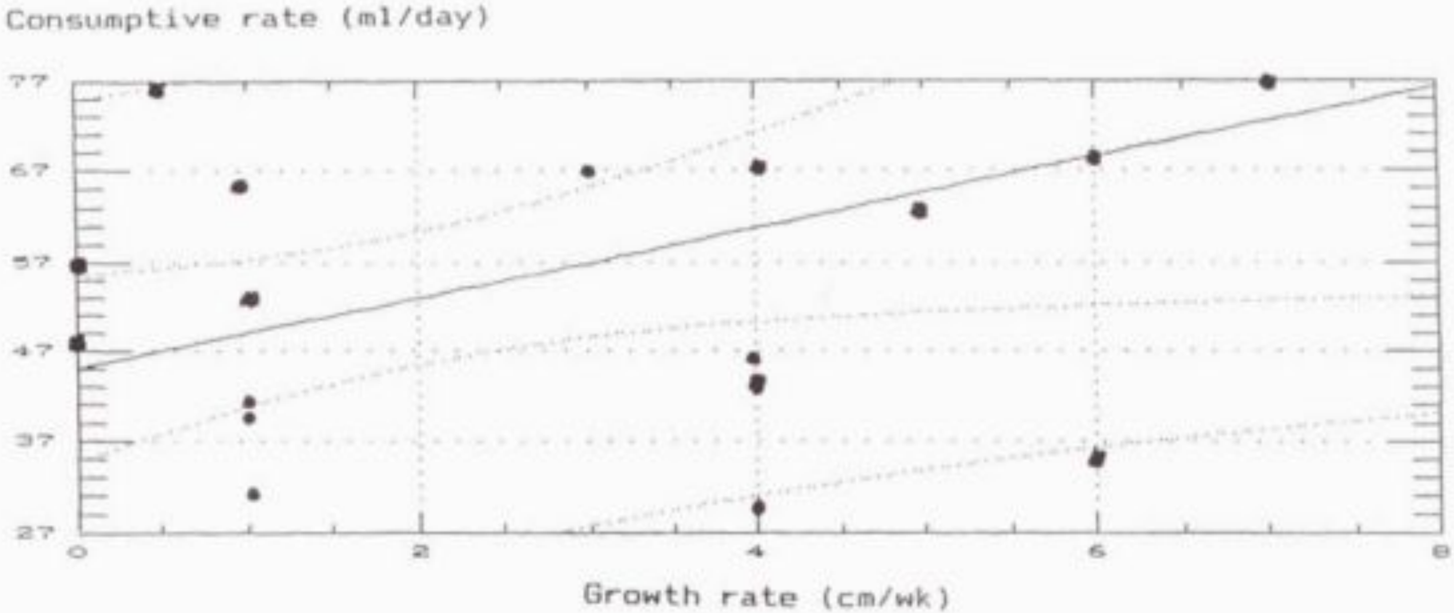
App. 5.3. Regression line showing a relationship between growth rate and water consumptive rate of RL in non-compacted soil at -20 kPa.

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	8.9468	5.53847	1.61539	0.132195
Slope	16.8882	1.34611	12.546	2.94118E-8

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	22592.776	1	22592.776	157.401	.00000
Error	1722.4382	12	143.5365		
Total (Corr.)	24315.214	13			

Correlation Coefficient = 0.963931 R-squared = 92.92 percent
Stnd. Error of Est. = 11.9807



App. 5.4. Regression line showing a relationship between growth rate and water consumptive rate of RL in compacted soil at -40 kPa.

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	45.101	4.79169	9.41234	6.86247E-7
Slope	3.91379	1.67919	2.33076	0.0380178

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	888.43103	1	888.43103	5.43245	.03802
Error	1962.4975	12	163.5415		
Total (Corr.)	2850.9286	13			

Correlation Coefficient = 0.558237 R-squared = 31.16 percent
Stnd. Error of Est. = 12.7883

App. 5.5. Stat. anal.

Analysis of Variance for 13.4 13.2 16 6.1 8.8 9.5 12.9 12.3 12.7 11.4 7.5 10.6 7

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	92.117222	3	30.705741	16.769	.0001
1 1 1 2 2 2 1 1 1 2	70.013889	1	70.013889	38.236	.0000
3 3 3 3 3 3 4 4 4 4	22.103333	2	11.051667	6.035	.0154
2-FACTOR INTERACTIONS	10.154444	2	5.0772222	2.773	.1024
1 1 1 2 2 3 3 3 3 3	10.154444	2	5.0772222	2.773	.1024
RESIDUAL	21.973333	12	1.8311111		
TOTAL (CORR.)	124.24500	17		TOTAL DRY MASS	

0 missing values have been excluded.

App. 5.6. Stat. anal.

Analysis of Variance for 11.6 10 12.6 4.9 7.2 7.8 10.4 9 10 9.4 6.3 8.9 6.1 4.7

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	54.483889	3	18.161296	12.825	.0005
1 1 1 2 2 2 1 1 1 2	35.560556	1	35.560556	25.111	.0003
3 3 3 3 3 3 4 4 4 4	18.923333	2	9.461667	6.681	.0112
2-FACTOR INTERACTIONS	8.7677778	2	4.3838889	3.096	.0824
1 1 1 2 2 3 3 3 3 3	8.7677778	2	4.3838889	3.096	.0824
RESIDUAL	16.993333	12	1.4161111		
TOTAL (CORR.)	80.245000	17		TOP DRY MASS	

0 missing values have been excluded.

App. 5.7. Stat. anal.

Analysis of Variance for 1.8 3.2 3.5 1.2 1.6 1.7 2.5 3.3 2.6 2.0 1.2 1.7 1.4 1.8

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	4.8722222	3	1.6240741	7.327	.0047
1 1 1 2 2 2 1 1 1 2	4.3022222	1	4.3022222	19.409	.0009
3 3 3 3 3 3 4 4 4 4	.5700000	2	.2850000	1.286	.3119
2-FACTOR INTERACTIONS	.6877778	2	.3438889	1.551	.2516
1 1 1 2 2 3 3 3 3 3	.6877778	2	.3438889	1.551	.2516
RESIDUAL	2.6600000	12	.2216667		
TOTAL (CORR.)	8.2200000	17		ROOT DRY MASS	

App. 5.8. Stat. anal.

Analysis of Variance for 6.3 3.1 3.6 4.2 4.5 4.5 5.1 2.7 3.8 4.8 5.1 5.3 4.4 2.7

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	2.3416667	3	.7805556	.838	.4985
1 1 1 2 2 2 1 1 1 2	1.0272222	1	1.0272222	1.103	.3143
3 3 3 3 3 3 4 4 4 4	1.3144444	2	.6572222	.706	.5131
2-FACTOR INTERACTIONS	1.1811111	2	.5905556	.634	.5472
1 1 1 2 2 3 3 3 3 3	1.1811111	2	.5905556	.634	.5472
RESIDUAL	11.173333	12	.9311111		
TOTAL (CORR.)	14.696111	17		TOP:ROOT RATIO	

0 missing values have been excluded.

App. 5.9. Stat. anal.

Analysis of Variance for 1.5 1.8 1.9 1.3 1.2 1.5 2.1 1.8 1.8 1.5 1.0 1.4 1.1 1.2

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	1.0505556	3	.3501852	8.755	.0024
1 1 1 2 2 2 1 1 1 2	1.0272222	1	1.0272222	25.681	.0003
3 3 3 3 3 3 4 4 4 4	.0233333	2	.0116667	.292	.7522
2-FACTOR INTERACTIONS	.0344444	2	.0172222	.431	.6598
1 1 1 2 2 3 3 3 3 3	.0344444	2	.0172222	.431	.6598
RESIDUAL	.4800000	12	.0400000		
TOTAL (CORR.)	1.5650000	17	WATER USE EFFICIENCY		

0 missing values have been excluded.

App. 5.10. Stat. anal.

Analysis of Variance for 985 957 1051 673 628 741 903 883 920 761 594 777 685 47

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	269494.11	3	89831.37	13.362	.0004
1 1 1 2 2 2 1 1 1 2	225792.00	1	225792.00	33.586	.0001
3 3 3 3 2 3 4 4 4 4	43702.11	2	21851.06	3.250	.0745
2-FACTOR INTERACTIONS	20034.333	2	10017.167	1.490	.2642
1 1 1 2 2 3 3 3 3 3	20034.333	2	10017.167	1.490	.2642
RESIDUAL	80674.667	12	6722.8889		
TOTAL (CORR.)	370203.11	17		LEAF AREA	

0 missing values have been excluded.

App. 5.11. Stat. anal.

Analysis of Variance for 288 283 293 142 131 179 322 282 271 147 115 151 121 120

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	101186.00	3	33728.67	113.205	.0000
1 1 1 2 2 2 1 1 1 2	100053.56	1	100053.56	335.813	.0000
3 3 3 3 3 3 4 4 4 4	1132.44	2	566.22	1.900	.1919
2-FACTOR INTERACTIONS	315.11111	2	157.55556	.529	.6024
1 1 1 2 2 3 3 3 3 3	315.11111	2	157.55556	.529	.6024
RESIDUAL	3575.3333	12	297.94444		
TOTAL (CORR.)	105076.44	17		ROOT AREA	

0 missing values have been excluded.

App. 5.12. Stat. anal.

Analysis of Variance for 0.3 0.3 0.3 0.2 0.2 0.2 0.4 0.3 0.3 0.2 0.2 0.2 0.2 0.3

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.0366667	3	.0122222	7.333	.0047
1 1 1 2 2 2 1 1 1 2	.0355556	1	.0355556	21.333	.0006
3 3 3 3 3 3 4 4 4 4	.0011111	2	.0005556	.333	.7230
2-FACTOR INTERACTIONS	.0077778	2	.0038889	2.333	.1393
1 1 1 2 2 3 3 3 3 3	.0077778	2	.0038889	2.333	.1393
RESIDUAL	.0200000	12	.0016667		
TOTAL (CORR.)	.0644444	17	ROOT AREA:LEAF AREA RATIO		

0 missing values have been excluded.

App. 5.13. Stat. anal.

Analysis of Variance for 6.8 7.2 8.2 4.5 7.1 6.2 6.0 6.7 7.0 7.5 6.7 7.4 6.3 5.1

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	7.0166667	3	2.3388889	3.529	.0486
1 1 1 2 2 2 1 1 1 2	3.0422222	1	3.0422222	4.590	.0534
3 3 3 3 3 3 4 4 4 4	3.9744444	2	1.9872222	2.998	.0879
2-FACTOR INTERACTIONS	5.7877778	2	2.8938889	4.366	.0376
1 1 1 2 2 3 3 3 3 3	5.7877778	2	2.8938889	4.366	.0376
RESIDUAL	7.9533333	12	.6627778		
TOTAL (CORR.)	20.757778	17		WATER UPTAKE	

0 missing values have been excluded.

App. 5.14. Stat. anal.

Analysis of Variance for 9.0 7.5 7.8 6.7 11.2 8.4 6.6 7.6 7.6 9.9 11.2 9.5 9.2 1

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	8.6750000	3	2.8916667	1.470	.2721
1 1 1 2 2 2 1 1 1 2	8.4050000	1	8.4050000	4.273	.0610
3 3 3 3 3 3 4 4 4 4	.2700000	2	.1350000	.069	.9340
2-FACTOR INTERACTIONS	5.5433333	2	2.7716667	1.409	.2821
1 1 1 2 2 3 3 3 3 3	5.5433333	2	2.7716667	1.409	.2821
RESIDUAL	23.606667	12	1.9672222		
TOTAL (CORR.)	37.825000	17	WATER UPTAKE PER LEAF AREA		

0 missing values have been excluded.

App. 5.15. Stat. anal.

Analysis of Variance for 2.26 2.3 2.5 2.65 2.7 2.7 2.2 2.67 2.6 2.87 2.66 2.98 3

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.6915722	3	.2305241	8.983	.0022
1 1 1 2 2 2 1 1 1 2	.5582722	1	.5582722	21.756	.0005
3 3 3 3 3 3 4 4 4 4	.1333000	2	.0666500	2.597	.1155
2-FACTOR INTERACTIONS	.0019444	2	9.72222E-004	.038	.9629
1 1 1 2 2 3 3 3 3 3	.0019444	2	9.72222E-004	.038	.9629
RESIDUAL	.3079333	12	.0256611		
TOTAL (CORR.)	1.0014500	17		N-CONCENTRATION	

0 missing values have been excluded.

App. 5.16. Stat. anal.

Analysis of Variance for .20 .24 .22 .21 .3 .23 .21 .22 .21 .25 .19 .22 .26 .26

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.0029111	3	.0009704	1.386	.2944
1 1 1 2 2 2 1 1 1 2	.0018000	1	.0018000	2.571	.1348
3 3 3 3 3 3 4 4 4 4	.0011111	2	.0005556	.794	.4746
2-FACTOR INTERACTIONS	4.00000E-004	2	2.00000E-004	.286	.7564
1 1 1 2 2 3 3 3 3 3	4.00000E-004	2	2.00000E-004	.286	.7564
RESIDUAL	.0084000	12	7.00000E-004		
TOTAL (CORR.)	.0117111	17		P-CONCENTRATION	

0 missing values have been excluded.

App. 5.17. Stat. anal.

Analysis of Variance for .14 .17 .15 .18 .19 .19 .18 .15 .15 .21 .21 .21 .2 .17

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.0045000	3	.0015000	10.000	.0014
1 1 1 2 2 2 1 1 1 2	.0037556	1	.0037556	25.037	.0003
3 3 3 3 3 3 4 4 4 4	.0007444	2	.0003722	2.481	.1253
2-FACTOR INTERACTIONS	.0016778	2	8.38889E-004	5.593	.0192
1 1 1 2 2 3 3 3 3 3	.0016778	2	8.38889E-004	5.593	.0192
RESIDUAL	.0018000	12	1.50000E-004		
TOTAL (CORR.)	.0079778	17		K-CONCENTRATION	

0 missing values have been excluded.

App. 5.18. Stat. anal.

Analysis of Variance for 3 2.98 3.1 2.5 2.55 2.65 3.2 3.4 3.1 2.9 2.5 2.87 2.86

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	1.1252833	3	.3750944	11.321	.0006
1 1 1 2 [illegible] 2 1 1 [illegible]	1.0034722	1	1.0034722	30.286	.0001
3 3 3 3 3 3 4 4 4 4	.1218111	2	.0609056	1.838	.2012
2-FACTOR INTERACTIONS	3.44444E-004	2	1.72222E-004	.005	.9948
1 1 1 2 2 3 3 3 3 3	3.44444E-004	2	1.72222E-004	.005	.9948
RESIDUAL	.3976000	12	.0331333		
TOTAL (CORR.)	1.5232278	17		Ca-CONCENTRATION	

0 missing values have been excluded.

App. 5.19. Stat. anal.

Analysis of Variance for .43 .42 .42 .42 .37 .41 .44 .46 .41 .4 .4 .37 .41 .51 .

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.0099000	3	.0033000	3.194	.0626
1 1 1 2 2 2 1 1 1 2	.0037556	1	.0037556	3.634	.0808
3 3 3 3 3 3 4 4 4 4	.0061444	2	.0030722	2.973	.0894
2-FACTOR INTERACTIONS	7.44444E-004	2	3.72222E-004	.360	.7048
1 1 1 2 2 3 3 3 3 3	7.44444E-004	2	3.72222E-004	.360	.7048
RESIDUAL	.0124000	12	.0010333		
TOTAL (CORR.)	.0230444	17		Mg-CONCENTRATION	

0 missing values have been excluded.

App. 5.20. Stat. anal.

Analysis of Variance for 7 7.1 7.3 5.9 6.9 6.5 7.2 7.5 7.7 7.4 6.3 7.8 7 5.7 5.6

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	3.6833333	3	1.2277778	4.732	.0211
1 1 1 2 2 2 1 1 1 2	2.1355556	1	2.1355556	8.231	.0141
3 3 3 3 3 3 4 4 4 4	1.5477778	2	.7738889	2.983	.0888
2-FACTOR INTERACTIONS	.4411111	2	.2205556	.850	.4516
1 1 1 2 2 3 3 3 3 3	.4411111	2	.2205556	.850	.4516
RESIDUAL	3.1133333	12	.2594444		
TOTAL (CORR.)	7.2377778	17			

Ca:Mg RATIO

0 missing values have been excluded.

App. 5.21. Stat. anal.

Analysis of Variance for .33 .4 .36 .43 .51 .46 .41 .33 .37 .52 .52 .57 .49 .33

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
M[illegible]FEC	.0832111	3	.0277370	13.530	.0004
1 1 1 2 [illegible] 1 1 2	.0648000	1	.0648000	31.610	.0001
3 3 3 3 3 3 4 4 4 4	.0184111	2	.0092056	4.491	.0350
2-FACTOR INTERACTIONS	.0050333	2	.0025167	1.228	.3273
1 1 1 2 2 3 3 3 3 3	.0050333	2	.0025167	1.228	.3273
RESIDUAL	.0246000	12	.0020500		
TOTAL (CORR.)	.1128444	17			

K:Mg RATIO

0 missing values have been excluded.

App. 5.22. Stat. anal.

Analysis of Variance for .05 .06 .05 .07 .07 .07 .06 .04 .05 .07 .08 .07 .07 .06

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.0020500	3	.0006833	13.667	.0004
1 1 1 2 2 2 1 1 1 2	.0020056	1	.0020056	40.111	.0000
3 3 3 3 3 3 4 4 4 4	.0000444	2	.0000222	.444	.6513
2-FACTOR INTERACTIONS	4.44444E-005	2	2.22222E-005	.444	.6513
1 1 1 2 2 3 3 3 3 3	4.44444E-005	2	2.22222E-005	.444	.6513
RESIDUAL	6.00000E-004	12	5.00000E-005		
TOTAL (CORR.)	.0026944	17			

K:Ca RATIO

0 missing values have been excluded.

App. 5.23. Stat. anal.

Analysis of Variance for .04 .05 .04 .06 .07 .06 .05 .04 .04 .06 .07 .06 .06 .05

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.0016167	3	.0005389	12.125	.0006
1 1 1 2 2 2 1 1 1 2	.0016056	1	.0016056	36.125	.0001
3 3 3 3 3 3 4 4 4 4	.0000111	2	.0000056	.125	.8836
2-FACTOR INTERACTIONS	1.11111E-005	2	5.55556E-006	.125	.8836
1 1 1 2 2 3 3 3 3 3	1.11111E-005	2	5.55556E-006	.125	.8836
RESIDUAL	5.33333E-004	12	4.44444E-005		
TOTAL (CORR.)	.0021611	17			

K:(Ca+Mg) RATIO

0 missing values have been excluded.

App. 5.24. Stat. anal.

Analysis of Variance for 842 845 929 479 483 545 522 872 483 788 600 551 599 420

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	213415.67	3	71138.56	4.650	.0223
1 1 1 2 2 2 1 1 1 2	149786.89	1	149786.89	9.790	.0097
3 3 3 3 3 3 4 4 4 4	63628.78	2	31814.39	2.079	.1677
2-FACTOR INTERACTIONS	114838.11	2	57419.056	3.753	.0542
1 1 1 2 2 3 3 3 3 3	114838.11	2	57419.056	3.753	.0542
RESIDUAL	183597.33	12	15299.778		
TOTAL (CORR.)	511851.11	17			

Fe-CONCENTRATION

0 missing values have been excluded.

App. 5.25. Stat. anal.

Analysis of Variance for 71 54 47 83 62 89 60 77 51 66 102 84 56 60 38 32 37 29

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	5185.5556	3	1728.5185	10.316	.0012
1 1 1 2 2 2 1 1 1 2	1840.2222	1	1840.2222	10.983	.0062
3 3 3 3 3 3 4 4 4 4	3345.3333	2	1672.6667	9.983	.0028
2-FACTOR INTERACTIONS	5.7777778	2	2.8888889	.017	.9829
1 1 1 2 2 3 3 3 3 3	5.7777778	2	2.8888889	.017	.9829
RESIDUAL	2010.6667	12	167.55556		
TOTAL (CORR.)	7202.0000	17			

Mn-CONCENTRATION

0 missing values have been excluded.

App. 5.26. Stat. anal.

Analysis of Variance for 3 7.5 12 9 10.5 1.5 18 9 4.5 31.5 9 22.5 24 16.5 16.5 1

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	446.74333	3	148.91444	3.676	.0436
1 1 1 2 2 2 1 1 1 2	82.77556	1	82.77556	2.043	.1784
3 3 3 3 3 3 4 4 4 4	363.96778	2	181.98389	4.492	.0350
2-FACTOR INTERACTIONS	95.301111	2	47.650556	1.176	.3416
1 1 1 2 2 3 3 3 3 3	95.301111	2	47.650556	1.176	.3416
RESIDUAL	486.10667	12	40.508889		
TOTAL (CORR.)	1028.1511	17	Cu-CONCENTRATION		

0 missing values have been excluded.

App. 5.27. Stat. anal.

Analysis of Variance for 41 123 62 54 54 54 47 42 65 63 48 89 99 42 69 67 65 78

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	381.11111	3	127.03704	.234	.9707
1 1 1 2 2 2 1 1 1 2	18.00000	1	18.00000	.033	.8604
3 3 3 3 3 3 4 4 4 4	363.11111	2	181.55556	.335	.7219
2-FACTOR INTERACTIONS	1017.3333	2	508.66667	.938	.4182
1 1 1 2 2 3 3 3 3 3	1017.3333	2	508.66667	.938	.4182
RESIDUAL	6506.0000	12	542.16667		
TOTAL (CORR.)	7904.4444	17	Zn-CONCENTRATION		

0 missing values have been excluded.

App. 5.28. Stat. anal.

Analysis of Variance for 262 232 315 130 196 211 231 240 264 270 167 265 189 146

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	19609.889	3	6536.630	5.013	.0176
1 1 1 2 2 2 1 1 1 2	17797.556	1	17797.556	13.648	.0031
3 3 3 3 3 3 4 4 4 4	1812.333	2	906.167	.695	.5181
2-FACTOR INTERACTIONS	6068.1111	2	3034.0556	2.327	.1400
1 1 1 2 2 3 3 3 3 3	6068.1111	2	3034.0556	2.327	.1400
RESIDUAL	15648.000	12	1304.0000		
TOTAL (CORR.)	41326.000	17			N-CONTENT

0 missing values have been excluded.

App. 5.29. Stat. anal.

Analysis of Variance for 23 24 28 10 22 18 22 20 21 24 12 20 16 12 14 21 23 24

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	205.88889	3	68.62963	4.627	.0226
1 1 1 2 2 2 1 1 1 2	186.88889	1	186.88889	12.599	.0040
3 3 3 3 3 3 4 4 4 4	19.00000	2	9.50000	.640	.5442
2-FACTOR INTERACTIONS	38.111111	2	19.055556	1.285	.3122
1 1 1 2 2 3 3 3 3 3	38.111111	2	19.055556	1.285	.3122
RESIDUAL	178.00000	12	14.833333		
TOTAL (CORR.)	422.00000	17			P-CONTENT

0 missing values have been excluded.

App. 5.30. Stat. anal.

Analysis of Variance for 16 17 19 9 14 15 19 14 15 20 13 19 12 8 12 17 16 15.5

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	70.708333	3	23.569444	3.543	.0481
1 1 1 2 2 2 1 1 1 2	39.013889	1	39.013889	5.864	.0322
3 3 3 3 3 3 4 4 4 4	31.694444	2	15.847222	2.382	.1345
2-FACTOR INTERACTIONS	41.694444	2	20.847222	3.134	.0804
1 1 1 2 2 3 3 3 3 3	41.694444	2	20.847222	3.134	.0804
RESIDUAL	79.833333	12	6.6527778		
TOTAL (CORR.)	192.23611	17			K-CONTENT

0 missing values have been excluded.

App. 5.31. Stat. anal.

Analysis of Variance for 350 297 384 121 184 207 328 309 315 276 157 255 174 137

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	102984.17	3	34328.06	24.466	.0000
1 1 1 2 2 2 1 1 1 2	101100.06	1	101100.06	72.054	.0000
3 3 3 3 3 3 4 4 4 4	1884.11	2	942.06	.671	.5292
2-FACTOR INTERACTIONS	8802.1111	2	4401.0556	3.137	.0802
1 1 1 2 2 3 3 3 3 3	8802.1111	2	4401.0556	3.137	.0802
RESIDUAL	16837.333	12	1403.1111		
TOTAL (CORR.)	128623.61	17			Ca-CONTENT

0 missing values have been excluded.

App. 5.32. Stat. anal.

Analysis of Variance for 50 42 53 21 27 32 46 41 41 38 25 33 25 24 27 47 46 48

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	1464.3333	3	488.1111	24.960	.0000
1 1 1 2 2 2 1 1 1 2	1458.0000	1	1458.0000	74.557	.0000
3 3 3 3 3 3 4 4 4 4	6.3333	2	3.1667	.162	.8523
2-FACTOR INTERACTIONS	121.00000	2	60.500000	3.094	.0825
1 1 1 2 2 3 3 3 3 3	121.00000	2	60.500000	3.094	.0825
RESIDUAL	234.66667	12	19.555556		
TOTAL (CORR.)	1820.0000	17			Mg-CONTENT

0 missing values have been excluded.

App. 5.33. Stat. anal.

Analysis of Variance for 9.8 8.4 11.7 2.3 3.5 4.2 5.4 7.8 4.8 7.4 3.8 4.9 3.6 2

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	72.742778	3	24.247593	13.368	.0004
1 1 1 2 2 2 1 1 1 2	43.245000	1	43.245000	23.841	.0004
3 3 3 3 3 3 4 4 4 4	29.497778	2	14.748889	8.131	.0059
2-FACTOR INTERACTIONS	29.560000	2	14.780000	8.148	.0058
1 1 1 2 2 3 3 3 3 3	29.560000	2	14.780000	8.148	.0058
RESIDUAL	21.766667	12	1.8138889		
TOTAL (CORR.)	124.06944	17			Fe-CONTENT

0 missing values have been excluded.

App. 5.34. Stat. anal.

Analysis of Variance for .82 .54 .58 .41 .44 .69 .62 .69 .51 .62 .69 .75 .34 .28

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.5127333	3	.1709111	16.747	.0001
1 1 1 2 2 2 1 1 1 2	.0000222	1	.0000222	.002	.9640
3 3 3 3 3 3 4 4 4 4	.5127111	2	.2563556	25.119	.0001
2-FACTOR INTERACTIONS	.0416444	2	.0208222	2.040	.1727
1 1 1 2 2 3 3 3 3 3	.0416444	2	.0208222	2.040	.1727
RESIDUAL	.1224667	12	.0102056		
TOTAL (CORR.)	.6768444	17			Mn-CONTENT

0 missing values have been excluded.

App. 5.35. Stat. anal.

Analysis of Variance for .03 .07 .15 .04 .08 .01 .19 .08 .05 .3 .06 .2 .15 .08 .

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.0234611	3	.0078204	1.751	.2099
1 1 1 2 2 2 1 1 1 2	.0024500	1	.0024500	.549	.4809
3 3 3 3 3 3 4 4 4 4	.0210111	2	.0105056	2.352	.1375
2-FACTOR INTERACTIONS	.0109000	2	.0054500	1.220	.3293
1 1 1 2 2 3 3 3 3 3	.0109000	2	.0054500	1.220	.3293
RESIDUAL	.0536000	12	.0044667		
TOTAL (CORR.)	.0879611	17			Cu-CONTENT

0 missing values have been excluded.

App. 5.36. Stat. anal.

Analysis of Variance for .47 1.22 .77 .27 .39 .42 .48 .38 .65 .59 .3 .79 .6 .2 .

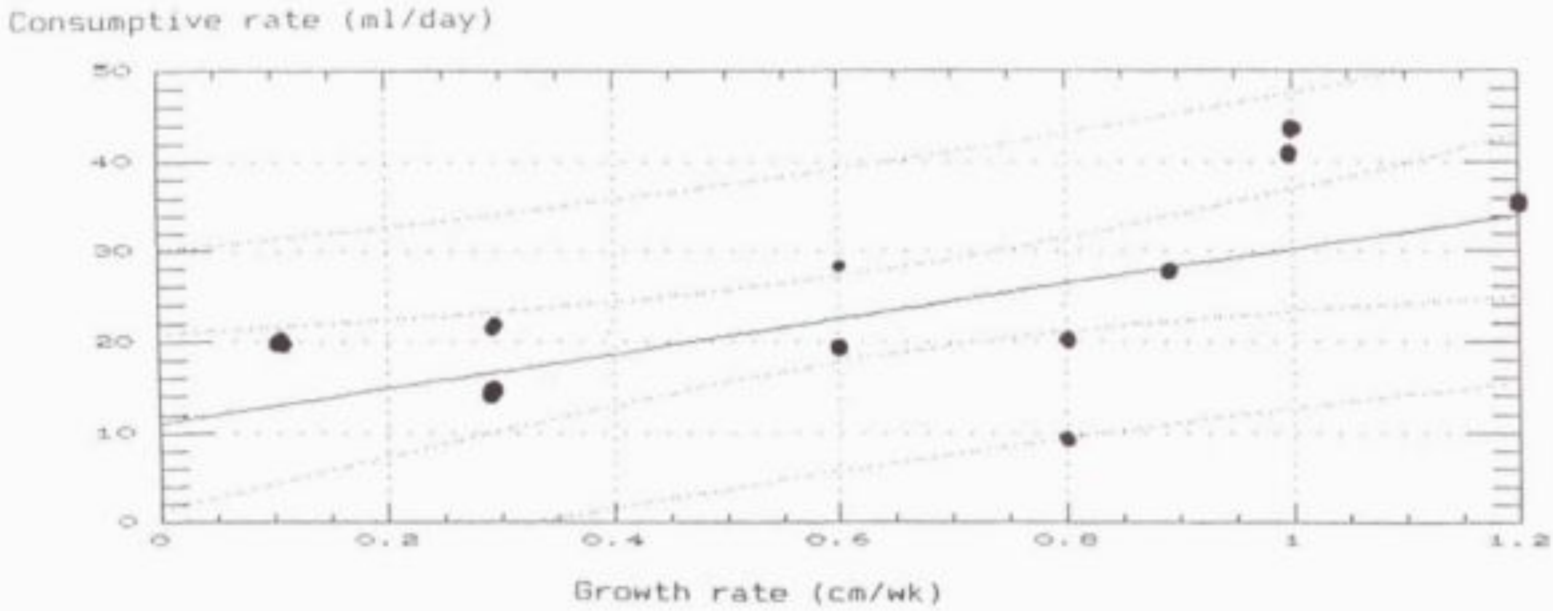
Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.1779889	3	.[illegible]93296	1.319	.3138
1 1 1 2 2 2 1 1 1 2	.0747556	1	.0747556	1.662	.2216
3 3 3 3 3 3 4 4 4 4	.1032333	2	.0516167	1.148	.3499
2-FACTOR INTERACTIONS	.2478778	2	.1239389	2.756	.1036
1 1 1 2 2 3 3 3 3 3	.2478778	2	.1239389	2.756	.1036
RESIDUAL	.5397333	12	.0449778		
TOTAL (CORR.)	.9656000	17			Zn-CONTENT

0 missing values have been excluded.

KEY:

1 = Non-compacted; 2 = Compacted

3 = −10 kPa; 4 = −20 kPa; 5 = −40 kPa



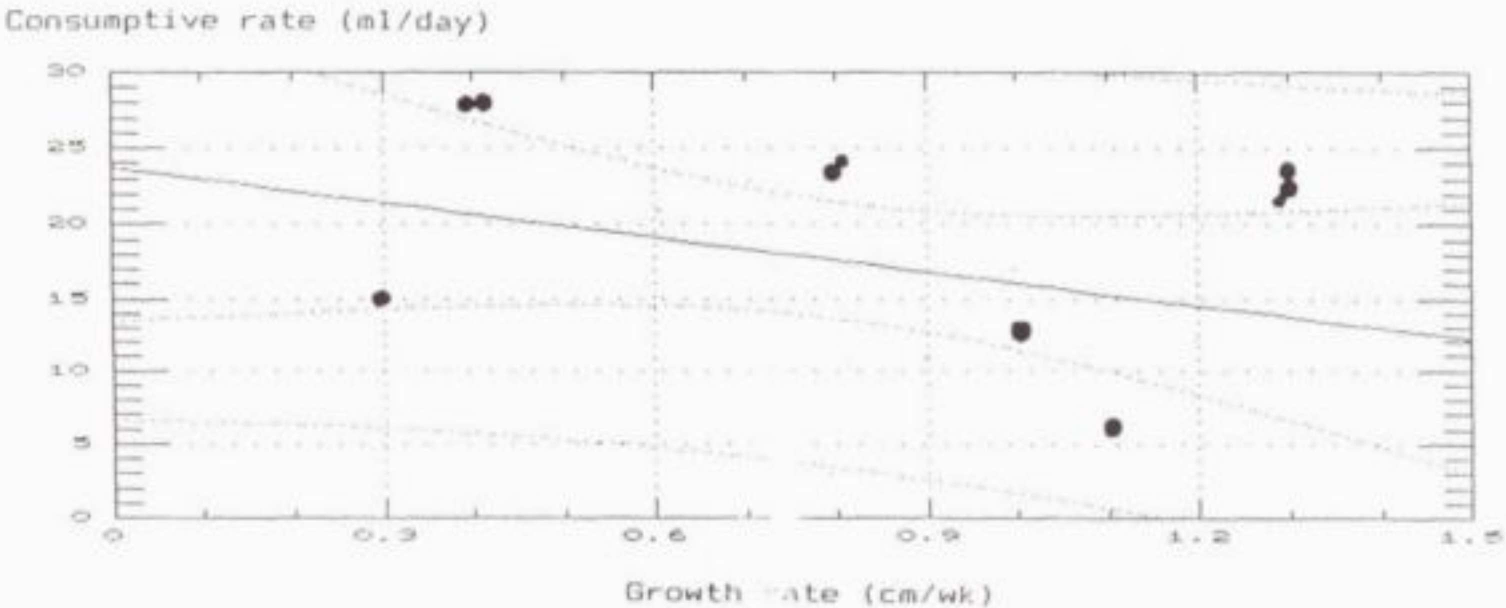
App. 6.1. Regression line showing a relationship between growth rate and water consumptive rate of RL in compacted soil at -30 kPa.

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	11.0561	4.43491	2.49297	0.031828
Slope	19.122	6.1799	3.09422	0.0113621

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	499.72033	1	499.72033	9.57417	.01136
Error	521.94634	10	52.19463		
Total (Corr.)	1021.6667	11			

Correlation Coefficient = 0.699373 R-squared = 48.91 percent
Stnd. Error of Est. = 7.22459



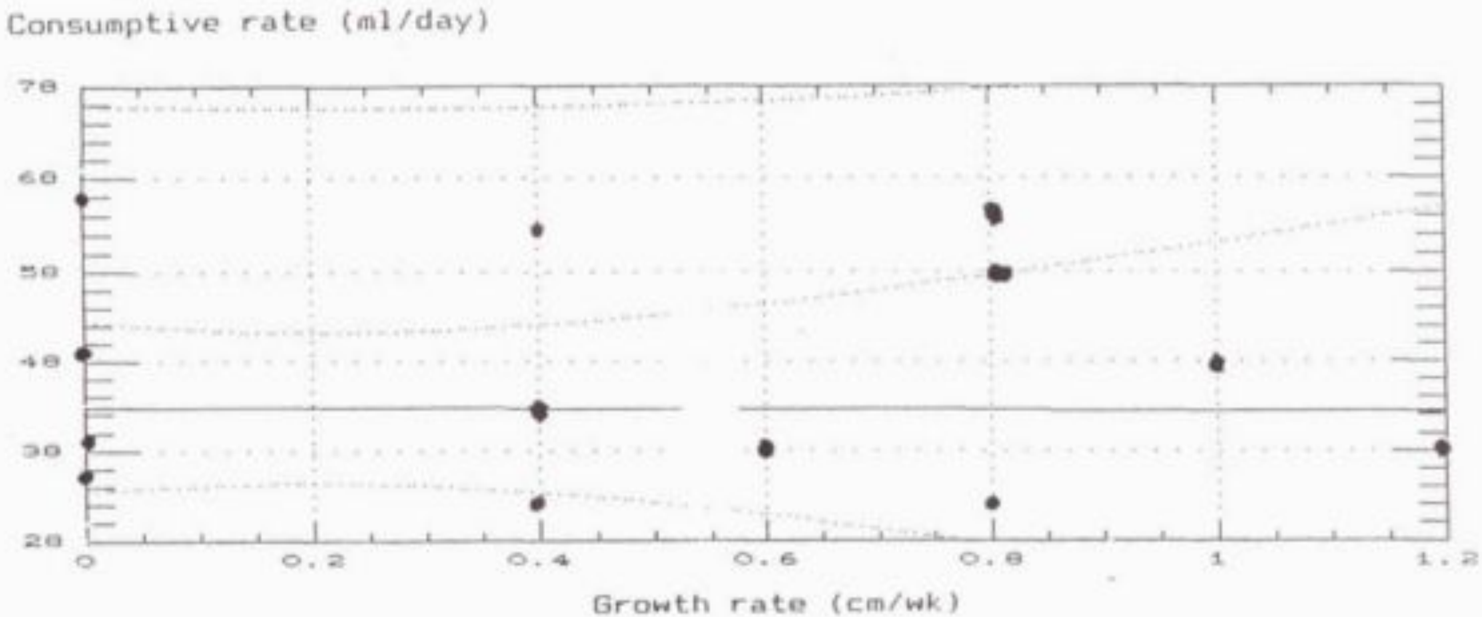
App. 6.2. Regression line showing a relationship between growth rate and water consumptive rate of RL in compacted soil at -20 kPa.

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	23.7372	4.62747	5.12962	4.44418E-4
Slope	-7.69231	5.34929	-1.43801	0.180981

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	76.923077	1	76.923077	2.067860	.18098
Error	371.99359	10	37.19936		
Total (Corr.)	448.91667	11			

Correlation Coefficient = -0.413948 R-squared = 17.14 percent
Stnd. Error of Est. = 6.09913



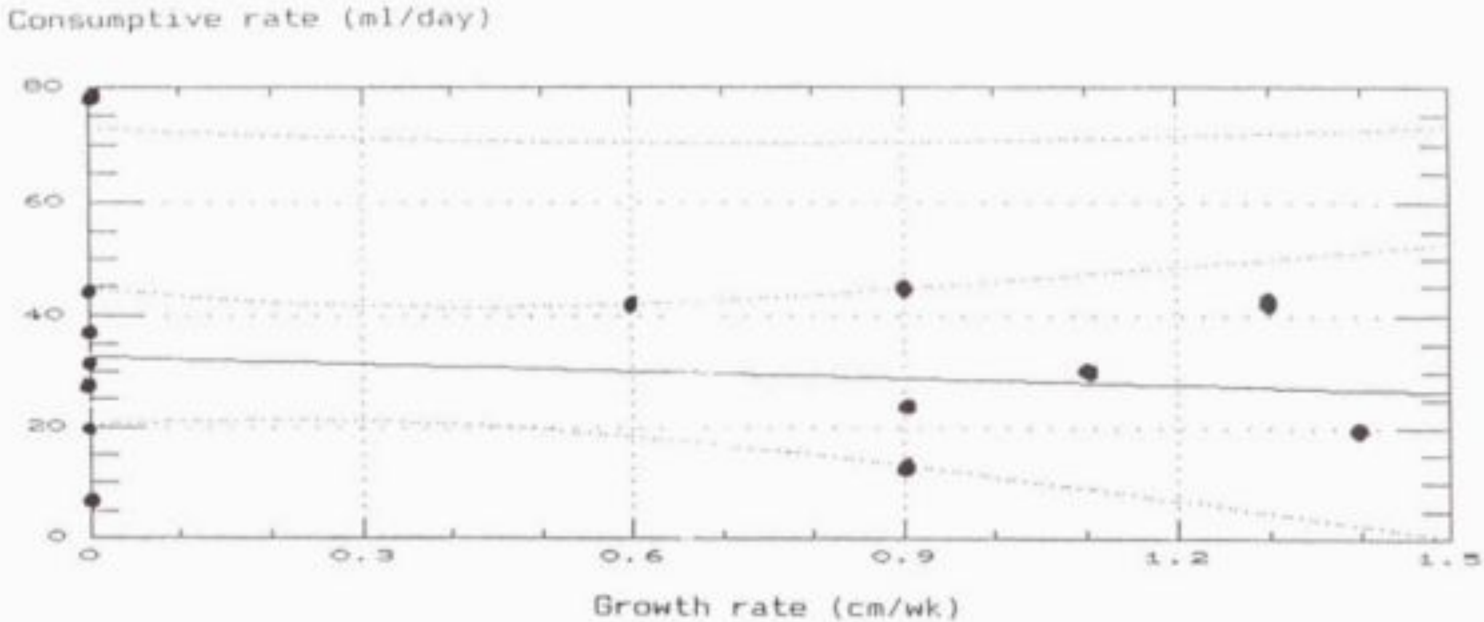
App. 6.3. Regression line showing a relationship between growth rate and water consumptive rate of RL in compacted soil at −10 kPa.

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	42.8652	4.36364	9.82326	4.34082E-7
Slope	-0.383775	9.60427	-0.0399588	0.968783

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	.3371741	1	.3371741	.0015967	.96878
Error	2534.0200	12	211.1683		
Total (Corr.)	2534.3571	13			

Correlation Coefficient = -0.0115344 R-squared = .01 percent
Stnd. Error of Est. = 14.5316



App. 6.4. Regression line showing a relationship between growth rate and water consumptive rate of RL in compacted soil at -30 kPa.

Parameter	Estimate	Standard Error	T Value	Prob. Level
Intercept	32.643	5.54826	5.88346	7.44105E-5
Slope	-4.09128	9.35919	-0.43714	0.669773

Analysis of Variance

Source	Sum of Squares	Df	Mean Square	F-Ratio	Prob. Level
Model	59.206612	1	59.206612	.191091	.66977
Error	3718.0077	12	309.8340		
Total (Corr.)	3777.2143	13			

Correlation Coefficient = -0.125199 R-squared = 1.57 percent
Stnd. Error of Est. = 17.6021

App. 6.5. Stat. anal.

One-Way Analysis of Variance

Data: 1.24 0.58 0.67 2.69 1.74 2.12 0.29 0.27

Level codes: 1 1 1 2 2 2 3 3

Labels: Total dry mass: 1 = 10 kPa; 2 = 20 kPa; 3 = 30 kPa

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	5.0043333	2	2.5021667	17.530	.0055
Within groups	.7136667	5	.1427333		
Total (corrected)	5.7180000	7			

0 missing value(s) have been excluded.

App. 6.6. Stat. anal.

One-Way Analysis of Variance

Data: 0.55 0.26 0.31 1.39 0.90 1.24 0.20 0.19

Level codes: 1 1 1 2 2 2 3 3

Labels: Shoot dry matter: 1 = 10 kPa; 2 = 20 kPa; 3 = 30 kPa

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	1.4726167	2	.7363083	21.136	.0036
Within groups	.1741833	5	.0348367		
Total (corrected)	1.6468000	7			

0 missing value(s) have been excluded.

App. 6.7. Stat. anal.

One-Way Analysis of Variance

Data: 0.69 0.32 0.26 1.30 0.84 0.88 0.09 0.08

Level codes: 1 1 1 2 2 2 3 3

Labels: Root dry matter: 1 = 10 kPa; 2 = 20 kPa; 3 = 30 kPa

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	1.0810167	2	.5405083	12.725	.0109
Within groups	.2123833	5	.0424767		
Total (corrected)	1.2934000	7			

0 missing value(s) have been excluded.

App. 6.8. Stat. anal.

One-Way Analysis of Variance

Data: 0.8 0.81 0.86 1.07 1.07 1.41 2.22 2.38

Level codes: 1 1 1 2 2 2 3 3

Labels: Top:root ratio: 1 = -10 kPa: 2 = -20 kPa: 3 = -30 kPa

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	2.7164167	2	1.3582083	73.869	.0002
Within groups	.0919333	5	.0183867		
Total (corrected)	2.8083500	7			

0 missing value(s) have been excluded.

App. 6.9. Stat. anal.

One-Way Analysis of Variance

Data: 4.02 3.34 3.25 3.36 2.81 3.26 3.29 2.85

Level codes: 1 1 1 2 2 2 3 3

Labels: Total water consumption: 1 = 10 kPa; 2 = 20 kPa; 3 = 30 kPa

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.3414167	2	.1707083	1.370	.3354
Within groups	.6229333	5	.1245867		
Total (corrected)	.9643500	7			

0 missing value(s) have been excluded.

App. 6.10. Stat. anal.

One-Way Analysis of Variance

Data: 0.308 0.173 0.206 0.800 0.619 0.650 0.088 0.095

Level codes: 1 1 1 2 2 2 3 3

Labels: Water use efficiency: 1 = 10 kPa; 2 = 20 kPa; 3 = 30 kPa

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.5212727	2	.2606364	45.453	.0006
Within groups	.0286712	5	.0057342		
Total (corrected)	.5499439	7			

0 missing value(s) have been excluded.

App. 6.11. Stat. anal.

One-Way Analysis of Variance

Data: 94.2 74.4 55.3 241.2 209.8 283.3 50.6 37.5

Level codes: 1 1 1 2 2 2 3 3

Labels: Leaf area: 1 = 10 kPa; 2 = 20 kPa; 3 = 30 kPa

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	63480.410	2	31740.205	44.545	.0007
Within groups	3562.698	5	712.540		
Total (corrected)	67043.109	7			

0 missing value(s) have been excluded.

App. 6.12. Stat. anal.

One-Way Analysis of Variance

Data: 55.0 44.6 35.8 76.5 59.8 65.1 25.9 20.6

Level codes: 1 1 1 2 2 2 3 3

Labels: Root area: 1 = 10 kPa; 2 = 20 kPa; 3 = 30 kPa

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	2347.9704	2	1173.9852	17.042	.0059
Within groups	344.4383	5	68.8877		
Total (corrected)	2692.4087	7			

0 missing value(s) have been excluded.

App. 6.13. Stat. anal.

One-Way Analysis of Variance

Data: 0.58 0.60 0.65 0.32 0.29 0.23 0.51 0.55

Level codes: 1 1 1 2 2 2 3 3

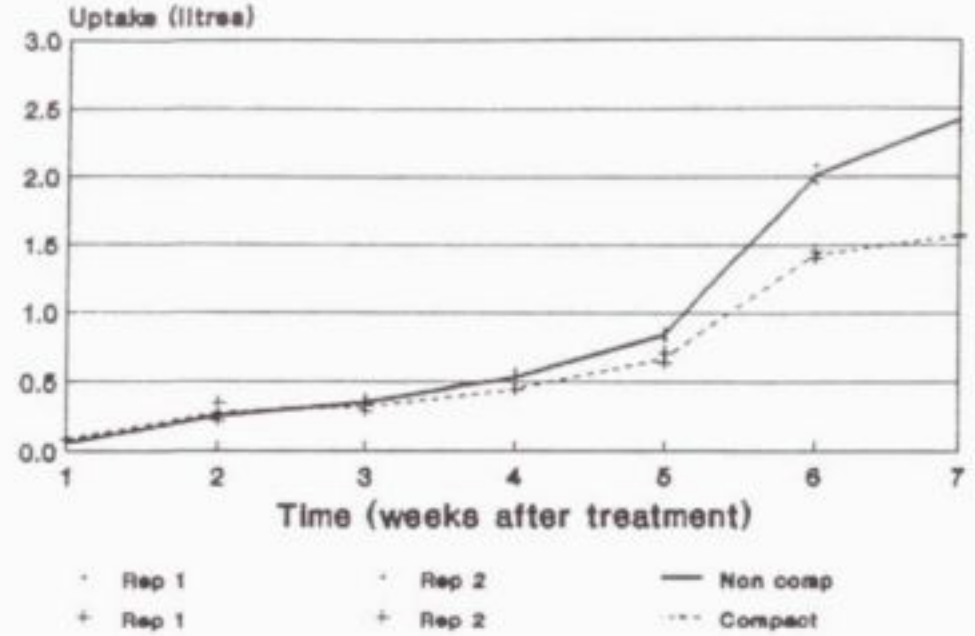
Labels: RA:LA ratio: 1 = 10 kPa; 2 = 20 kPa; 3 = 30 kPa

Range test: Conf. Int.   Confidence level: 95

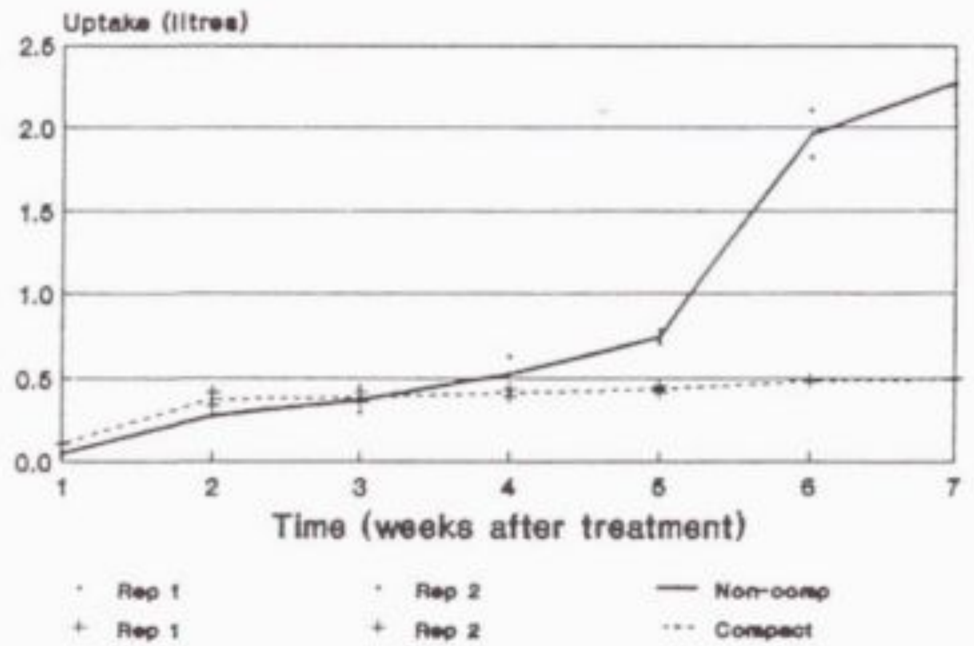
Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.1741875	2	.0870938	57.299	.0004
Within groups	.0076000	5	.0015200		
Total (corrected)	.1817875	7			

0 missing value(s) have been excluded.



App. 6.14. Cumulative water consumption by RL in compacted and non-compacted soil at -20 kPa.



App. 6.15. Cumulative water consumption by RL in compacted and non-compacted soil at -30 kPa.

App. 6.16. Stat. anal.

Analysis of Variance for 1.33 1.57 1.00 1.15 0.51 0.40 0.32 1.04 0.90 1.23 0.51

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	1.2090750	3	.4030250	6.662	.0245
1 1 2 2 1 1 2 2 1 1	.1850083	1	.1850083	3.058	.1309
3 3 3 3 4 4 4 4 5 5	1.0240667	2	.5120333	8.465	.0179
2-FACTOR INTERACTIONS	.3602667	2	.1801333	2.978	.1264
1 1 2 2 1 3 3 3 3 4	.3602667	2	.1801333	2.978	.1264
RESIDUAL	.3629500	6	.0604917		
TOTAL (CORR.)	1.9322917	11		TOTAL DRY MASS	

0 missing values have been excluded.

App. 6.17. Stat. anal.

Analysis of Variance for 1.01 1.12 0.31 0.31 0.48 0.20 0.19 0.79 0.62 0.79 0.25

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.5560167	3	.1853389	4.624	.0529
1 1 2 2 1 1 2 2 1 1	.3888000	1	.3888000	9.700	.0207
3 3 3 3 4 4 4 4 5 5	.1672167	2	.0836083	2.086	.2052
2-FACTOR INTERACTIONS	.4293500	2	.2146750	5.356	.0463
1 1 2 2 1 3 3 3 3 4	.4293500	2	.2146750	5.356	.0463
RESIDUAL	.2405000	6	.0400833		
TOTAL (CORR.)	1.2258667	11		TOP DRY MASS	

0 missing values have been excluded.

App. 6.18. Stat. anal.

Analysis of Variance for 0.32 0.45 0.69 0.84 0.03 0.2 0.13 0.25 0.28 0.44 0.26 0

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.4052583	3	.1350861	14.750	.0036
1 1 2 2 1 1 2 2 1 1	.0374083	1	.0374083	4.085	.0898
3 3 3 3 4 4 4 4 5 5	.3678500	2	.1839250	20.083	.0022
2-FACTOR INTERACTIONS	.1270167	2	.0635083	6.934	.0275
1 1 2 2 1 3 3 3 3 4	.1270167	2	.0635083	6.934	.0275
RESIDUAL	.0549500	6	.0091583		
TOTAL (CORR.)	.5872250	11		ROOT DRY MASS	

0 missing values have been excluded.

App. 6.19. Stat. anal.

Analysis of Variance for 3.16 2.49 0.45 0.37 1.22 1.00 1.46 3.16 2.21 1.80 0.96

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	1.8172250	3	.6057417	2.041	.2097
1 1 2 2 1 1 2 2 1 1	1.7100750	1	1.7100750	5.761	.0533
3 3 3 3 4 4 4 4 5 5	.1071500	2	.0535750	.180	.8392
2-FACTOR INTERACTIONS	6.6646500	2	3.3323250	11.227	.0094
1 1 2 2 1 3 3 3 3 4	6.6646500	2	3.3323250	11.227	.0094
RESIDUAL	1.7809500	6	.2968250		
TOTAL (CORR.)	10.262825	11		TOP:ROOT RATIO	

0 missing values have been excluded.

App. 6.20. Stat. anal.

Analysis of Variance for 291 217 62 114 348 348 469 435 347 181 37 113

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	161765.00	3	53921.667	15.165	.0033
1 1 2 2 1 1 2 2 1 1	21000.33	1	21000.333	5.906	.0511
3 3 3 3 4 4 4 4 5 5	140764.67	2	70382.333	19.794	.0023
2-FACTOR INTERACTIONS	53092.667	2	26546.333	7.466	.0236
1 1 2 2 1 3 3 3 3 4	53092.667	2	26546.333	7.466	.0236
RESIDUAL	21334.000	6	3555.6667		
TOTAL (CORR.)	236191.67	11	ROOT AREA:ROOT MASS RATIO		

0 missing values have been excluded.

App. 6.21. Stat. anal.

Analysis of Variance for 2.55 2.76 1.73 1.73 2.5 2.34 1.57 1.58 2.14 2.41 0.48 0

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	5.6424750	3	1.8808250	157.721	.0000
1 1 2 2 1 1 2 2 1 1	4.2126750	1	4.2126750	353.264	.0000
3 3 3 3 4 4 4 4 5 5	1.4298000	2	.7149000	59.950	.0001
2-FACTOR INTERACTIONS	.5432000	2	.2716000	22.776	.0016
1 1 2 2 1 3 3 3 3 4	.5432000	2	.2716000	22.776	.0016
RESIDUAL	.0715500	6	.0119250		
TOTAL (CORR.)	6.2572250	11		WATER UPTAKE	

0 missing values have been excluded.

App. 6.22. Stat. anal.

Analysis of Variance for 0.50 0.55 0.55 0.64 0.18 0.15 0.17 0.63 0.4 0.49 0.92 0

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	463558	3	.1546528	7.480	.0188
1 1 2 2 1 1 2 2 1 1	.170408	1	.1704083	8.242	.0284
3 3 3 3 4 4 4 4 5 5	.2935500	2	.1467750	7.099	.0262
2-FACTOR INTERACTIONS	.0578167	2	.0289083	1.398	.3173
1 1 2 2 1 3 3 3 3 4	.0578167	2	.0289083	1.398	.3173
RESIDUAL	.1240500	6	.0206750		
TOTAL (CORR.)	.6458250	11	WATER USE EFFICIENCY		

0 missing values have been excluded.

App. 6.23. Stat. anal.

Analysis of Variance for 230 274 48 90 182 155 74 121 120 128 20 38

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	55273.000	3	18424.333	31.468	.0005
1 1 2 2 1 1 2 2 1 1	40600.333	1	40600.333	69.343	.0002
3 3 3 3 4 4 4 4 5 5	14672.667	2	7336.333	12.530	.0072
2-FACTOR INTERACTIONS	6954.6667	2	3477.3333	5.939	.0378
1 1 2 2 1 3 3 3 3 4	6954.6667	2	3477.3333	5.939	.0378
RESIDUAL	3513.0000	6	585.50000		
TOTAL (CORR.)	65740.667	11			LEAF AREA

0 missing values have been excluded.

App. 6.24. Stat. anal.

Analysis of Variance for 93.2 97.6 42.8 95.4 70.7 69.5 61 108.7 97.1 79.6 9.6 24

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	4281.9850	3	1427.3283	3.058	.1132
1 1 2 2 1 1 2 2 1 1	2279.7633	1	2279.7633	4.885	.0691
3 3 3 3 4 4 4 4 5 5	2002.2217	2	1001.1108	2.145	.1982
2-FACTOR INTERACTIONS	3691.8117	2	1845.9058	3.955	.0802
1 1 2 2 1 3 3 3 3 4	3691.8117	2	1845.9058	3.955	.0802
RESIDUAL	2800.0700	6	466.67833		
TOTAL (CORR.)	10773.867	11			

ROOT AREA

0 missing values have been excluded.

App. 6.25. Stat. anal.

Analysis of Variance for 0.40 0.36 0.89 1.06 0.39 0.45 0.83 0.90 0.81 0.62 0.48

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.2702750	3	.0900917	10.057	.0093
1 1 2 2 1 1 2 2 1 1	.2670083	1	.2670083	29.806	.0016
3 3 3 3 4 4 4 4 5 5	.0032667	2	.0016333	.182	.8378
2-FACTOR INTERACTIONS	.3060667	2	.1530333	17.083	.0033
1 1 2 2 1 3 3 3 3 4	.3060667	2	.1530333	17.083	.0033
RESIDUAL	.0537500	6	.0089583		
TOTAL (CORR.)	.6300917	11			

ROOT AREA:LEAF AREA RATIO

0 missing values have been excluded.

App. 6.26. Stat. anal.

Analysis of Variance for 11.09 10.07 36.04 19.21 13.74 15.13 21.23 13.11 17.88 1

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	128.64361	3	42.88120	1.453	.3182
1 1 2 2 1 1 2 2 1 1	106.86301	1	106.86301	3.621	.1057
3 3 3 3 4 4 4 4 5 5	21.78060	2	10.89030	.369	.7061
2-FACTOR INTERACTIONS	194.66487	2	97.332433	3.298	.1081
1 1 2 2 1 3 3 3 3 4	194.66487	2	97.332433	3.298	.1081
RESIDUAL	177.06795	6	29.511325		
TOTAL (CORR.)	500.37643	11			

WATER UPTAKE PER LEAF AREA

0 missing values have been excluded.

App. 6.27. Stat. anal.

Analysis of Variance for 27.2 26.9 23.1 24.7 19.9 21.2 17.7 18.4 17.9 17 14.5 14

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	216.33917	3	72.113056	146.920	.0000
1 1 2 2 1 1 2 2 1 1	26.10750	1	26.107500	53.190	.0003
3 3 3 3 4 4 4 4 5 5	190.23167	2	95.115833	193.784	.0000
2-FACTOR INTERACTIONS	.3050000	2	.1525000	.311	.7441
1 1 2 2 1 3 3 3 3 4	.3050000	2	.1525000	.311	.7441
RESIDUAL	2.9450000	6	.4908333		
TOTAL (CORR.)	219.58917	11			

SOIL WATER CONTENT

0 missing values have been excluded.

App. 6.28. Stat. anal.

Analysis of Variance for 14.4 14.7 12.9 11.3 21.7 20.4 18.3 17.6 23.7 24.6 21.5

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	211.29917	3	70.433056	143.497	.0000
1 1 2 2 1 1 2 2 1	21.06750	1	21.067500	42.922	.0006
3 3 3 3 4 4 4 4 5 5	190.23167	2	95.115833	193.784	.0000
2-FACTOR INTERACTIONS	.3050000	2	.1525000	.311	.7441
1 1 2 2 1 3 3 3 3 4	.3050000	2	.1525000	.311	.7441
RESIDUAL	2.9450000	6	.4908333		
TOTAL (CORR.)	214.54917	11			

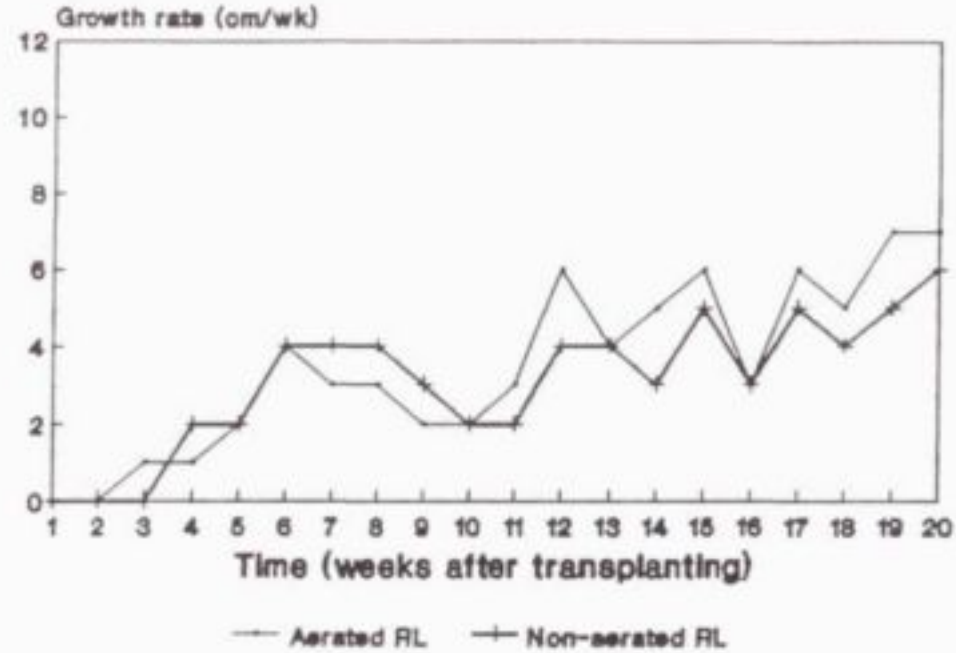
AIR-FILLED PORE

0 missing values have been excluded.

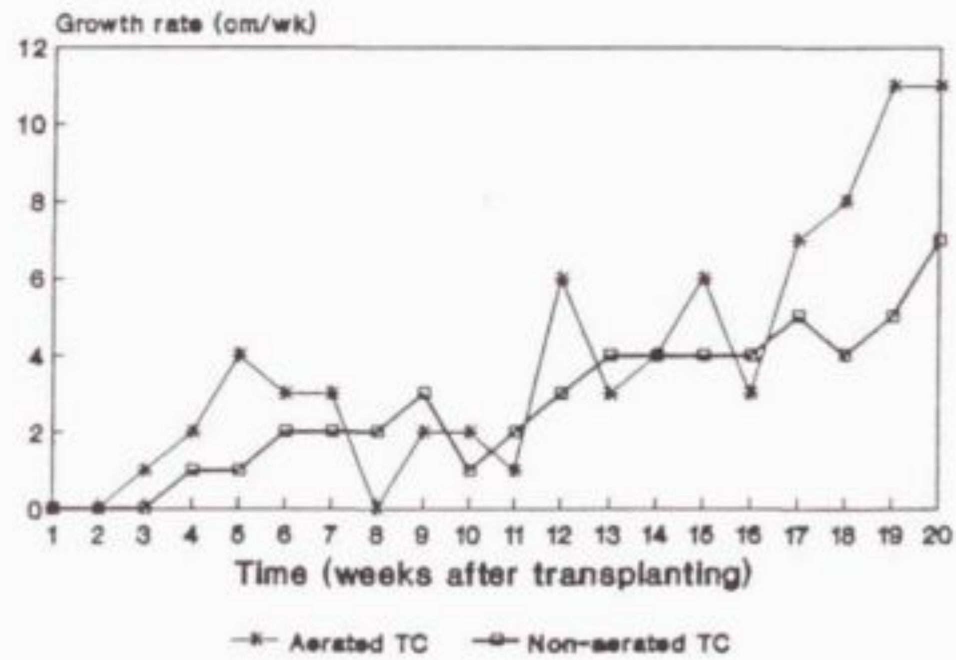
KEY:

1 = Non-compacted; 2 = Compacted

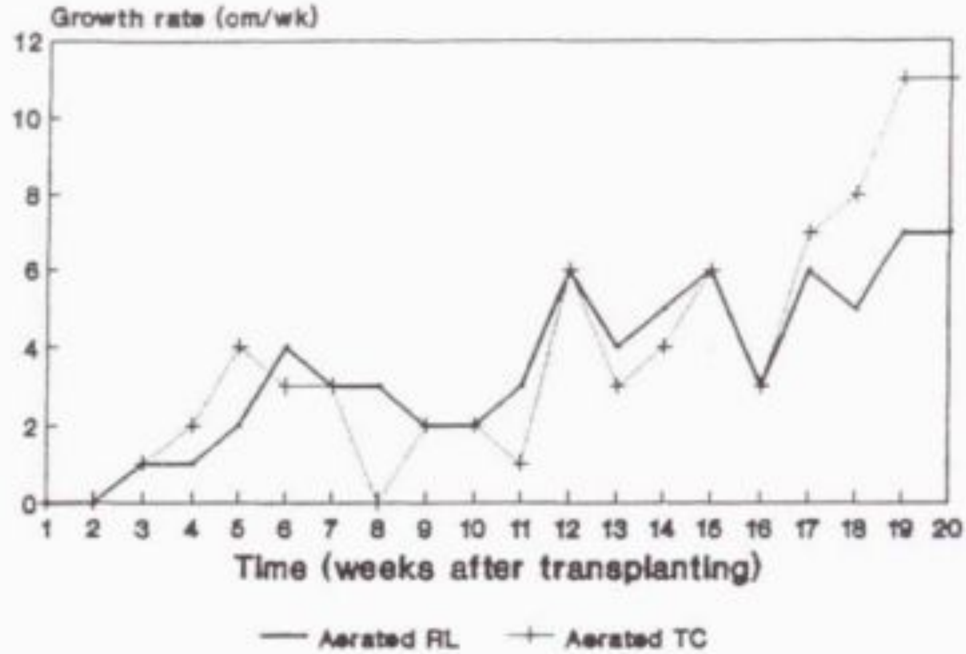
3 = -10 kPa; 4 = -20 kPa; 5 = -30 kPa



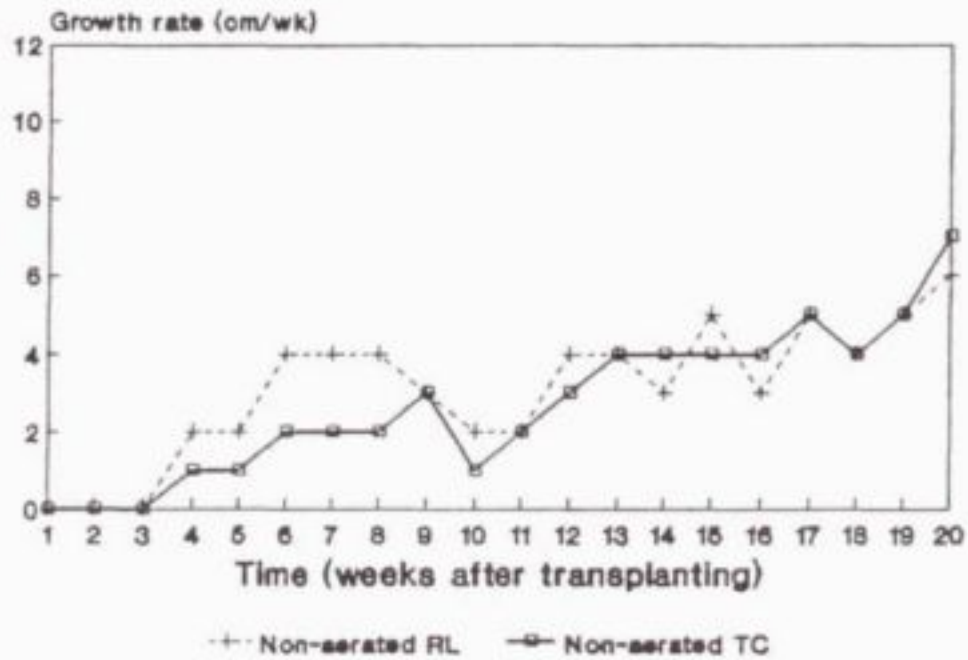
App. 7.1. Growth rate of RL in aerated and non-aerated nutrient solution.



App. 7.2. Growth rate of TC in aerated and non-aerated nutrient solution.



App. 7.3. Growth rate of RL and TC in aerated nutrient solution.



App. 7.4. Growth rate of RL and TC in non-aerated nutrient solution.

App. 7.5. Stat. anal.

One-Way Analysis of Variance

Data: 38.3 43.3 48.9 31.0 27.5 32.1 14.9 18.2 18.6 14.0 10.3 16.3

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: Total mass: 1=RL aerated; 2=RL anoxia; 3=TC aerated; 4=TC anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	1668.3233	3	556.10778	47.151	.0000
Within groups	94.3533	8	11.79417		
Total (corrected)	1762.6767	11			

0 missing value(s) have been excluded.

App. 7.6. Stat. anal.

One-Way Analysis of Variance

Data: 32.9 36.3 41.1 27.7 23.9 28.7 11.8 14.1 13.8 11.7 8.13 13.1

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: Shoot mass: 1=RL aerated; 2=RL anoxia; 3=TC aerated; 4=TC anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	1317.3822	3	439.12741	55.731	.0000
Within groups	63.0353	8	7.87941		
Total (corrected)	1380.4175	11			

0 missing value(s) have been excluded.

App. 7.7. Stat. anal.

One-Way Analysis of Variance

Data: 5.41 7.02 7.76 3.33 3.59 3.43 3.10 4.11 4.82 2.23 2.13 3.27

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: Root mass: 1=RL aerated; 2=RL anoxia; 3=TC aerated; 4=TC anoxia

Range test: Conf. Int. Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	29.228800	3	9.7429333	14.952	.0012
Within groups	5.213067	8	.6516333		
Total (corrected)	34.441867	11			

0 missing value(s) have been excluded.

App. 7.8. Stat. anal.

One-Way Analysis of Variance

Data: 6.1 5.2 5.3 8.3 6.7 8.4 3.8 3.4 2.9 5.3 3.8 4.0

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: Top:root ratio: 1=RL aerated: 2=RL anoxia; 3=TC aerated: 4=TC anoxia

Range test: Conf. Int. Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	32.726667	3	10.908889	21.602	.0003
Within groups	4.040000	8	.505000		
Total (corrected)	36.766667	11			

0 missing value(s) have been excluded.

App. 7.9. Stat. anal.

One-Way Analysis of Variance

Data: 2371 2488 3276 1841 1492 2060 780 721 755 658 572 712

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: Leaf area: 1=RL aerated; 2=RL anoxia; 3=TC aerated; 4=TC anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	8465988.3	3	2821996.1	34.117	.0001
Within groups	661712.7	8	82714.1		
Total (corrected)	9127701.0	11			

0 missing value(s) have been excluded.

App. 7.10. Stat. anal.

One-Way Analysis of Variance

Data: 399 870 1090 405 500 399 261 383 452 195 295 415

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: Root area: 1=RL aerated; 2=RL anoxia; 3=TC aerated; 4=TC anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	421771.33	3	140590.44	3.766	.0593
Within groups	298636.67	8	37329.58		
Total (corrected)	720408.00	11			

0 missing value(s) have been excluded.

App. 7.11. Stat. anal.

One-Way Analysis of Variance

Data: 0.17 0.35 0.40 0.22 0.34 0.22 0.33 0.53 0.57 0.30 0.52 0.58

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: RA:LA ratio: 1=RL aerated: 2=RL anoxia: 3=TC aerated: 4=TC anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.1098250	3	.0366083	2.538	.1300
Within groups	.1154000	8	.0144250		
Total (corrected)	.2252250	11			

0 missing value(s) have been excluded.

App. 7.12. Stat. anal.

One-Way Analysis of Variance

Data: 1.01 0.58 0.54 0.47 0.43 0.41 0.62 0.46 0.30 0.45 0.35 0.37

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: Root hydr. cond. 1=RL aerated: 2=RL anoxia: 3=TC aerated: 4=TC anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.1854250	3	.0618083	2.543	.1295
Within groups	.1944667	8	.0243083		
Total (corrected)	.3798917	11			

0 missing value(s) have been excluded.

App. 7.13. Stat. anal.

One-Way Analysis of Variance

Data: 72.6 123.9 140.5 121.6 139.5 116.3 94.2 92.2 92.8 87.4 135.5 126.7

Level codes: 1 1 1 2 2 2 3 3 3 4 4 4

Labels: BA:root mass: 1 = AE SL; 2 = NAE SL; 3 = AE TC; 4 = NAE TC

Range test: LSD   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	2059.4233	3	686.47444	1.309	.3368
Within groups	4194.7933	8	524.34917		
Total (corrected)	6254.2167	11			

0 missing value(s) have been excluded.

App. 8.1. Stat. anal.

Analysis of Variance for 7 7.9 4.4 6.14 5.45 6.26 6.1 4.3 6.76 3.87 4.27 3.38 4.

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	9.8336125	2	4.9168062	3.191	.0774
1 1 1 1 1 1 1 1 2 2	8.7468062	1	8.7468062	5.677	.0346
3 3 3 3 4 4 4 4 3 3	1.0868062	1	1.0868062	.705	.4262
2-FACTOR INTERACTIONS	.3875062	1	.3875062	.252	.6303
1 1 1 1 1 3 3 3 3 4	.3875062	1	.3875062	.252	.6303
RESIDUAL	18.488275	12	1.5406896		
TOTAL (CORR.)	28.709394	15	TOTAL DRY MASS (TC)		

0 missing values have been excluded.

App. 8.2. Stat. anal.

Analysis of Variance for 5.85 5.56 3.6 4 3.77 4 4.39 2.7 5.4 2.7 2.8 2.46 3.06 4

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	4.1454500	2	2.0727250	1.942	.1859
1 1 1 1 1 1 1 1 2 2	3.[illegible]52250	1	3.1152250	2.919	.1133
3 3 3 3 4 4 4 4 3 3	1.0302250	1	1.0302250	.965	.3555
2-FACTOR INTERACTIONS	1.1236000	1	1.1236000	1.053	.3251
1 1 1 1 1 3 3 3 3 4	1.1236000	1	1.1236000	1.053	.3251
RESIDUAL	12.806450	12	1.0672042		
TOTAL (CORR.)	18.075500	15	TOP DRY MASS (TC)		

0 missing values have been excluded.

App. 8.3. Stat. anal.

Analysis of Variance for 1.17 2.35 0.8 2.15 1.68 2.27 1.7 1.6 1.33 1.15 1.44 0.9

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	1.5256250	2	.7628125	3.681	.0567
1 1 1 1 1 1 1 1 2 2	1.5252250	1	1.5252250	7.361	.0188
3 3 3 3 4 4 4 4 3 3	.0004000	1	.0004000	.002	.9661
2-FACTOR INTERACTIONS	.1681000	1	.1681000	.811	.3949
1 1 1 1 1 3 3 3 3 4	.1681000	1	.1681000	.811	.3949
RESIDUAL	2.4864500	12	.2072042		
TOTAL (CORR.)	4.1801750	15	ROOT DRY MASS (TC)		

0 missing values have been excluded.

App. B.4. Stat. anal.

Analysis of Variance for 5 2.4 4.7 1.9 2.2 1.8 2.6 1.7 4.1 2.4 2 2.7 2.2 4 4 4.3

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	1.0825000	2	.5412500	.491	.6239
1 1 1 1 1 1 1 1 2 2	.7225000	1	.7225000	.655	.4425
3 3 3 3 4 4 4 4 3 3	.3600000	1	.3600000	.326	.5843
2-FACTOR INTERACTIONS	5.0625000	1	5.0625000	4.590	.0534
1 1 1 1 1 3 3 3 3 4	5.0625000	1	5.0625000	4.590	.0534
RESIDUAL	13.235000	12	1.1029167		
TOTAL (CORR.)	19.380000	15			

TOP:ROOT RATIO (TC)

0 missing values have been excluded.

App. B.5. Stat. anal.

Analysis of Variance for 291 278 213 175 202 187 230 123 267 137 150 136 177 229

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	6224.1250	2	3112.0625	1.185	.3[illegible]
[illegible] 1 1 2 2	4522.5625	1	4522.5625	1.7[illegible]2	.2[illegible]
[illegible] 4 4 3 3	1701.5625	1	1701.5625	.648	.[illegible]50
2-FACTOR INTERACTIONS	4389.0625	1	4389.0625	1.671	.2204
1 1 1 1 1 3 3 3 3 4	4389.0625	1	4389.0625	1.671	.2204
RESIDUAL	31516.750	12	2626.3958		
TOTAL (CORR.)	42129.938	15			

LEAF AREA (TC)

0 missing values have been excluded.

App. B.6. Stat. anal.

Analysis of Variance for 183 392 172 171 291 385 250 238 244 237 201 154 177 198

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	22160.000	2	11080.000	2.346	.1380
1 1 1 1 1 1 1 1 2 2	21904.000	1	21904.000	4.639	.0523
3 3 3 3 4 4 4 4 3 3	256.000	1	256.000	.054	.8223
2-FACTOR INTERACTIONS	11449.000	1	11449.000	2.425	.1454
1 1 1 1 1 3 3 3 3 4	11449.000	1	11449.000	2.425	.1454
RESIDUAL	56666.000	12	4722.1667		
TOTAL (CORR.)	90275.000	15			

ROOT AREA (TC)

0 missing values have been excluded.

App. 8.7. Stat. anal.

Analysis of Variance for 0.63 1.4 0.8 0.98 1.44 2.06 1.09 1.94 0.9 1.73 1.34 1.1

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.2640625	2	.1320313	1.189	.3381
1 1 1 1 1 1 1 1 2 2	.1785062	1	.1785062	1.607	.2290
3 3 3 3 4 4 4 4 3 3	.0855563	1	.0855563	.770	.4066
2-FACTOR INTERACTIONS	1.1395563	1	1.1395563	10.259	.0076
1 1 1 1 1 3 3 3 3 4	1.1395563	1	1.1395563	10.259	.0076
RESIDUAL	1.3329250	12	.1110771		
TOTAL (CORR.)	2.7365437	15	ROOT AREA:LEAF AREA RATIO (TC)		

0 missing values have been excluded.

App. 8.8. Stat. anal.

Analysis of Variance for 11.8 10.2 10.8 10.2 11.3 11.2 11.9 11.5 9.2 9.2 8.6 8.0

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	21.512500	2	10.756250	34.744	.0000
1 1 1 1 1 1 1 1 2 2	20.702500	1	20.702500	66.872	.0000
3 3 3 3 4 4 4 4 3 3	.810000	1	.810000	2.616	.1317
2-FACTOR INTERACTIONS	.3025000	1	.3025000	.977	.3528
1 1 1 1 1 3 3 3 3 4	.3025000	1	.3025000	.977	.3528
RESIDUAL	3.7150000	12	.3095833		
TOTAL (CORR.)	25.530000	15	TOTAL DRY MASS (RL)		

0 missing values have been excluded.

App. 8.9. Stat. anal.

Analysis of Variance for 9.4 7.8 8.6 7.5 8.5 8.6 9 8.2 7.8 7.6 6.7 6.3 7.1 6.7 7

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	6.8825000	2	3.4412500	8.833	.0044
1 1 1 1 1 1 1 1 2 2	6.7600000	1	6.7600000	17.352	.0013
3 3 3 3 4 4 4 4 3 3	.1225000	1	.1225000	.314	.5912
2-FACTOR INTERACTIONS	.0225000	1	.0225000	.058	.8167
1 1 1 1 1 3 3 3 3 4	.0225000	1	.0225000	.058	.8167
RESIDUAL	4.6750000	12	.3895833		
TOTAL (CORR.)	11.580000	15	TOP DRY MASS (RL)		

0 missing values have been excluded.

App. B.10. Stat. anal.

Analysis of Variance for 2.35 2.43 2.26 2.66 2.78 2.66 2.88 3.2 1.39 1.66 1.89 1

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	3.9084125	2	1.9542063	44.082	.0000
1 1 1 1 1 1 1 1 2 2	3.6195062	1	3.6195062	81.647	.0000
3 3 3 3 4 4 4 4 3 3	.2889063	1	.2889063	6.517	.0253
2-FACTOR INTERACTIONS	.1387563	1	.1387563	3.130	.1022
1 1 1 1 1 3 3 3 3 4	.1387563	1	.1387563	3.130	.1022
RESIDUAL	.5319750	12	.0443313		
TOTAL (CORR.)	4.5791438	15	ROOT DRY MASS (RL)		

0 missing values have been excluded.

App. B.11. Stat. anal.

Analysis of Variance for 4 3.2 3.8 2.8 3.1 3.2 3.1 2.6 5.6 4.6 3.6 3.7 3.6 4.4 4

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	4.8325000	2	2.4162500	6.060	.0152
1 1 1 1 1 1 1 1 2 2	4.4100000	1	4.4100000	11.060	.0060
3 3 3 3 4 4 4 4 3 3	.4225000	1	.4225000	1.060	.3236
2-FACTOR INTERACTIONS	.0625000	1	.0625000	.157	.7033
1 1 1 1 1 3 3 3 3 4	.0625000	1	.0625000	.157	.7033
RESIDUAL	4.7850000	12	.3987500		
TOTAL (CORR.)	9.6800000	15	TOP:ROOT RATIO (RL)		

0 missing values have been excluded.

App. B.12. Stat. anal.

Analysis of Variance for 798 614 767 683 639 641 660 624 664 697 584 560 563 536

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	40621.250	2	20310.625	5.747	.0178
1 1 1 1 1 1 1 1 2 2	24492.250	1	24492.250	6.930	.0219
3 3 3 3 4 4 4 4 3 3	16129.000	1	16129.000	4.564	.0539
2-FACTOR INTERACTIONS	484.00000	1	484.00000	.137	.7217
1 1 1 1 1 3 3 3 3 4	484.00000	1	484.00000	.137	.7217
RESIDUAL	42410.500	12	3534.2083		
TOTAL (CORR.)	83515.750	15	LEAF AREA (RL)		

App. 8.13. Stat. anal.

Analysis of Variance for 651 592 581 623 740 740 677 803 368 430 454 424 530 472

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	236586.50	2	118293.25	76.957	.0000
1 1 1 1 1 1 1 1 2 2	197580.25	1	197580.25	128.539	.0000
3 3 3 3 4 4 4 4 3 3	39006.25	1	39006.25	25.376	.0003
2-FACTOR INTERACTIONS	3481.0000	1	3481.0000	2.265	.1582
1 1 1 1 1 3 3 3 3 4	3481.0000	1	3481.0000	2.265	.1582
RESIDUAL	18445.500	12	1537.1250		
TOTAL (CORR.)	258513.00	15		ROOT AREA (RL)	

0 missing values have been excluded.

App. 8.14. Stat. anal.

Analysis of Variance for 0.8 0.96 0.76 0.9 1.16 1.15 1.03 1.3 0.55 0.6 0.8 0.8 0

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	.4467125	2	.2233563	17.788	.0003
1 1 1 1 1 1 1 1 2 2	.2139062	1	.2139062	17.036	.0014
3 3 3 3 4 4 4 4 3 3	.2328063	1	.2328063	18.541	.0010
2-FACTOR INTERACTIONS	.0162563	1	.0162563	1.295	.2774
1 1 1 1 1 3 3 3 3 4	.0162563	1	.0162563	1.295	.2774
RESIDUAL	.1506750	12	.0125563		
TOTAL (CORR.)	.6136437	15	ROOT AREA:LEAF AREA RATIO		

0 missing values have been excluded.

KEY:

1 = pH 7; 2 = pH 4

3 = Aerated; 4 = Non-aerated

App. 9.1. Stat. anal.

One-Way Analysis of Variance

Data: 11.95 11.28 15.39 13.22 14.52 9.27 7.58 8.04 6.19 6.01

Level codes: 1 1 1 1 1 2 2 2 2 2

Labels: Total mass: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	85.673290	1	85.673290	35.893	.0003
Within groups	19.095360	8	2.386920		
Total (corrected)	104.76865	9			

0 missing value(s) have been excluded.

App. 9.2. Stat. anal.

One-Way Analysis of Variance

Data: 8.41 7.89 12.08 8.03 9.96 6.59 5.89 5.77 4.00 4.17

Level codes: 1 1 1 1 1 2 2 2 2 2

Labels: Shoot mass: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	39.800250	1	39.800250	17.936	.0029
Within groups	17.752440	8	2.219055		
Total (corrected)	57.552690	9			

0 missing value(s) have been excluded.

App. 9.3. Stat. anal.

One-Way Analysis of Variance

Data: 3.54 3.39 3.31 5.19 4.56 2.68 1.69 2.27 2.19 1.84

Level codes: 1 1 1 1 1 2 2 2 2 2

Labels: Root mass: 1 = aerated; 2 = anoxia

Range test: Conf. Int. Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	8.6862400	1	8.6862400	20.482	.0019
Within groups	3.3928000	8	.4241000		
Total (corrected)	12.079040	9			

0 missing value(s) have been excluded.

App. 9.4. Stat. anal.

One-Way Analysis of Variance

Data: 2.38 2.33 3.65 1.55 2.18 2.46 3.49 2.54 1.83 2.27

Level codes: 1 1 1 1 1 2 2 2 2 2

Labels: Top:root ratio: 1 = aerated: 2 = non-aerated

Range test: Conf. Int. Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.0250000	1	.0250000	.052	.8271
Within groups	3.8205600	8	.4775700		
Total (corrected)	3.8455600	9			

0 missing value(s) have been excluded.

App. 9.5. Stat. anal.

One-Way Analysis of Variance

Data: 363.4 341.1 312.3 548.7 485.4 285.2 358.8 287.7 176.1 185.4

Level codes: 1 1 1 1 1 2 2 2 2 2

Labels: Leaf area: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	57562.569	1	57562.569	7.090	.0287
Within groups	64950.680	8	8118.835		
Total (corrected)	122513.25	9			

0 missing value(s) have been excluded.

App. 9.6. Stat. anal.

One-Way Analysis of Variance

Data: 237.2 303.7 242.0 367.0 299.2 212.9 191.6 185.3 186.6 172.0

Level codes: 1 1 1 1 1 2 2 2 2 2

Labels: Root area: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	25070.049	1	25070.049	16.470	.0036
Within groups	12177.116	8	1522.140		
Total (corrected)	37247.165	9			

0 missing value(s) have been excluded.

App. 9.7. Stat. anal.

One-Way Analysis of Variance

Data: 19 35 11 35 30 16 7 13 14 13

Level codes: 1 1 1 1 1 2 2 2 2 2

Labels: Root volume: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	448.90000	1	448.90000	7.223	.0276
Within groups	497.20000	8	62.15000		
Total (corrected)	946.10000	9			

0 missing value(s) have been excluded.

App. 9.8. Stat. anal.

One-Way Analysis of Variance

Data: 0.653 0.889 0.772 0.669 0.616 0.748 0.534 0.644 1.059 0.927

Level codes: 1 1 1 1 1 2 2 2 2 2

Labels: RA:LA ratio: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.0097969	1	.0097969	.343	.5804
Within groups	.2286280	9	.0285785		
Total (corrected)	.2384249	9			

0 missing value(s) have been excluded.

App. 9.9. Stat. anal.

One-Way Analysis of Variance

Data: 0.812 0.194 0.812 0.516 0.274 0.162 0.169 0.280 0.251 0.236

Level codes: 1 1 1 1 1 2 2 2 2 2

Labels: Root hydraulic conductivity: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.2280100	1	.2280100	5.240	.0513
Within groups	.3481044	8	.0435131		
Total (corrected)	.5761144	9			

0 missing value(s) have been excluded.

App. 9.10. Stat. anal.

One-Way Analysis of Variance

Data: 3.96 2.23 3.77 3.74 3.50 3.29

Level codes: 1 1 1 2 2 2

Labels: N concentration: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.0541500	1	.0541500	.114	.7561
Within groups	1.9016000	4	.4754000		
Total (corrected)	1.9557500	5			

0 missing value(s) have been excluded.

App. 9.11. Stat. anal.

One-Way Analysis of Variance

Data: 0.34 0.28 0.36 0.35 0.32 0.35

Level codes: 1 1 1 2 2 2

Labels: P concentration: 1 = serated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.0002667	1	.0002667	.262	.6407
Within groups	.0040667	4	.0010167		
Total (corrected)	.0043333	5			

0 missing value(s) have been excluded.

App. 9.12. Stat. anal.

One-Way Analysis of Variance

Data: 3.16 3.19 2.81 3.04 3.44 3.00

Level codes: 1 1 1 2 2 2

Labels: K concentration: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.0170667	1	.0170667	.329	.6029
Within groups	.2076667	4	.0519167		
Total (corrected)	.2247333	5			

0 missing value(s) have been excluded.

App. 9.13. Stat. anal.

One-Way Analysis of Variance

Data: 0.06 0.04 0.04 0.08 0.05 0.05

Level codes: 1 1 1 2 2 2

Labels: Na concentration: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	2.66667E-004	1	2.66667E-004	1.231	.3295
Within groups	8.66667E-004	4	2.16667E-004		
Total (corrected)	.0011333	5			

0 missing value(s) have been excluded.

App. 9.14. Stat. anal.

One-Way Analysis of Variance

Data: 159 201 180 244 328 234

Level codes: 1 1 1 2 2 2

Labels: Fe concentration: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	11792.667	1	11792.667	7.593	.0511
Within groups	6212.667	4	1553.167		
Total (corrected)	18005.333	5			

0 missing value(s) have been excluded.

App. 9.15. Stat. anal.

One-Way Analysis of Variance

Data: 1035 1244 1346 1274 1604 1311

Level codes: 1 1 1 2 2 2

Labels: Mn concentration: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	53016.00	1	53016.000	1.834	.2471
Within groups	115641.33	4	28910.333		
Total (corrected)	168657.33	5			

0 missing value(s) have been excluded.

App. 9.16. Stat. anal.

One-Way Analysis of Variance

Data: 2.65 3.08 2.97 2.68 2.86 2.58

Level codes: 1 1 1 2 2 2

Labels: Ca concentration: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.0560667	1	.0560667	1.601	.2744
Within groups	.1400667	4	.0350167		
Total (corrected)	.1961333	5			

0 missing value(s) have been excluded.

App. 9.17. Stat. anal.

One-Way Analysis of Variance

Data: 1.19 1.04 0.95 1.13 1.20 1.16

Level codes: 1 1 1 2 2 2

Labels: K:Ca ratio: 1 = aerated; 2 = anoxia

Range test: Conf. Int. Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.0160167	1	.0160167	2.010	.2292
Within groups	.0318667	4	.0079667		
Total (corrected)	.0478833	5			

0 missing value(s) have been excluded.

App. 9.18. Stat. anal.

One-Way Analysis of Variance

Data: 0.24 0.23 0.23 0.24 0.26 0.28

Level codes: 1 1 1 2 2 2

Labels: Mg concentration: 1 = aerated; 2 = anoxia

Range test: Conf. Int. Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.0010667	1	.0010667	4.923	.0907
Within groups	.0008667	4	.0002167		
Total (corrected)	.0019333	5			

0 missing value(s) have been excluded.

App. 9.19. Stat. anal.

One-Way Analysis of Variance

Data: 1.09 0.96 0.88 1.04 1.10 1.05

Level codes: 1 1 1 2 2 2

Labels: X:(Ca+Mg) ratio: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.0112667	1	.0112667	1.837	.2468
Within groups	.0245333	4	.0061333		
Total (corrected)	.0358000	5			

0 missing value(s) have been excluded.

App. 9.20. Stat. anal.

One-Way Analysis of Variance

Data: 11.04 13.39 12.91 11.17 11.00 9.21

Level codes: 1 1 1 2 2 2

Labels: Ca:Mg ratio: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	5.9202667	1	5.9202667	4.352	.1053
Within groups	5.4414667	4	1.3603667		
Total (corrected)	11.361733	5			

0 missing value(s) have been excluded.

App. 9.21. Stat. anal.

One-Way Analysis of Variance

Data: 33.0 22.5 12.0 7.5 0.0 1.5

Level codes: 1 1 1 2 2 2

Labels: Zn concentration: 1 = aerated; 2 = anoxia

Range test: Conf. Int. Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	570.37500	1	570.37500	9.054	.0396
Within groups	252.00000	4	63.00000		
Total (corrected)	822.37500	5			

0 missing value(s) have been excluded.

App. 9.22. Stat. anal.

One-Way Analysis of Variance

Data: 13.17 13.87 12.22 12.67 13.23 10.71

Level codes: 1 1 1 2 2 2

Labels: K:Mg ratio: 1 = aerated; 2 = anoxia

Range test: Conf. Int. Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	1.1704167	1	1.1704167	.961	.3924
Within groups	4.8735333	4	1.2183833		
Total (corrected)	6.0439500	5			

0 missing value(s) have been excluded.

App. 9.23. Stat. anal.

One-Way Analysis of Variance

Data: 10.0 0.0 0.0 1.5 6.0 3.0

Level codes: 1 1 1 2 2 2

Labels: Cu concentration: 1 = aerated: 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.041667	1	.041667	.002	.9656
Within groups	77.166667	4	19.291667		
Total (corrected)	77.208333	5			

0 missing value(s) have been excluded.

App. 9.24. Stat. anal.

One-Way Analysis of Variance

Data: 333 269 376 247 206 190

Level codes: 1 1 1 2 2 2

Labels: N content: 1 = aerated: 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	18704.167	1	18704.167	9.940	.0344
Within groups	7526.667	4	1881.667		
Total (corrected)	26230.833	5			

0 missing value(s) have been excluded.

App. 9.25. Stat. anal.

One-Way Analysis of Variance

Data: 28.6 33.8 35.9 23.1 18.8 20.2

Level codes: 1 1 1 2 2 2

Labels: P content: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	218.40667	1	218.40667	23.071	.0086
Within groups	37.86667	4	9.46667		
Total (corrected)	256.27333	5			

0 missing value(s) have been excluded.

App. 9.26. Stat. anal.

One-Way Analysis of Variance

Data: 266 385 280 200 203 173

Level codes: 1 1 1 2 2 2

Labels: K content: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	21004.167	1	21004.167	9.328	.0379
Within groups	9006.667	4	2251.667		
Total (corrected)	30010.833	5			

0 missing value(s) have been excluded.

App. 9.27. Stat. anal.

One-Way Analysis of Variance

Data: 223 372 296 177 169 149

Level codes: 1 1 1 2 2 2

Labels: Ca content: 1 = aerated: 2 = anoxia

Range test: Conf. Int. Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	26136.000	1	26136.000	9.077	.0394
Within groups	11518.000	4	2879.500		
Total (corrected)	37654.000	5			

0 missing value(s) have been excluded.

App. 9.28. Stat. anal.

One-Way Analysis of Variance

Data: 20.2 27.8 22.9 15.8 15.3 16.2

Level codes: 1 1 1 2 2 2

Labels: Mg content: 1 = aerated; 2 = anoxia

Range test: Conf. Int. Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	92.826667	1	92.826667	12.339	.0246
Within groups	30.093333	4	7.523333		
Total (corrected)	122.92000	5			

0 missing value(s) have been excluded.

App. 9.29. Stat. anal.

One-Way Analysis of Variance

Data: 5.0 4.8 4.0 5.3 2.9 2.9

Level codes: 1 1 1 2 2 2

Labels: Na content: 1 = aerated: 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	1.2150000	1	1.2150000	1.105	.3526
Within groups	4.4000000	4	1.1000000		
Total (corrected)	5.6150000	5			

0 missing value(s) have been excluded.

App. 9.30. Stat. anal.

One-Way Analysis of Variance

Data: 1.3 2.4 1.8 1.6 1.9 1.4

Level codes: 1 1 1 2 2 2

Labels: Fe content: 1 = aerated: 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.0600000	1	.0600000	.327	.6036
Within groups	.7333333	4	.1833333		
Total (corrected)	.7933333	5			

0 missing value(s) have been excluded.

App. 9.31. Stat. anal.

One-Way Analysis of Variance

Data: 8.7 15.0 13.4 8.4 9.4 7.6

Level codes: 1 1 1 2 2 2

Labels: Mn content: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	22.815000	1	22.815000	3.955	.1176
Within groups	23.073333	4	5.768333		
Total (corrected)	45.888333	5			

0 missing value(s) have been excluded.

App. 9.32. Stat. anal.

One-Way Analysis of Variance

Data: 0.28 0.27 0.12 0.05 0.00 0.01

Level codes: 1 1 1 2 2 2

Labels: Zn content: 1 = aerated; 2 = anoxia

Range test: Conf. Int.   Confidence level: 95

Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	.0620167	1	.0620167	14.202	.0196
Within groups	.0174667	4	.0043667		
Total (corrected)	.0794833	5			

0 missing value(s) have been excluded.

App. 9.33. Stat. anal.

One-Way Analysis of Variance

Data: 66.9 85.6 73.1 70.7 65.6 79.4 113.4 81.6 85.2 93.5

Level codes: 1 1 1 1 1 2 2 2 2 2

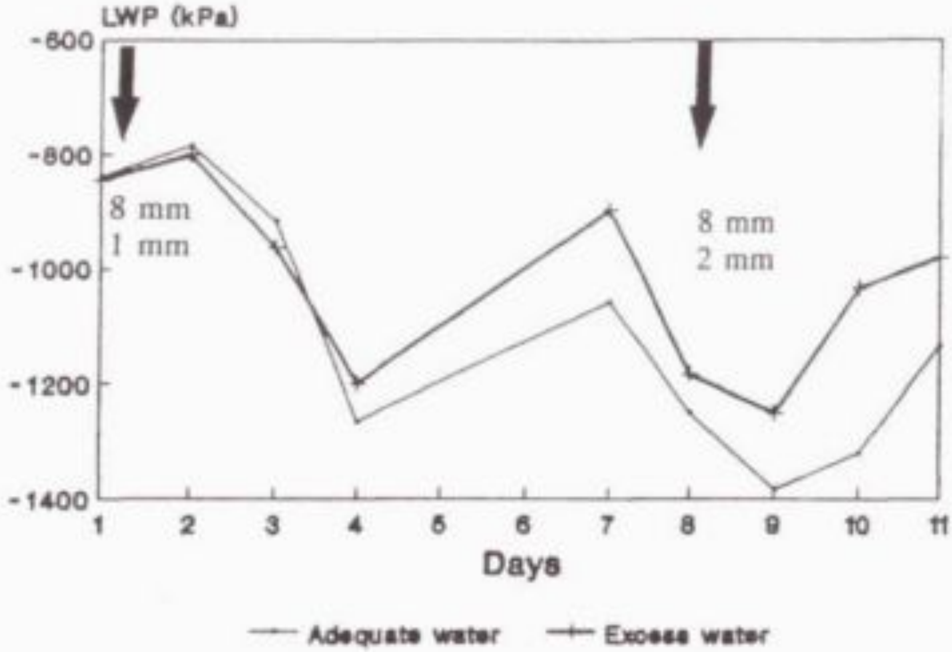
Labels: RA:root mass: 1 = Aerated: 2 = Non-aerated

Range test: LSD   Confidence level: 95

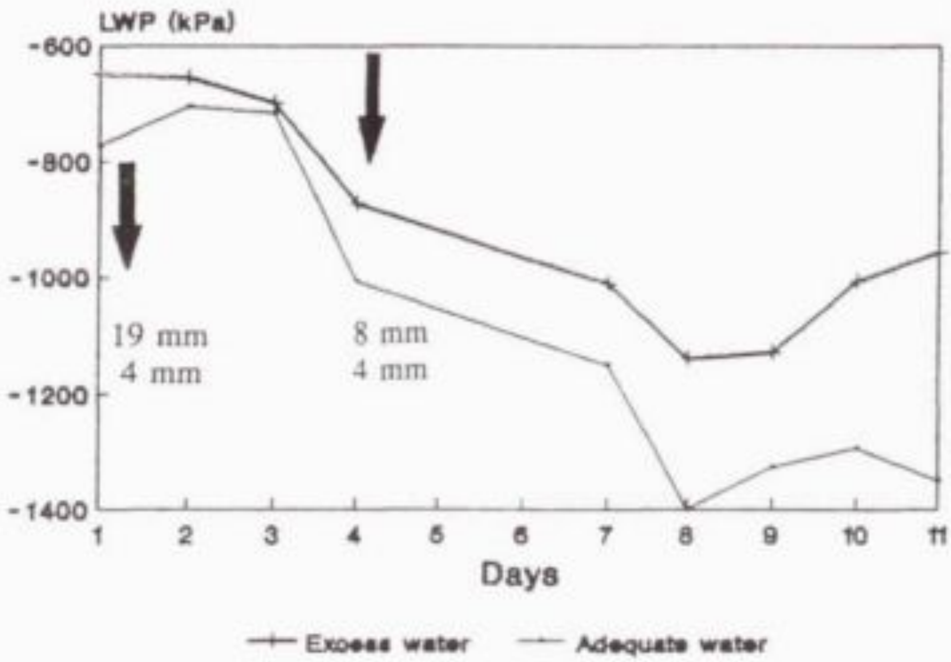
Analysis of variance

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
Between groups	831.7440	1	831.74400	4.537	.0338
Within groups	1017.9560	8	127.24450		
Total (corrected)	1849.7000	9			

0 missing value(s) have been excluded.



App. 10.1. Leaf water potential of citrus in excessively and moderately watered Sterkspruit soil profile at 15H30.



App. 10.2. Leaf water potential of citrus in excessively and moderately watered Hutton soil profile at 15H00.