VINE ROOTS

E ARCHER | D SAAYMAN

Vine Roots

All rights reserved

Copyright © 2018 The Institute for Grape and Wine Sciences (IGWS), Stellenbosch University

The authors have made every effort to obtain permission for and acknowledge the use of copyrighted material.

No part of this book may be reproduced or transmitted in any form or by any electronic, photographic or mechanical means, including photocopying and recording on record, tape or laser disk, on microfilm, via the Internet, by e-mail, or by any other information storage and retrieval system.

First edition 2018

ISBN 978-1-928314-44-8 (e-book)

Set in Futura Bk BT 11/14.5
Cover design, typesetting and production by AFRICAN SUN MeDIA

www.africansunmedia.co.za

MONASH SOUTH AFRICA | villa

MONASH SOUTH AFRICA IN PARTNERSHIP WITH VILLA, YIELDING A BETTER TOMORROW

BRIDGING THE AGRICULTURAL SKILLS GAP IN SA

The 2017 World Economic Forum Report states that Africa's skills gap at secondary school level is high. In most African countries, local business executives are of the opinion that secondary school graduates do not possess, on average, the skills employers demand from a productive workforce.

Add to this the fact that leading South African farming entities share the common sentiment that agricultural colleges are no longer delivering the well-rounded, technically skilled professionals that is critical in the role of not only production managers, but also lesser skilled workers.

It's clear that young Africans deserve urgent and tangible actions to be taken to adequately equip them for future roles in the agri-industry. They need an enabling environment that will prepare them for competing in the 'global village' where interconnectivity and technology-dense work environments define labour markets.

State intervention and support on the African continent is generally slow and fraught with bureaucratic impediment. The logical solution is to involve private industry, i.e. the required skills, experience and funding – effective public-private collaboration can contribute to reduce skill-gaps at national and regional levels.

Villa is taking action

It's against this backdrop that Villa is introducing the new Monash / Villa partnership in training – a private enterprise partnership aimed at addressing some of the key issues highlighted above. The Villa Academy is joining forces with Monash South Africa, a world class educational institution dedicated to supporting South Africa and the continent to meet its diverse economic and educational needs by providing internationally recognised qualifications.

The role of agriculture in the South African economy

The South African economy is heavily reliant on the agricultural sector. Agriculture delivers more jobs per Rand invested than any other productive sector, and remains critical in the face of rural poverty and food insecurity (DAFF, 2016). The primary production component of the agricultural sector contributes about 3% to the country's GDP, but if the entire value chain of agriculture is taken into account, its contribution to GDP increases to about 12%.

Agriculture is often neither a study direction, nor a career, of first choice. Partly to blame for this reality is limited awareness and understanding of the vast number of agri-business and entrepreneurship career opportunities that exist along the entire length of the food and nutrition value chain. Much can be, and should be, done to change perceptions, which are currently evident at both school and higher education levels.

Appropriately trained graduates: South Africa

The NQF (National Qualification Framework) of South Africa abounds with registered qualifications in the field of agriculture, but they predominantly focus on primary production and research.

In light of the variety of components comprising the total agricultural supply chain, it should be recognised that not only skills linked with university degrees are required, but that skills should also come from a wider range of disciplines outside of the traditional agriculture-focused qualifications.

The 'boundary' of agriculture is pliable – there are numerous qualifications and courses with links to the field of agriculture. In order to be relevant, Agricultural Education and Training (AET) needs to focus on building capacities not only for agricultural production, but also to equip a broader range of professionals and practitioners with the necessary skills to engage successfully with the key nodes (links) in the agricultural value chain.

In addition to relevance, curricula should be multi- and transdisciplinary in order to build capacity for solving modern-day challenges such as evolving environments (e.g. climate change), new weeds and pests, resistance to pesticides, improved crops and livestock through classical breeding and genetic modification, etc.

A challenge facing AET in South Africa and other countries on the continent is how to allocate scarce resources towards both commercial and small-scale farming. The argument, in particular for South Africa, is that currently there is skewed focus towards commercial agriculture; however, the reverse is true in certain other African countries, or perceived as more equitable. Where there is consensus, across all levels of agricultural endeavour, is that socio-economic aspects get too little attention.

More practical exposure needed in student studies

The South African agri-industry, over a prolonged period, has lamented the lack of practical exposure and experience of university graduates in particular. This unfortunate chasm in practical experience vested in graduates, which exist between university and industry, puts the brake, temporarily at least, on not only a company's competitiveness but also that of the country.

Funding and resource allocation

Funding for education is a contentious issue. In all forums where AET have been workshopped, the need for increased funding is raised – top of the item list slated for increased funding is "practical, vocationally relevant training".

Lack of funding is a debilitating factor for schools delivering agricultural science as a programme or subject. Shortcomings include lack of adequate infrastructure for practical training. Inefficient channelling and management of funding has been identified as problematic.

The new partnership between Villa and Monash will go some distance to bridging not only the funding gap, but the skills gap as well... giving a vast number of young Africans the opportunity to pursue long and successful careers across all spheres of the agri-industry.

INSTITUTE FOR GRAPE AND WINE SCIENCES (IGWS)

The Institute for Grape and Wine Sciences (IGWS) is an initiative of the wine and table grape industries and Stellenbosch University (SU). The aims of the IGWS are the establishment of world class training in grape and wine science, the promotion of research relevant to the local industry, as well as technology transfer to the wine and table grape industries. The initial focus was especially on the improvement of the infrastructure of training cellars and the purchase of modern research equipment. The establishment of critical human resources in training and research at the University, relevant to the wine and table grape industries, is a priority. Seven platforms have been established, and each platform is managed by a coordinator to give effect to the aims of the IGWS. These include an analytical, internship, sensory, viticulture, oenology, viticulture technology transfer, as well as an oenology technology transfer platform.

One of the chief focuses of the IGWS is technology transfer and to communicate existing as well as new research and information to the industry. The purpose of this is to expand and reinforce the knowledge of people involved in the industry and thus improve the quality of South African viticulture and oenology. This contributes to an industry which is more competitive internationally.

A needs assessment was done in the wine industry to identify priority themes for technology transfer. One of the great needs was the packaging of available information on vine roots. As a result, the IGWS initiated and coordinated a project which led to the publication of this book. Due to the involvement of Villa-Monash Academy in training, they kindly also contributed financially to make the publication possible.

In addition, in future the IGWS will focus on ensuring much closer ties between academics and the industry by initiating innovation projects and to further development initiatives originating from research. Specific attention will be given to projects which can have relevance for the industry if they can be developed into products, services or courses.

For more information on the IGWS, visit the website www.igws.co.za. The website also contains articles, e-books, fact sheets and a variety of information and resources for winemakers and viticulturists.

IGWS
INSTITUTE FOR GRAPE
AND WINE SCIENCES

DEDICATED TO 'OOM' TIENIE

This book is dedicated to M.S. le Roux (`Oom´ Tienie)

Intensive vine root studies of vineyards were done here in South Africa in 1941 by M.S. le Roux, later deputy director of the then Department of Agriculture's Research Institute for Viticulture and Oenology. His results were presented in the form of an MSc dissertation. They never appeared in local or international journals and as a result remained practically unknown. The accompanying photograph comes from his thesis and shows him busy with extensive excavations at the Welgevallen experimental farm of the University of Stellenbosch.

CONTENTS

VIABLE VITICULTURE NECESSITATES SCIENTIFIC FARMING WITH ROOTS AND SUNLIGHT

- Eben Archer

FOREWORD - dr. Jakob Deist

Because of climate change, South Africa is constantly becoming drier while the increasing population results in a constantly growing demand for water. This results in agriculture receiving a constantly diminishing fraction of the available water. The viticulture and wine industries, therefore, have to supply sufficient high quality products to the consumer with less water. The future of the South African wine industry further depends on the production of high quality, uniquely South African wines. The effect of, among others, the soil on wine quality and uniqueness is affected through the roots and their interaction with their environment.

There is, therefore, a growing need for knowledge and information on the vine root. A summary of the existing knowledge on vine roots and their interaction with their environment is therefore of great value for planning of new research and formulation of more efficient technologies. The authors of this publication succeed very well in summarising the existing knowledge on vine roots – their structure and physiology, their reaction to internal and external factors and their effect on vegetative growth, crop and grape composition from more than 240 publications from across the wine world.

It was my privilege to have known both authors as colleagues over many years. They are well equipped to have done this summary of the existing knowledge on vine roots, seeing their schooling in viticulture and soil science, their own research on vine roots over many years, and their practical experience as specialist advisers in the wine industry.

FOREWORD - dr. Albert Strever

Vine roots are a difficult topic in which to train students, for a variety of reasons. Especially for the student who is new to viticulture, the vine root system is something which they are not regularly exposed to in practice. In addition, the theory about vine roots is mostly dispersed among theoretical studies about spacing, rootstocks, trellising systems, diseases and pests, etc. Thus there are few theoretical manuals containing a comprehensive overview of vine roots from an anatomical/morphological, as well as plant physiological and soil perspective.

This book I can thus, as a trainer in Viticulture, recommend with full confidence as a basic work to which each student in the field should be exposed. Its comprehensive nature, and the attention to detail, should leave each student (whether specialising in viticulture or oenology or as representative of fertiliser/spray product companies), with great respect for the vine, but specifically then for the less visible underground part of the vine.

In many of my lectures I emphasise that a large percentage of success in viticulture is determined by elements which are not visible every day, i.e. the vine roots, reserves, bud fertility. Thus it is important that the student develops a good understanding of the links between these less visible elements and the visible/easily measurable elements. In my opinion this book provides an excellent foundation for this.

I would thus like to compliment the authors and the team responsible for publishing this work with an incredibly relevant contribution to the field, and something on which future expansions and updates can build. The reader will be impressed by the level of detail and experience which is conveyed. It is not only a mere synthesis of the available literature, but it is a product of the authors' impressive, long careers in close contact with the vine, the soil, and the roots. This certainly sets an example for other sectors of agriculture of how practical and theoretical knowledge built up over many years can be conveyed to a new generation of young agriculturists/viticulturists.

CHAPTER 1

GROWTH, MORPHOLOGY AND ANATOMY OF VINE ROOTS

CHAPTER 1

GROWTH, MORPHOLOGY AND ANATOMY OF VINE ROOTS

1.1 Root growth and expansion

Differences in the behaviour of vines on different soils as well as between rootstocks are probably found in root behaviour, but little information exists about this (Branas & Vergnes, 1957). From literature it is clear that information on vine roots is scarce, relative to research done on the above-ground parts. This is ascribed to the difficulty of root studies where several tons of soil must be shifted to uncover the roots with the aid of various means (water, air pressure, sharp implements, etc.). Late in the 1800's, researchers already realised that the reaction of roots to their environment is a powerful factor in determining plant performance (Rogers, 1939). The productivity and performance of all plants, including vines, depend mainly on a root system that can sustain them in periods of stress (Russell, 1977).

According to their origin, vine roots are classified into primordial and adventitious roots (Ribereau-Gayon & Peynaud, 1971). Primordial roots develop from germinating seeds and are of less importance for commercial viticulture where vegetative propagation is used. It is important in breeding where germinating seeds play an important role. Adventitious roots, which develop from canes or cuttings, are classified into primary (main) and secondary (lateral) roots. Primary roots are also known as tap roots or framework roots and are normally 6 - 10 mm thick and mainly found at 30 - 35 cm soil depth. Their number normally remains constant after three years following planting (Mullins *et al.*, 1962). Thicker tap roots than mentioned above are frequently found with vine root studies in South Africa. Lateral roots develop from the tap roots and according to

Mullins *et al.* (1962) they have a diameter of 2 - 6 mm. These roots grow horizontally or downwards and further branching from them are fibrous or absorbing roots that remain functional for one season, during which they are constantly replaced by new laterals. Although downward growing roots can reach considerable depths, the fibrous secondary roots are mainly found in 25 - 50 cm soil depth depending on soil characteristics, cultivar and age of the vine (Champagnol, 1984). Roots developing from any other organ than a root are regarded as adventitious roots.

According to Comas *et al.* (2010), the woody parts of the root system are regarded as structural framework roots, and are functional mainly for transport. They also anchor the vine and serve as storage sites for carbohydrates and nutrients. These roots annually produce non-woody, fine lateral roots, the so-called absorbing roots, which form the primary sites of water and nutrient absorption. According to Fitter (1982), the fundamentally fine roots without branching are called the first order roots, while those with first order laterals are known as second order roots. Anatomical studies have shown that the more permanent woody roots are third and fourth order roots and are characterised by secondary growth, a loss of cortex, the presence of mycorrhiza, enlarged xylem vessels and development of cork periderm. First and second order roots with intact cortex form the majority of total root length and are primarily responsible for the absorption of water and nutrients. It may also be that first and second order roots typically reach a length of two to three centimetres only and that this growth occurs within one to three days (Volder *et al.*, 2005).

Most vineyards are found in Mediterranean and/or semi-arid climatic regions on soils with inherent low fertility, often containing an abundance of lime and/or salts. The vine root system must, therefore, adapt to water stress, waterlogging, ion imbalances and toxic ions (Mullins *et al.* , 1992). The hardiness of the vine is probably due to root characteristics such as tolerance to unfavourable conditions, ability to penetrate the soil to three meters and deeper (Champagnol, 1984), its ability to generate new roots, its ability to store organic nutrients, including amino-acids (Nassar & Kliewer, 1966), and its association with mycorrhiza (Possingham & Groot-Obbinck, 1971).

According to Branas and Vergnes (1957), the development of the vine root system is independent of the nature of the plant material (cuttings, rooted vines, grafted or not grafted). The development undergoes several

phases, whether the vine is cultivated or not. The soil zone with the highest root development is mostly dictated by temperature and water. Roots grow towards the warmer, humid and aerated soil layers and find a balance at a depth of 25 - 45 cm for soils deeper than 85 cm in Mediterranean climate. The depth of this preference zone is determined by climate: in cooler climate this zone is shallower and in warmer climate it is deeper. In soils with a shallow water table, this preference zone is shallower to escape the negative effect of waterlogging.

Branas and Vergnes (1957) described three phases of root development:

1. **Juvenile or colonisation phase:** During the year of planting, new roots grow from the cutting and elongate and spread by forming hair roots, relatively far away from the root tips, in the root zones where cell differentiation is completed. During the second leaf, root elongation and spreading are mainly because of development of hair roots from the periderm that can remain as laterals. The number of root tips is few during the first year but increase rapidly in the second year. The annual elongation decreases because the total growth capacity is divided between numerous root tips. If the vine grows freely, the horizontal dimension of the roots conforms well to that of the above-ground growth when it is not pruned. Over time both the canopy and the root system decline, even if there is no competition, as in the case of an isolated vine.
2. **Adult phase:** It is the phase when the average annual root elongation becomes very sparse and is regarded as the beginning of root size stabilisation. During phase 1, the nature of the root system is dictated by soil characteristics but it seldom lasts longer than seven to eight years. At this age, root colonisation is practically completed and above-ground vigour (*Ev = Expression vegetative*) reaches a maximum that will not be exceeded during the lifespan of the vine. In other studies, *Ev* is also defined as 'Total Vegetative Reaction' (TVR) and it comprises cane and leaf mass, annual increase in the above-ground permanent vine parts, as well as increase in root growth. In practice it is measured as annual cane mass. The elasticity of the root system and its sensitivity to external conditions thus manifest only at the beginning of the lifetime of the vine
3. **Aged phase:** Ageing of vine roots is the result of many causes such as increased complexity of the vascular bundles which is similar to that of the above-ground parts and damage caused by pests and diseases.

A comparison between the root mass of 12-year-old and 58-year-old vines showed a more than six-fold increase over 46 years (Fig 1.1.1). The root distribution was similar, with a 25 - 45 cm deep preferential zone, but in the case of the older vines a decrease in shallower as well as deeper roots was found. According to Branas and Vergnes (1957), this was probably caused by numerous periods of desiccation in the topsoil, combined with too deep cultivation of the soil surface, as well as periodical waterlogging of the deeper soil layers.

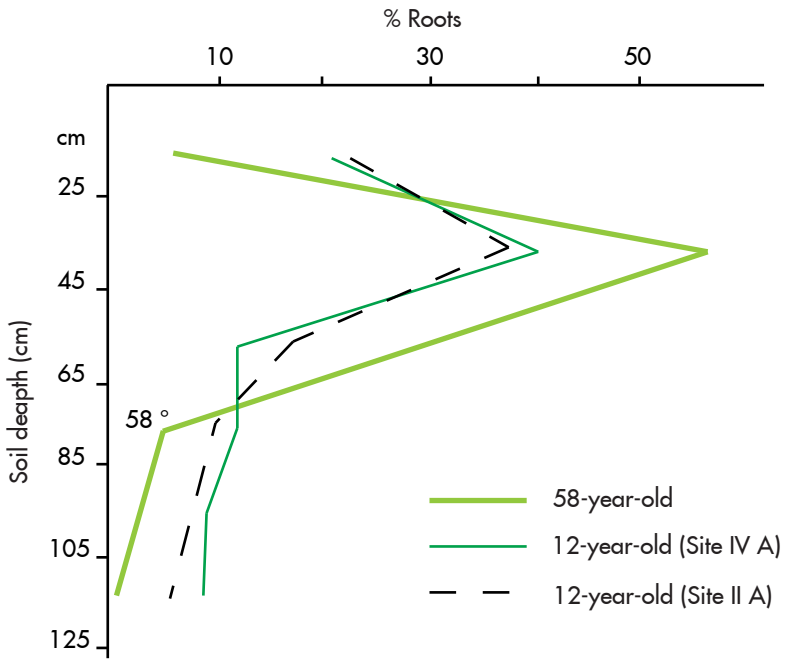


Fig. 1.1.1 Root mass and distribution of 12 year and 58 year old Riparia vines (Redrawn from Branas & Vergnes, 1957)

Branas and Vergnes (1957) found that the water tables of sandy soils in the coastal Mediterranean area of France caused the death of deep roots. They identified 'normal' and 'abnormal' roots. The abnormal roots grew back to the bases of and into dead roots which formed in first seasons and have died because of excess water. McKenry (1984) found that the root skeletons had the same pattern as those of framework roots and this is indicative of living roots penetrating old skeletons. Root skeletons are of two types, those decaying from the inside and others decaying from the outside. Long

structural roots and their young growing laterals preferably invade these zones of decaying material, but also penetrate natural cracks in the soil as a second preferred habitat. According to Branas and Vergnes (1957), dying or stressed roots show first an internal reddish colour, sometimes intensely coloured, followed by localised necrosis near the base, but eventually total necrosis near the root tips where they die. The root bases generally stay alive for longer periods, but eventually also die if unfavourable circumstances prevail. They found with four different rootstocks of 58 years old identical root distribution under circumstances where shallow and deep roots were destroyed and concluded that genetic differences as reported by, *inter alia*, Perold (1926), are dominated by soil characteristics.

Although the general conception is that root mass increases with an increase in above-ground vigour, Branas and Vergnes (1957) found a not so strong relationship (Fig 1.1.2).

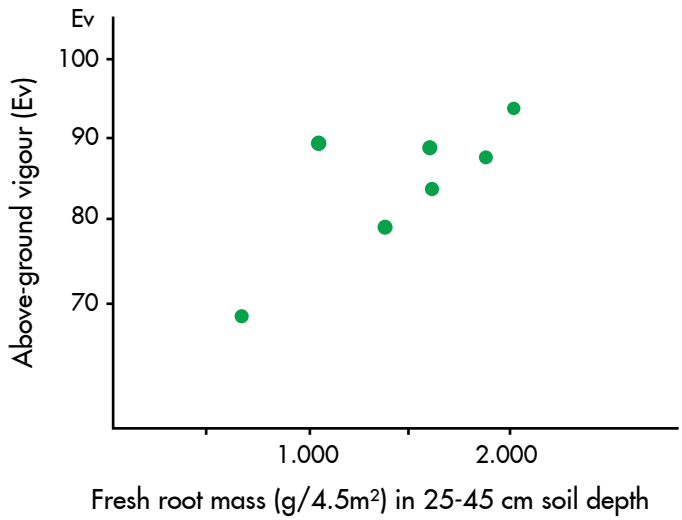


Fig. 1.1.2 The relationship between above-ground vigour and fresh root mass of Rupestris du Lot in the 25 - 45 cm soil layer (Redrawn from Branas & Vergnes, 1957)

It is impossible to establish a simple relationship between the root mass of the vine and above-ground development, but it probably increases positively when the root profile remains constant and all other factors such as age, vine spacing, soil, pruning system, pruning and other wounds, as well as crop load are the same.

With the exception of the detailed study of Branas and Vergnes (1957), although limited to the shallow soils of the Midi, little information concerning the root distribution of the vine exist as a result of the difficulty of these kind of studies. According to Seguin (1972), Guillon in 1905 accentuated the differences in the angle of geotropism between rootstocks when cuttings were grown in a nutrient suspension or in very porous soil. From this the concept originated of horizontal (creeping) or vertical (plunging) roots. Branas and Vergnes (1957) have shown that with old vines these differences do not exist. Numerous observations since then made *in situ* in vineyards in Bordeaux confirmed these findings. Degrully and Ravaz (1905) showed that roots originating from the bottoms of Rupestris du Lot cuttings, grew upwards towards the soil surface and then extended horizontally (Fig 1.1.3). This phenomenon is far from general and was observed in exceptional cases. It can well happen when the roots of a young vine are crammed on the bottom of the planting hole, forcing the initial root growth to the surface where it will develop further in the more porous soil layer, depending on the planting hole.

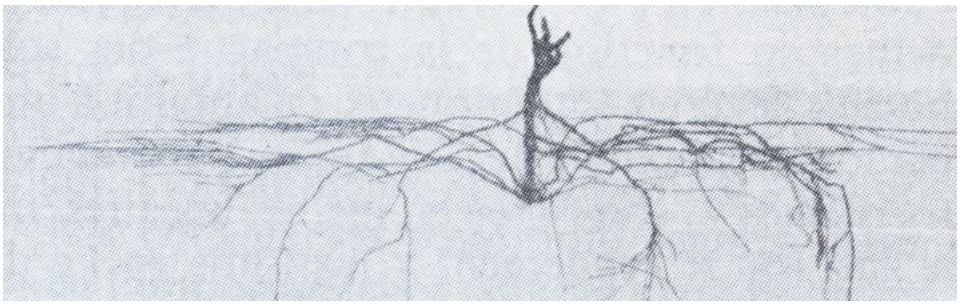


Fig. 1.1.3 The root profile is limited to a superficial preference zone by a shallow water table (Degrully & Ravaz, 1905)

It is the chemical and especially the physical soil characteristics which determine to a large extend the nature of the root system (Seguin, 1972). Roots develop and branch in the most porous soil layers. It is known that root penetration can only take place if the dimensions of soil pores or cracks are adequate. It is frequently observed that primary roots do not develop with the normal angle of 360° but with 180° and even 90°. The cuttings are frequently planted against the compacted wall of the planting hole and as a result the first roots develop in the more porous soil zone according to the nature of the hole. The bigger, live and healthy roots are frequently found in passages and tunnels of old, decomposed roots, in earth worm

passages and glaciation slicken-slides found in the Quaternary terraces of the Garonne. Roots are temporary blocked by compacted horizons (clay layers with strong structure, massive iron (Fe) concretions) and they can only penetrate when a fault plane is found (Seguin, 1970). In this respect, it could always be confirmed that soil structure is more important than texture. In several 'grand crus' vineyards of Graves, a deep, thick clay layer was observed with a strong prismatic structure but still allowing deep penetration of roots. In these cases the hair roots covered the surfaces of the structural units in a very dense network. When roots are stopped by a physically unfavourable horizon, they branch on the surface thereof, but do not penetrate. This is observed on massive Fe concretions or at the upper boundary of the capillary rise of the soil water table.

Roots do not develop in free water, for example in the Medoc the depth of root penetration is limited by the water table in the soil and this is the reason why 'grand crus' vineyards are situated on low mounds and never in low positions. Few roots are found in the top soil layer because of evaporation during the biggest part of the vegetative cycle, as well as seasonal cultivation that destroys the superficial roots.

Vine root colonisation can reach great depths. Observations in the alluvial soils of the Garonne showed root penetrations of six to seven meters, allowing satisfactory mineral uptake even though analyses showed the soil to be nutritionally poor. With deep root penetration the roots spread through the total upper part of the soil profile, with relatively few roots in the lower layers. Roots are frequently spread unevenly according to the nature of the soil.

Seguin (1970) found that the vertical colonisation of roots in the 'grand crus' vineyards of Bordeaux correlated with chemical and physical soil properties, especially permeability. This played a primordial role in the water supply to the vine. This determined greatly the occurrence of berry cracking after rain and consequential botrytis infection (Seguin & Compagnon, 1970). This had decisive negative effects on the chemical composition of the must as well as its organoleptic characteristics.

Knowledge of the growth and distribution of roots is a logical prerequisite and indispensable for studying and understanding water consumption, mineral nutrition and the agronomical implications thereof (Champagnol, 1984). The distribution of vine roots is known, due to various

investigations (Seguin, 1972). When there are no limitations such as wet clay layers, conglomerates and compact parent rock, root distribution can reach great depths of up to three meters and more. These great depths originate from the well-known ability of the vine to resist suffocation, which leads to resistance to drought, an ability which disappear when the root system is shallow. It seems that the drought resistance of the vine is a consequence of its resistance to asphyxiation. In spite of this deep root penetration, halve and sometimes more of the root mass and lengths are found in a preferential zone, which is not too shallow (so that it is not subjected to desiccation) and not to deep (so that it does not suffocate) (Fig. 1.1.4).

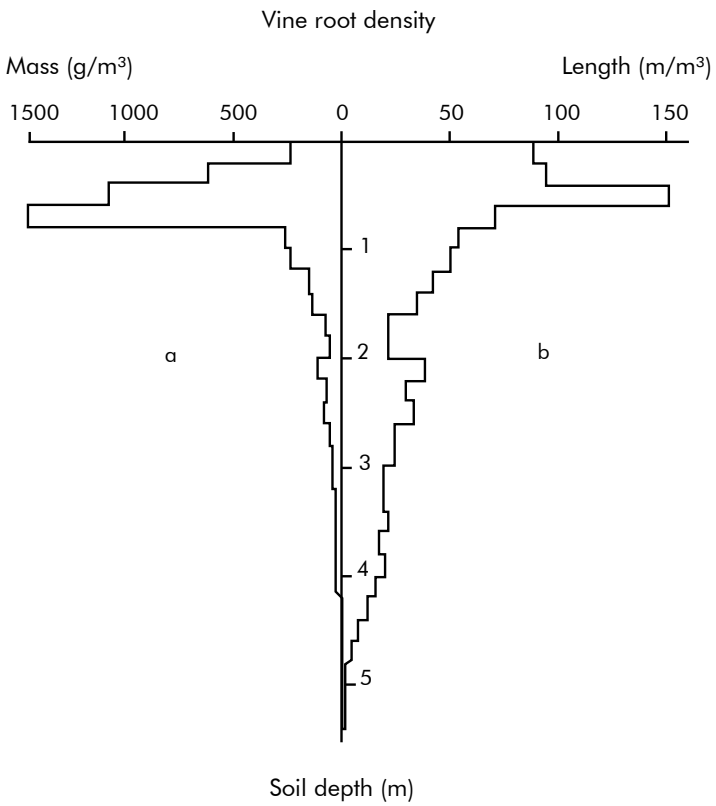


Fig. 1.1.4 The root distribution of Palomino/161 - 49 Couderc in Jerez. Root density expressed as (a) g roots per m^3 soil and (b) m root length per m^3 soil. (Champagnol, 1984 as redrawn from Garcia de Lujan Gil de Bernabe & Gil Monreal, 1982)

In soil with heterogeneous layers, root distribution varies according to the favourability of the soil material (Fig. 1.1.5).

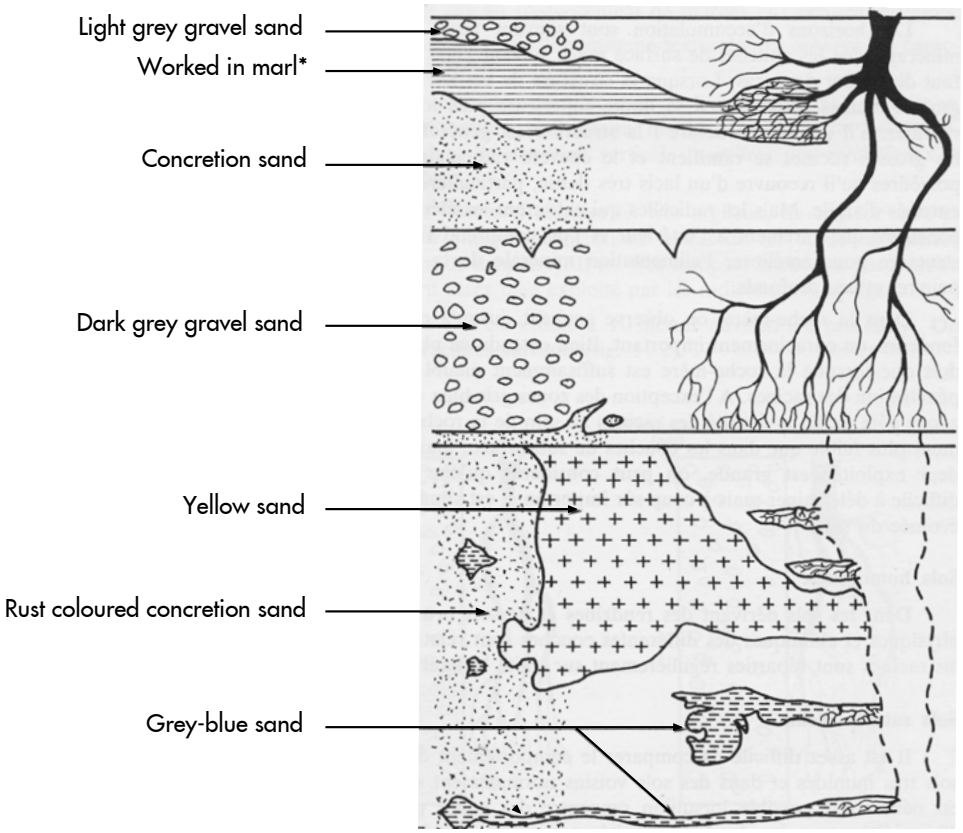


Fig. 1.1.5 Root distribution in Médoc soil as affected by the properties of different soil layers (Redrawn from Seguin, 1971)

The zone of root distribution is independent of the depth of planting. When the planting is too deep under suffocating conditions, the roots grow upwards if water logging is present initially or they die at the end of the young stage if free water is present. In both cases a second root system is formed closer to the soil surface (Fig. 1.1.6).

A B

Fig. 1.1.6 A & B Suffocation as a result of water logging at the end of the young stage; A: The early formation of a second root system close to the soil surface. B: The later growth of this second root system (Pictures: E. Archer, 2016)

The angle of geotropism is noticeable only during the first year of establishment in homogeneous, well loosened soil and has no effect on the eventual root distribution. The effect of rootstock on root distribution is also much less than that of the soil properties. Branas and Vergnes (1957) found a similar form of the root profile for different rootstocks, but that deeper roots occurred for Riparia Gloire de Montpellier, 3306 Couderc, 1616 Couderc and 44 - 53 Malèque than for Riparia Berlandieri. It is logical to think that, contrary to what is sometimes indicated, cultivars with deeper root systems are those that are better adapted to suffocation compared to those preferring to root closer to the soil surface. According to Champagnol (1984), C. Maertens in 1970 defined the quality of soil utilisation as the mesh of colonisation, indicating the volume of soil between two adjacent roots. The higher the root density, the smaller the mesh of colonisation and the better the absorption of water and nutrients. In the horizon of maximum colonisation, root density can reach 200 m/m^3 or 1.0 - 1.5 kg/m^3 of soil. If the roots are regarded as

parallel and proportional to each other, this maximum density represents a root distribution of seven centimetres between each root. This value is not well representative of reality as it does not consider absorbing root hairs which can greatly increase the exchange surface between roots and soil. It is further increased by fungi hyphae which live in symbiosis with the root system. The exchange surface, however, is very small in comparison to that of the soil particles. Maertens calculated that the root surface (including root hairs) of a wheat plant is approximately 6 m^2, while the total surface of the soil which it exploited is approximately 10 000 m^2. For the vine it is even less than for annual crops.

Root growth is a function of environmental conditions, age of the vines and the activity of the aerial parts. The extensive root studies of Degrully and Ravaz (1905) illustrated, *inter alia*, the effect of a shallow water table (< 1 m):

1. Roots emerging close to the soil surface displayed a sharp angle to the vertical and tended to plunge downwards.
2. Roots emerging deeper showed variable growth planes according to soil cultivation and grew rectangular to the vertical.
3. Roots emerging further down showed a blunt angle to the vertical and tended to grow upwards with an opposite curve than those emerging close to the soil surface.
4. Over time, all roots establish at the same level, which varied, but are relatively close to the soil surface.
5. From creeping roots, from time to time, other roots developed which plunged to the deeper soil layers (Fig. 1.1.5).

Except for drought, lack of oxygen because of waterlogging or too strong or too diluted soil solution, mechanical resistance is an important factor inhibiting root development. According to Champagnol (1984), E.M. Ionescu in 1978 found a negative parabolic relationship between the number of roots (y^1, in meter/m^3) or yield (y^2, in kg) and soil resistance (x, bar):

$y^1 = -ax^2 + bx + c$ en $y^2 = -a'x^2 + b'x = c'$.

Fig 1.1.7 illustrates the dramatic effect of soil density on root development.

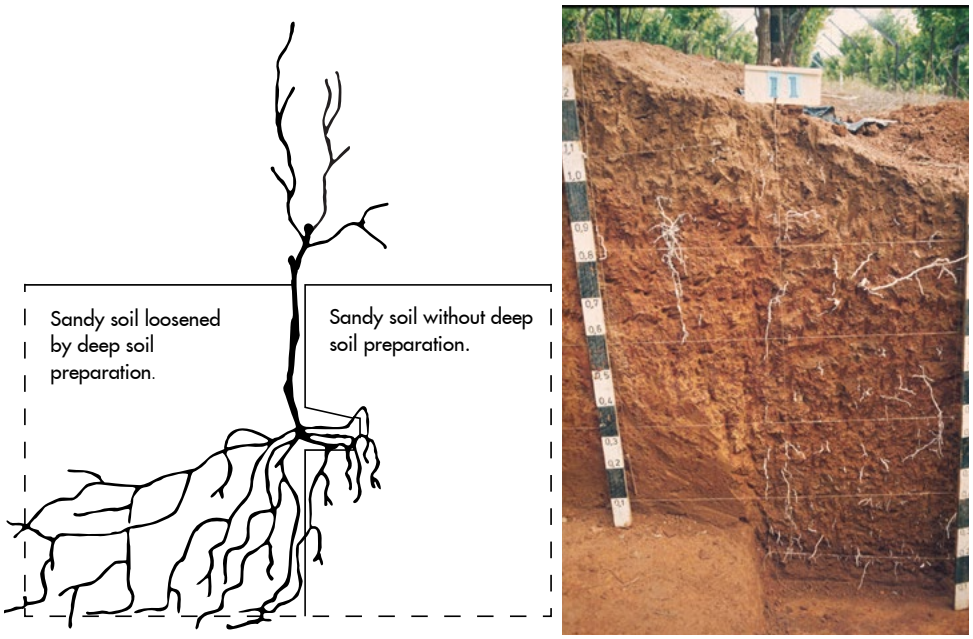


Fig. 1.1.7 The effect of soil resistance as caused by the presence or absence of deep soil preparation, on the development of the root system. Drawing left: Roots colonise deeply loosened sandy soil with 10 bar resistance (left in the drawing) much better than compacted sandy soil with 28 bar resistance (right in the drawing). (Champagnol, 1984, as redrawn from Ionescu, 1978). Picture right: Roots colonise deeply prepared soil (right in the picture) much better than non-prepared soil (left in the picture). (Picture: Viticultural and Oenological Research Institute (VORI))

Factors affecting root branching are not well-known. Two types of root branching are distinguished, namely roots with real ramifications and roots with numerous hair roots. It seems that root branching is positively affected by favourable physical soil conditions and physical restrictions (obstructions, low water- and osmotic potential), but new roots are scarce in unfavourable conditions. Fertile conditions favour growth, branching and abundance of hair roots because nutrition is easy and root growth and branching are maximum, lateral root extension is large and the mesh of colonisation is small. An extreme example of this was observed with a 12-year-old Chardonnay/Ramsey vineyard on fertile soil in Robertson during 2017 (Fig. 1.1.8). Under such conditions, above-ground growth can reach large proportions. In poor soil, root growth is slow, branching is less, lateral root extension is small and a large mesh of colonisation exists, therefore vigour is curbed. This is the basis for the choice of vine spacing.

Fig. 1.1.8 Intensive root growth and colonisation of Chardonnay/Ramsey in fertile soil, Robertson (Picture: Johan de Jager, 2017)

Ageing of vines originates mainly from the areal parts where pruning wounds, parasites and fungus diseases make an important contribution. Decrease in root effectivity plays a minor role. The latter is the result of superficial and in depth changes of soil properties and, without doubt, also because of ageing of the roots, causing a general decline in root effectivity together with exhaustion of the soil. Over time, conditions in the rhizosphere become less than ideal. Ageing of the root system can be more ascribed to changes in the soil environment than to ageing *per se*. Consequently, vines reaching the age of 50 - 80 years can be ascribed to the care they received in protecting the trunk and cordon arms against ageing. The root system of these old vines is not different from those excavated earlier (Branas, 1974).

The growth, expansion and activity of vine roots are affected by numerous natural and man-made parameters and include impenetrable soil layers, soil compaction, irrigation patterns and genetic root growth characteristics (Le Roux, 1941; McKenry, 1984). Root distribution is dictated by soil type, but the density thereof is a function of scion and rootstock combination with rootstock being the main factor (Mullins *et al.*, 1992). Swanepoel and Southey (1989) also found that root distribution and density are mainly affected by the rootstock and that above-ground growth and crop increased

with an increase in these root system properties. Data of Smart *et al.* (2006) show that the depth distribution of vine roots is more affected by soil properties such as impenetrable layers, stoniness and presence of gravel lenses than by genotype. They found genotype differences to be small and recommended that other root properties than horizontal and vertical distribution be considered to explain key characteristics such as scion vigour and drought resistance. In accordance with this, Perold (1926) declared that geopatterns had a minor effect on root distribution compared to water attraction

The composition of soil air has a major effect on the growth of tap roots and Huck (1970) found a drastic decrease in growth when oxygen decreased below 10%. At a total adsence of oxygen, root tips died within hours.

Groups of expansion roots may grow as a front and colonise the soil quickly. Behind this front, lateral roots develop, but they are few and evenly spaced. Approximately 150 mm from its tip, the expansion root thickens while the laterals lengthen and branch in higher order laterals. Lower order laterals grow faster than higher order laterals. The increase in the number of lateral roots results in a concentration of short, fine roots that improve the utilisation of water and nutrients.

In studies on the effect of trellis systems on root distribution, Van Zyl and Van Huyssteen (1980) found a very uniform root distribution, utilising the total row width, but with the least roots in the top 10 cm soil layer. This conforms to many previous observations but is contrary to the classic model of water withdrawal which has a triangular shape (Israelson & Hansen, 1967) with 40% withdrawal from the top 25% of the soil and 10% from the deepest 25%. This generalisation of the water withdrawal pattern is thus not necessarily applicable to vines.

Araujo and Williams (1988) found that root growth mainly takes place when excessive photosynthetic products from the leaves are available. Root colonisation always follows the path of least resistance. It starts slowly in spring, but increases quickly to maximum in mid-summer before it decreases again to a lower peak in autumn (Freeman & Smart, 1976). Root growth can start up to 10 weeks after budding which means that absorption during winter must supply water and nutrients for more than half of the annual shoot growth period. In a micro-rhizotron study on Concord, root browning normally took three to four weeks and happened quicker when the roots

were formed after full-bloom. This is ascribed to warmer soil temperature at the time (Anderson *et al.*, 2003). Browning was found to be associated with the dying of the cortex and eventual death of the root (Comas *et al.*, 2000) resulting in a decrease in the accumulation of phenolic substances because of a loss of absorbing material with age.

With most woody plants (including vines), a linear relationship exists between root and shoot growth and this is greatly affected by the roots (Russell, 1977; Wang *et al.*, 2001; Archer & Hunter, 2004/5) although there are also findings that the vigour of the scion can influence the size of the root system (Harmon & Snyder, 1934). The relationship between subterranean and above-ground growth varies a lot. In a 10 year old Chenin blanc vineyard, Saayman and Van Huyssteen (1980) found a relationship of 1:2, in a 15-year-old Shiraz vineyard, Randall and Coombe (1978) found a relationship of 1:8, while Hunter (1998a) found a 1:2.5 relationship for a 10-year-old Cabernet Sauvignon vineyard. Similar studies with three year old Thompson Seedless vines (Araujo, 1988) and with 10-year-old Chenin blanc vines in the San Joaquin valley (Mullins *et al.*, 1992) showed relationships of 1:5.2 and 1:5.3 respectively.

The normal root system of vines consists of interception roots in the top soil layer and they are supported by tap roots in the deeper soil layers (Fig. 1.1.9). Most of the fine roots, the largest part of absorbing roots, are found in the top 100 - 600 mm soil depth (Barnard, 1932; Branas & Vergnes, 1957; Randall & Coombe, 1978; Van Huyssteen & Weber, 1980). The interception roots are also named fine roots, while the tap roots are called thick roots. The mass of the root system of a single vine varies between 4.5 kg and 7 kg depending on age, and increases with the years. A 12-year-old *Vitis rupestris* vineyard produced a total root mass of 20 t/ha, while a 58-year-old vineyard produced 31 t/ha (Essau, 1967). Harmon and Snyder (1934), working with vines of on average 25 years old and with different graft combinations, found a root mass of 5 - 30.8 t/ha with the longest root more than 6 m.

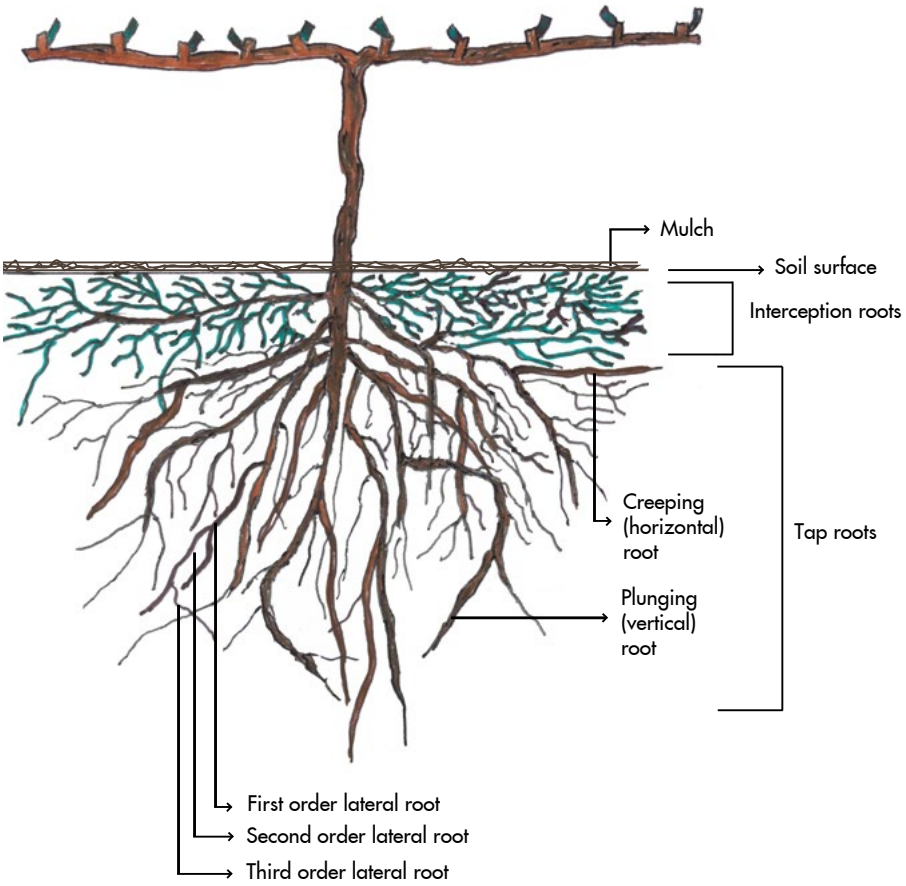


Fig.1.1.9 The root system of the vine (Drawn by E. Archer)

In a classical study with various rootstocks and vine age which varied from 7 - 52 years, Garcia de Lujan de Bernabe and Gil Monreal (1982) found that the thickest root measured 31 mm diameter close to the vine trunk and that the longest root of 12 m grew horizontally at a depth of 60 cm. With 41-B Mgt of different ages as well as same-aged 196 - 17 Castel, 161 - 49 Couderc and 420-A Mgt, they found 70 - 90% of all roots within 1 m depth in Albariza soil (white-coloured lime soil). With 161 - 49 Couderc on deep dark soil, they measured a rooting depth of 5.8 m. With 52-year-old 420-A Mgt they measured 7 kg root mass per vine (28 t/ha) and a total root length of more than 600 m/vine (2.5 km/ha). The depth distribution of the vine's own roots as well as that of neighbouring vines as was found

in this study for 420-A Mg, is presented in Fig 1.1.10. It is clear that most roots were found within 60 cm soil depth and that a liberal overlapping of the roots of neighbouring vines occurred.

In terms of root length, more than 80% roots of neighbouring vines occurred in the plant space soil volume of a single vine (Garcia de Lujan Gil de Bernabe & Gil Monreal, 1982). They found that most roots (mass and length) as well as most thick roots occurred at the original plant depth, with a 50 - 60 cm spreading to neighbouring vines. Irrespective of rootstock, vine spacing, cultivation and other factors, it seems that the factors most important for root development are soil water content and terrain properties. It seems that the root system establishes during the early years after planting and that it continues to increase in size and density even if it develops later.

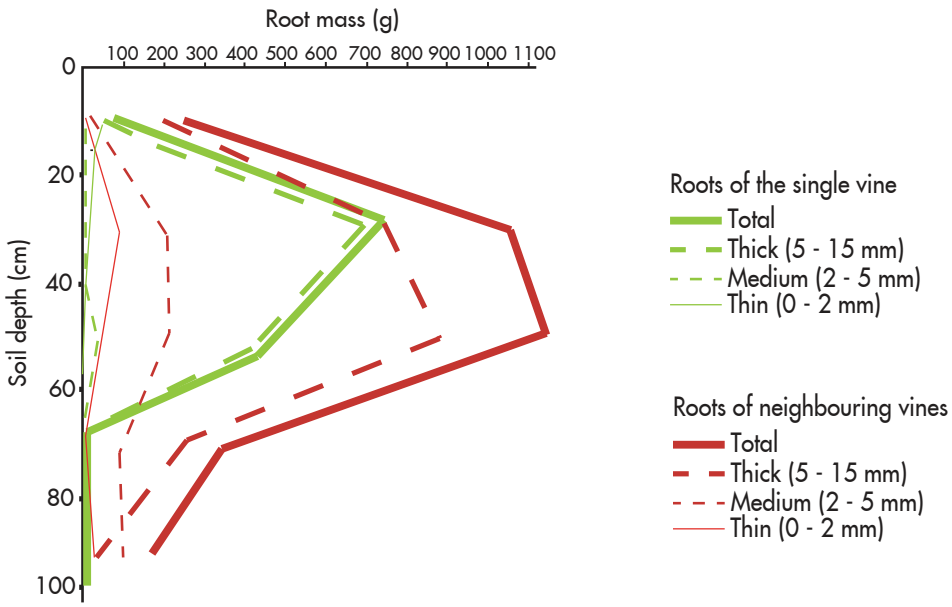


Fig. 1.1.10 The root mass in different soil depth layers of a single vine (420 A Mgt) as well as those of neighbouring vines present in the plant space volume of one vine (Adapted and redrawn from Garcia de Lujan Gil de Bernabe & Gil Monreal, 1982)

In his classical and original study of vine roots in South Africa, Le Roux (1941) found similar results to the above. The roots of seven different rootstocks grafted with four different scion cultivars in two different soil types were totally exposed and also studied with the profile wall method. He

found 90% of all roots in the top 90 cm of the deeper soil with no roots in the top 0 - 10 cm. In the shallower soil he found 100% of all roots in the top 90 cm, also with no roots in the superficial layers. For Jacquez, 333 EM and Rupestris du Lot, roots occurred within 4 - 4.3 m radius from the trunk, while more than 3 m depth penetration was general (Le Roux, 1941). He found all interception (fine) roots within 20 cm depth. He documented an intensive water attraction effect on vine roots, finding horizontal root lengths of up to 8.4 m growing to a water source. Le Roux (1941) classified vine roots into two classes, namely horizontal growing and deep plunging roots, stating that the latter is in the minority.

According to Barnard (1932), the structure of the root system can be regarded as similar to that of the above-ground parts of woody plants in that a number of main roots ramify to form the framework roots reflecting the above-ground branching. These roots are perennial, but their growth stopped in winter and resumed in spring with the older parts becoming woody, the same as the woody branches above-ground. Barnard (1932) found that small absorbing or feeding roots developed on the youngest parts of the permanent roots of Sultanina, similar to leaves on the youngest parts of branches. These young roots were seldom longer than 6 - 7 cm, they never turned woody and functioned for one season only. The main roots originated from the trunk base at 30 - 35 cm depth, spread quickly and had a somewhat downwards growth pattern. The number of main roots did not increase after the second or third growth season after planting. In the case of 8-year-old vines, lengths of 2.7 - 3.6 m were attained and depths of 45 - 50 cm were reached. Smaller permanent roots had an obvious tendency to grow upwards, although some of them developed below the level of the main roots (45 - 75 cm) and from them plunging roots developed, growing to depths of up to 120 cm. On the upward growing laterals, feeder roots developed in a zone 12 - 25 cm below the soil surface, but they can be shallower if not disturbed by cultivation.

Barnard (1932) found horizontal spreading of the root framework in all directions, with main roots reaching an average length of 3 m, with some of them growing to lengths of 4.5 to 7.2 m. Roots of neighbouring vines overlapped notably (up to 36.7%; Fig 1.1.11) and resulted in vigour decline as can be seen when the growth of end vines is compared to that of the third vine in the row. Of the 19 vines of each category measured, end vines had an average stem circumference of 2.4 cm and a pruning mass of 545 g

more than the third vine in the row. Different findings concerning root overlapping are found in literature. Barnard (1932), Le Roux (1941), Penkov (1974) and Garcia de Lujan Gil de Bernabe and Gil Monreal (1982) found obvious overlapping of horizontal root growth from 3 - 8 m, while Champagnol (1984), Archer and Strauss (1985) and Archer (1991/2) reported very little overlapping.

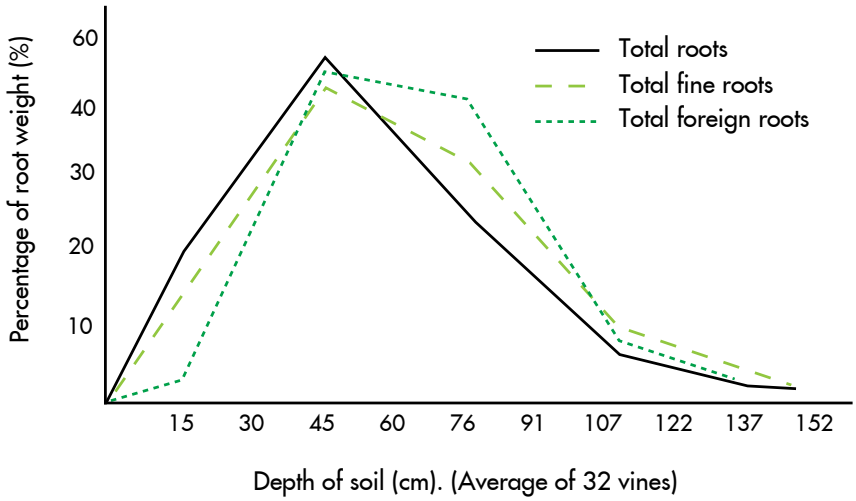


Fig. 1.1.11 Vertical distribution of total, fine and foreign roots (Redrawn from Harmon & Snyder, 1934)

In his investigations, Barnard (1932) found that some roots always grew further than the 2.4 m excavation. The main root of Solonis x Othello, 1613 was followed for more than 5.8 m where it still had a diameter of 6.4 mm. Twelve laterals of this main root were followed for an average distance of more than 3.5 m and still had diameters of 1 - 3 mm. The extent of overlapping probably has a direct relation to the effectiveness of soil and planting hole preparation, but it remains advisable to allow large areas or more than one buffer row for any experimental soil treatments.

Leached horizons, poorly supplied with nutrients, are vertically traversed by thick roots with very little branching (Seguin, 1972). Massive soil layers are penetrated by thick roots without any branching. In the case of strong structured layers (block or prism structures), thick roots branch and the resulting finer roots penetrate between the structural units and cover it with a very thick network of roots, without any penetration, especially when the

units are covered with clay films. In the parent material, roots are frequently found at great depths if the material is penetrable. At these depths, root density is less than in the shallow soil layers but because of the depth of penetration it can be accepted that an important part of the root system, difficult to quantify, occurs in the parent material.

In a study with 3-year-old Pinot noir x 99 Richter vines at different plant spacings where the roots were uncovered to 60 cm soil depth, Archer (1990) and Archer and Strauss (1985) found 6.63 to 49.1 km/ha roots for the narrowest and widest spacing respectively. More than 50% of vine roots colonise the upper 400 mm soil layer (Branas, 1974) and locally as well as internationally vine roots deeper than 5 m were found. Seguin (1972) found that most vine roots occurred in the top 50 - 100 cm soil layers, but that they are less abundant in the top 15 - 20 cm. He found roots deeper than 6 m. Archer *et al.* (1988), working with different trellis systems, found more than 50% of roots in the top 60 cm soil depth (Fig. 1.1.12), while Le Roux (1941), working with seven different rootstocks, found 90% of roots in the top 90 cm of the soil. The latter found that 75% of the total roots grew in the top 45 cm of the soil. Champagnol (1984) reported that the preferential zone of root colonisation varies between climatic regions: In the Midi and Madrid it is 25 - 50 cm, in San Joaquin, California 30 - 70 cm and in Jerez 40 - 70 cm. Juncu *et al.* (1969) found the deepest roots at 2.5 m with Kober 5BB.

Kocsis *et al.* (2016) studied the vine root distribution of different rootstocks and scion varieties in Hungary with the profile wall method. They confirmed the known low root density of vines with soil volume occupation of seldom more than 0.05%. The depth of penetration may vary, but is mostly 60 - 80 cm, while fine roots mostly occurred in the 10 - 60 cm soil layer. In this study, 55.9% of roots occurred in the 0 - 30 cm soil layer and 5.3% at 90 - 120 cm. Generally Teleki 5C and Georgikon 28 had the most fine roots ($\leq$ 2 mm diameter). The ratio of fine: thick roots ($<$ 2 mm $\div$ $>$ 2 mm) indicates the efficacy of the root system and was low for Teleki 8B (0.55) and Ruggeri 140 (0.7) grafted with Vinitor and the highest for Italian Riesling/ Teleki 5C (6.5). With micro-rhizotrons they observed differences in root growth on both sides of the vines, similar to the findings of Morlat and Venin (1981) who developed an Asymmetric Index (AI) for this phenomenon.

The root system extends through the soil by means of a combination of continued growth and branching. A growing root tip can exert a pressure of 800 - 1 200 kPa and the lower the pressure necessary to penetrate the soil, the faster the growth (Freeman, 1983). These extension roots are relatively thick (1 - 2 mm) and the growth rate can reach 1 m per day (Hilton & Khatamian, 1973). Tap roots vary in thickness, but are normally 6 - 100 mm in diameter with the thickest roots normally at 30 - 35 cm depth and their number does not increase after the third year following planting (Barnard, 1932). Kroemer (1909) classified the lateral roots in different orders according to their branching and found that a 14-year-old Riesling vine consisted of 40 first order, 1 100 second order, 2 800 third order and 1 000 fourth order roots. In accordance with this, Randall and Coombe (1978) found that a 15-year-old Shiraz vine contained approximately 10 000 roots of < 1 mm diameter.

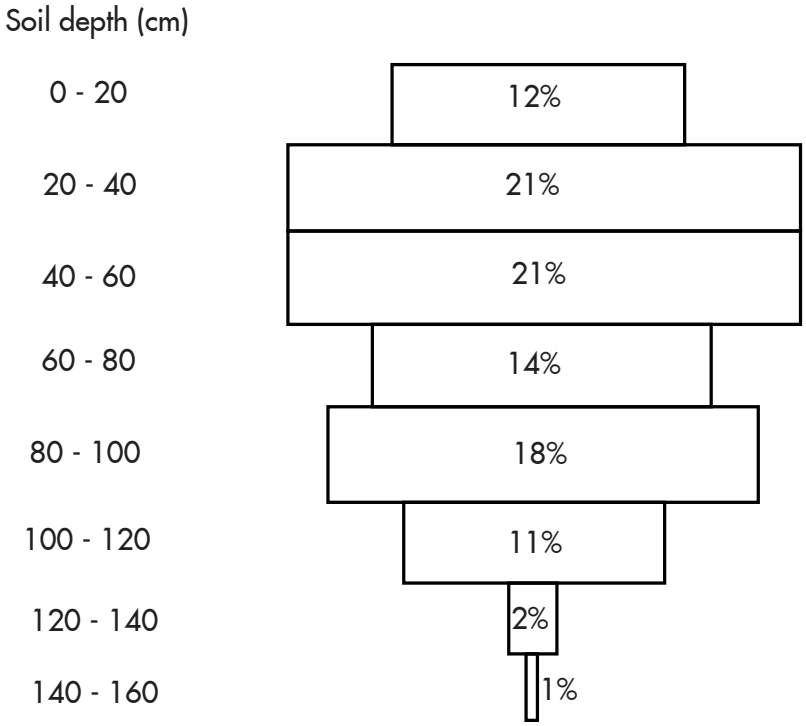


Fig. 1.1.12 Mean percentage of the number of vine roots of Chenin blanc/Richter 99 at different depths for four different trellises, namely: 2-wire Hedge, 3-wire Perold, 4-wire Hedge and 1.5 m Slanting trellis. (Compiled from Archer, Swanepoel & Strauss, 1988)

In fertile loess soil (wind deposited fine soil material), Doll (1954) followed root penetration of a six-year-old Concord vine to 4.4 m depth and a maximum horizontal colonisation of 6.7 m. The largest concentration of roots was found within a 1.8 m radius from the trunk and 2.4 m deep. In less fertile soil, a maximum of 2.9 m was reached with a maximum horizontal colonisation of 7.7 m, with small concentrations of roots directly below the trunk and also at the extremities of the two horizontal roots. From the drawings it is clear that root distribution took place far beyond the vine space and that more than 50% of the roots of neighbouring vines were present in the vine space of the sample vine (Fig. 1.1.13).

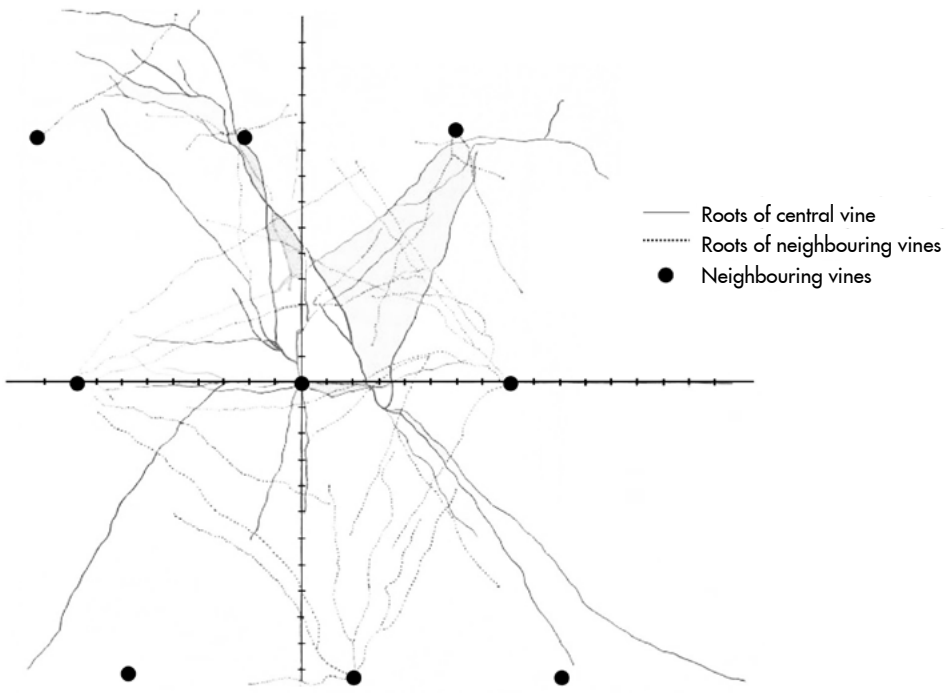


Fig. 1.1.13 View from the top of the most important roots of one vine as well as the overlapping roots of adjacent vines. (Redrawn from Doll, 1954)

Morlat and Jacquet (1993) found that roots with a diameter of < 1 mm contribute approximately 80% to total roots and that there is almost no significant effect of soil type on root distribution close to or far away from the vines. The effect of soil type on root distribution was highly significant and showed the importance of soil condition for root growth. The effect of soil horizons was very clear and showed poor homogeneous vertical root distribution. Second (20 - 40 cm) and third (40 - 60 cm) horizons normally

contained the most roots and this is in accordance with the work of Branas and Vergnes (1957), Hidalgo and Candela (1969), Van Zyl and Weber (1981) and Garcia de Lujan Gil de Bernabe and Gil Monreal (1982). The well established, highly significant interaction between soil horizon and soil type shows that the soil layers in which root growth concentrates can vary tremendously between soils.

The differences in the depth distribution of vine roots, as described in the studies mentioned above, are ascribed to differences in the efficacy of physical and chemical soil preparation as well as to the making of effective planting holes. This is probably the reason why South African research repeatedly shows deeper and better root distribution than what is found in other countries.

The dying of fine roots is a natural process and many of them die within a few weeks after emerging, to be continuously replaced by newly formed laterals (Reynolds, 1975). This short-lived nature of fine roots and the continuous abrasion of cortex tissue from living roots, make an important contribution to the organic content of the soil, and Champagnol (1984) reported that up to 8 t/ha/yr organic material was measured over the lifespan of the vineyard. On the contrary, thick roots do not die easily, and living roots can readily be found five years after uprooting. The woody parts of the root system form the structural framework and are used for translocation, anchorage and storage of reserve carbohydrates and nutrients.

Anderson *et al.* (2003) found that increasing soil depth and root diameter resulted in a longer lifespan of roots and that roots formed during flowering lived longer than roots formed later in the growth season. Pigmentation of roots resulted as part of normal ageing in the north-eastern regions of the USA and is connected to the cessation of metabolic activity (Anderson *et al.*, 2003).

As soon as soil temperature increases above 10°C after the winter (top soil layers first, followed by those deeper down), new root growth begins (Champagnol, 1984). On the other hand, Woodham *et al.* (1966) found that root growth started when soil temperature reached 6°C and that maximum root growth took place at 30°C. It is mainly the thicker roots that are responsible for new growth, and most roots of < 0.5 mm diameter do not show any regrowth. McKenry (1984) found that less than 5% of newly formed roots survived the growth peak in spring to form structural roots. In

autumn, soil temperature decreases below the level that can sustain growth and, although they did not die, root growth stopped (Perold, 1926). In areas where the soils warm up faster and root activities (growth, absorption and hormone production) start earlier, the vines bud earlier, buds are more fertile and yields are higher than in areas where the soils heat up later.

According to Rogers (1939), F. Resa found in 1877 that there are two important root growth peaks during the year. One occurs around flowering and the second after harvest. This is in accordance with the findings of Freeman and Smart (1976), Conradie (1980) and Van Zyl (1984) (Fig. 1.1.14). The peak after harvest is regarded to be very important, and that is why post-harvest irrigation and fertilisation proved to be critical for expansion and functioning of roots. It is also during this period when most carbohydrates are deposited in the permanent parts of the vine.

Mandel *et al*. (2001) emphasised the importance of a long vegetative period after harvest in the warmer areas of Australia and regarded this as a competitive advantage that must be maximised. The post-harvest period is important for root growth, absorption of nutrients, production of carbohydrates and storage thereof in the permanent vine parts. A well-developed root system ensures the optimising of these processes by maximising the up-take of water and nutrients. A shortage of stored carbohydrates is regarded as the main cause of restricted spring growth (RSG) and is probably involved in the occurrence of bunch stem necrosis. RSG is apparently the same as the growth arrestment phenomenon which occurs frequently in the Orange River region of the RSA and which is related to poor carbohydrate reserves in the trunk and roots because of early sudden loss of leaves caused by early frost (Saayman, 1983).

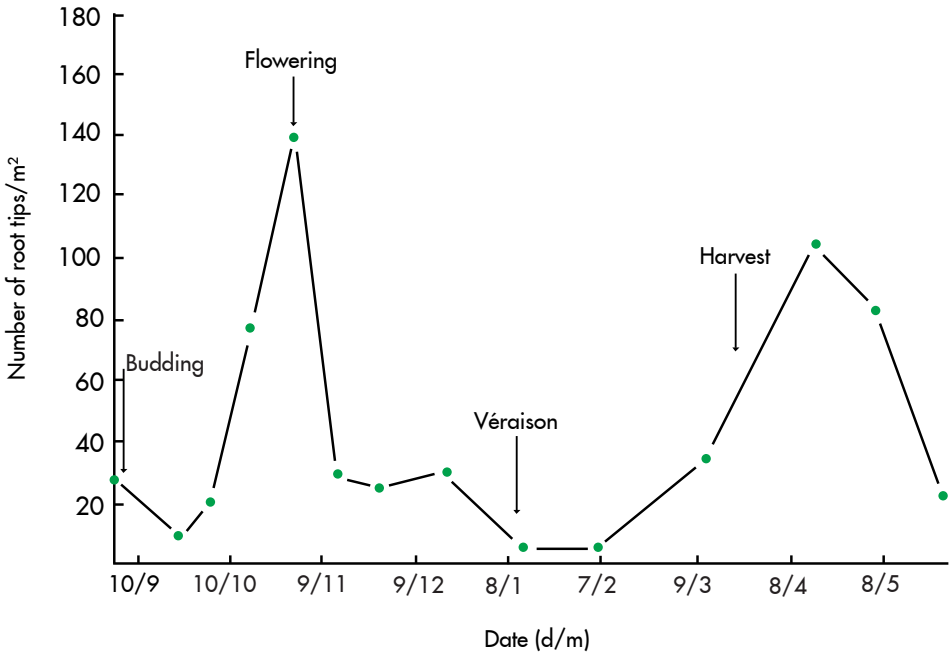


Fig. 1.1.14 The annual growth cycle of vine roots (Redrawn from Van Zyl, 1984)

The post-harvest peak is the reason why after harvest periodical deep cultivation between the rows to uplift compaction and to do root pruning is frequently advised (if the soil climate is favourable), so that new root growth can take place in loose soil. According to Goff (1898), root growth of many crops, including vines, starts before the beginning of shoot growth, especially in the topsoil close to the surface where the soil warms up first. On the other hand, other researchers found that root growth commences three weeks (Barnard, 1932) to 10 weeks (Freeman & Smart, 1976) after budding. According to this, it is clear that water uptake must take place through corked, adult roots and therefore it is important not to destroy these roots by cultivation or waterlogging.

Comas *et al.* (2010) are of the opinion that the fixed acceptance of a bimodal growth of vine roots, namely in spring and autumn, and that this pattern is driven by carbon competition with aerial growth as well as by a shortage of soil water in many climate zones, is based on limited data and cannot be regarded as universal. It seems that the main peak of vine root growth occurs at flowering and a smaller one after harvest (Freeman, 1983; Van Zyl, 1984). This is in accordance with the findings of McKenry (1984). In sub-tropical areas with a short growth period between budding and

harvest, most root growth takes place after harvest (Comas *et al.*, 2010). In cold-climate wine countries, only one root growth peak is frequently found between flowering and véraison, but sometimes there are two, one at véraison and a second one after harvest (Lehnart *et al.*, 2008). Comas *et al.* (2005) found one mid-season growth peak with Concord in the northeastern USA and ascribed this to a very short growth season. Clearly, the root growth cycle must be determined for every unique situation to adapt root management practices.

Jooste (1983) found that active root growth slowed down and even stopped before shoot growth started. This is in accordance with the findings of Freeman and Smart (1978) that a large root growth peak occurred when shoot growth slowed down, with a smaller peak after harvest and is contrary to the results of Barnard (1932). With rhizotron studies, using Shiraz in Australia, Freeman and Smart (1976) found two prominent root growth peaks from November to January and again in February to April with 100% ET irrigation, but very little new growth with excessive irrigation (300% ET).

Mullins *et al.* (1992) reported two typical root growth peaks in moderate climates namely, at flowering and again after harvest. Eissenstat *et al.* (2006), on the other hand, using minirhizotrons with Concord in New York and Merlot in Oakville, California, grafted onto both 101-14 Mgt and 1103 Paulsen, showed a root growth peak for Merlot between flowering and véraison with very little growth after véraison. Similar to Merlot, most root growth for Concord occurred between flowering and véraison, either as a single peak, or as relatively continuous growth without a clear peak.

In Hungary, Kocsis *et al.* (2016) found that root growth started later after shoot growth commenced (flowering) than reported earlier. This is contrary to findings that root growth reached a peak during mid- to late summer. Under their climate conditions, root growth slowed down at véraison, but continued up to the beginning of leaf fall. Their results support the general rule that root growth starts after budding and that early shoot growth is supported by reserves from the woody vine parts.

In the Mosel, Germany, Möhr (1996) found that the density of absorbing roots peaked at harvest, calculated as 3 500 km/ha and, including extension roots, at a total root density of 12 000 km/ha. Intensive growth of absorbing roots in the topsoil occurred one week after budding at 13 - 17°C during 1995, but at the beginning of flowering during the previous season.

According to him, it seems that there are two types of root tip growth in viticulture, namely:

1. In warm climate, especially in the southern hemisphere, two peaks are found, with the first during flowering when shoot growth slows down, and a second, smaller one after harvest. Subtropical climate conditions increase growth and explain why a peak of root tip growth occurred earlier, with a second regrowth period from after harvest to leaf fall, which can continue for several months and is very important for nutrient uptake.
2. In moderate climate regions, new root tips develop slowly and continue to increase till a peak is reached in late summer or at harvest. If leaves stay active after harvest, root tip growth can increase again and can continue for several weeks.

Between species as well as rootstocks, differences are found in the direction of tap root growth. The angle formed between the main roots and the vertical is known as the angle of geotropism and Perold (1926) described many differences that occurred naturally in the same medium (Table 1.1.1).

Table 1.1.1 Angle of geotropism of some species and varieties of Vitis (Perold, 1926).

Species or variety	Angle of geotropism
V. rupestris var. du Lot	20°
V. Berlandieri	25° - 30°
V. riparia	75° - 80°
V. rupestris x *V. Berlandieri*	40° - 50°
V. vinifera (Chasselas) x *V. Berlandieri:* 41 B	45°
V. riparia x V. rupestris	40° - 60°
V. riparia x V. Berlandieri	60° - 75°
V. riparia x *V. cordifolia* (106 - 8)	70°

Initially it was the opinion that the angle of geotropism plays an important role in choosing the rootstock cultivar. Those with wide angles were recommended for shallow soils and those with sharper angles for deeper soils. Furthermore, the angle of geotropism is also affected by the graft combination (Perold, 1926; Erlenwein, 1965). Perry *et al.* (1983) recommended that vineyards with *V. rotundifolia* rootstocks should not be deeply cultivated between rows because of the shallow root system

(angle of geotropism > 80°). Later findings showed that soil properties (e.g. fertility, hard pans, and chemical limitations) totally override the angle of geotropism (Champagnol, 1984).

Soar and Loveys (2007) found a very strong relationship between root volume and root dry mass ($r^2 = 0.8$). Hunter and Le Roux (1992), with different leaf thinning treatments, found that most roots occurred within 0 - 80 cm soil depth, with complete distribution between vines. Working with two-year-old vines in pots, Conradie (1980) found that roots contributed 65% of the dry mass of pruned vines. The increase in new growth dry mass was cancelled by a significant decrease in root dry mass. After harvest, a significant increase in the dry mass per vine was caused by a massive increase in root mass.

According to Huglin (1986), the process of root formation from vine parts where it does not occur normally, is called rhizogenesis. This normally takes place from the cambium of lignified canes and in the pith rays of cuttings (Fig. 1.1.15). Under special circumstances, root formation can also be achieved with green shoots. There is no direct relationship between the glucoside content of cuttings and its rhizogenic capabilities. The polarity of canes is important: roots originate almost always at the bottom extreme of the cutting. It points to rhizogenic substances, probably hormonal, that are produced by the buds and translocated through the phloem to the base of the cutting. The bud plays an important role in the root development of a cutting, as 70% of roots were found under the bud with only 10% when the bud was removed. It is also known that the graft can affect root formation. The natural stimulus of the bud can be replaced by applying the auxin naphthalene acetic acid to the apex of the cutting. Other growth substances such as gibberellic acid, stimulating root formation, and cytokinins, inhibiting root formation, can also play a complex role (Huglin, 1986).

Fig. 1.1.15 Emergence of a root from the cambium in the pith ray of a cutting. (Huglin, 1986)

In Mildura, Australia, sap flow in the xylem of Sultanina in the middle of August indicated the beginning of root activity although root growth only started in the third week of September (Barnard, 1932). During this period, the only available absorbing roots present were the few remaining from the previous season. The majority of roots were decayed, brown to black in colour and without any root hairs. It is remarkable that the sap flow, before the emergence of new roots, was sufficient to initiate budding and initial shoot growth. The mechanism by which the roots can quickly absorb water during this period is not fully understood, but it is possible that endophytic mycorrhizae as well as root pressure and mass inflow of water through root cracks play an important role. This late development of new roots was also noted by L. Rives in 1926 in France and is contrary to the general view (Perold, 1926) that the bleeding of the vine during pruning is caused by absorption of water by newly formed roots.

Morlat *et al.* (2010) used a root distribution index that is defined as: RDI (root distribution index) = $\sum$[R (1 - 2 mm) + R (2 - 5 mm)]/ $\sum$[R (5 - 10 mm) + R (> 10 mm)], where R = the number of roots in a specific diameter class. The utilisation of the soil volume by the roots can be described by the cumulative curves of the mass percentage of each class, as well as by the RDI (Fig. 1.1.16).

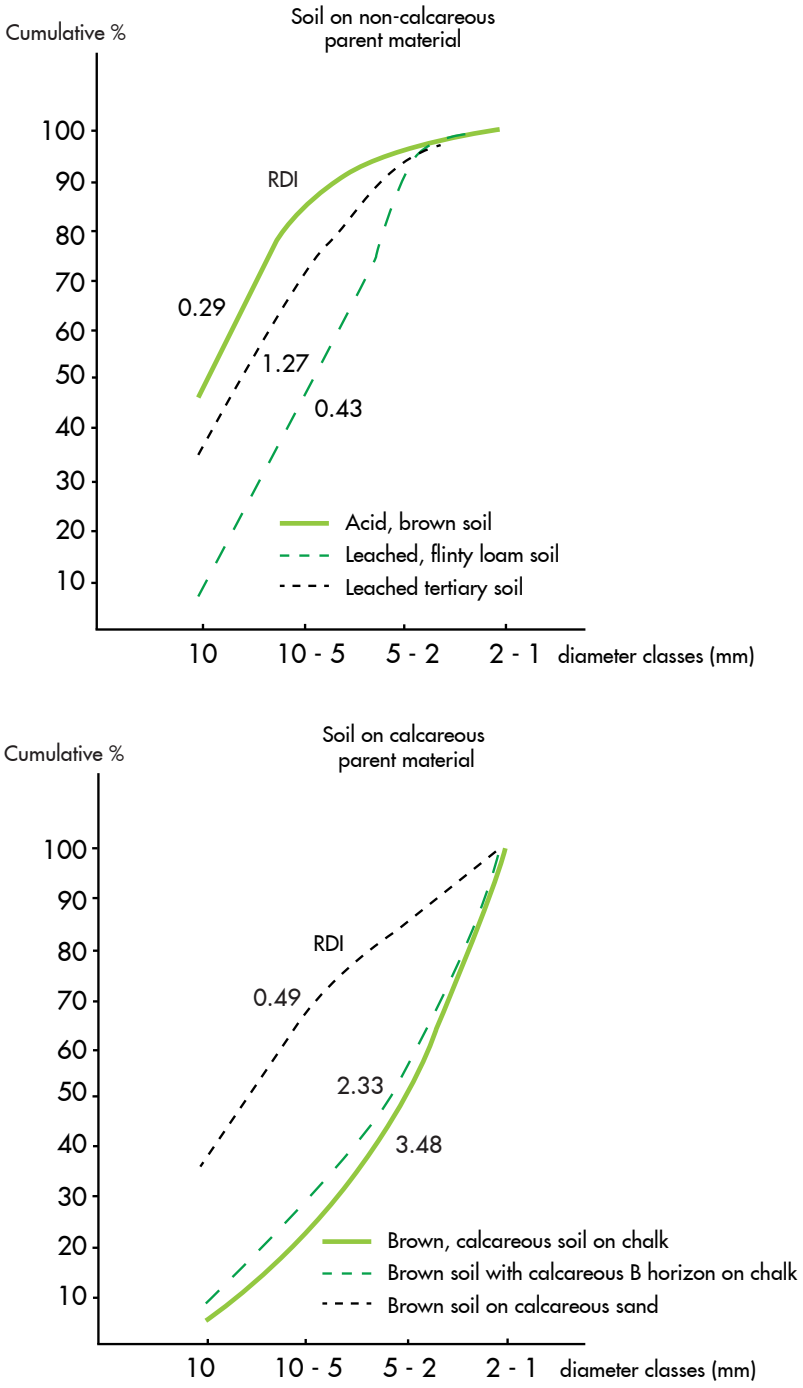


Fig. 1.1.16 Cumulative curves of root diameter classes in various soils. RDI = Root distribution index (Redrawn from Morlat *et al.*, 2010)

Thin roots are abundant in calcareous clay-loam soils with high RDIs of 2.33 < RDI < 3.48. On calcareous sandy soils, large and medium root classes decline with an RDI of 0.49, pointing to a poorer soil utilisation of roots per unit volume than in the calcareous clay-loam soils. In leached soils with signs of wetness with depth, rooting is relatively divided, with an RDI = 1.27 and well distributed. Against this, roots are poorly developed and branched in brown, acidic sands on sand-clay deposits (RDI = 0.29). In duplex soils, root colonisation and branching are poor (RDI = 0.43). Root development varies according to soil properties and the geological material. It seems that the different limiting factors (low water holding capacity, textural differences, wetness, soil strength) have similar detrimental effects on the distribution of the root system.

Morlat *et al.* (2010) also defined certain morphological parameters of roots > 2 mm diameter by measuring the theoretical length (TL), a straight line parallel to a part of the root, as well as the corresponding real length (RL), measured with a curvimeter. With this, the ratio of real to theoretical length (RL/TL) was calculated. They also measured the equivalent curve angle (ECA) where the root bent downwards, by measuring the angle between two straight lines, tangential to the root, where they cross above the bend. The diameter differences between the top and bottom parts of roots were also measured and expressed as ΔØ. The RL/TL ratio of roots, under certain conditions, showed the limiting effect of soil properties on deep root penetration. This ratio was always less than 1.3 in the favourable brown, clay-loam soils and varied very little between horizons. This ratio increased notably in very poor sandy soils under-laid by calcrete sand, which blocked the roots and reached values of 1.5 in duplex and clay soils, reflecting the poor physical soil properties perfectly.

The ECA showed the negative effect of textural differences between shallow and deep horizons. It is much smaller in the second horizon of most profiles, except in calcareous clay-loam soils where it varied little between 130 - 140°. They found a good negative curvilinear relationship between ECA and RL/ TL (Fig. 1.1.17).

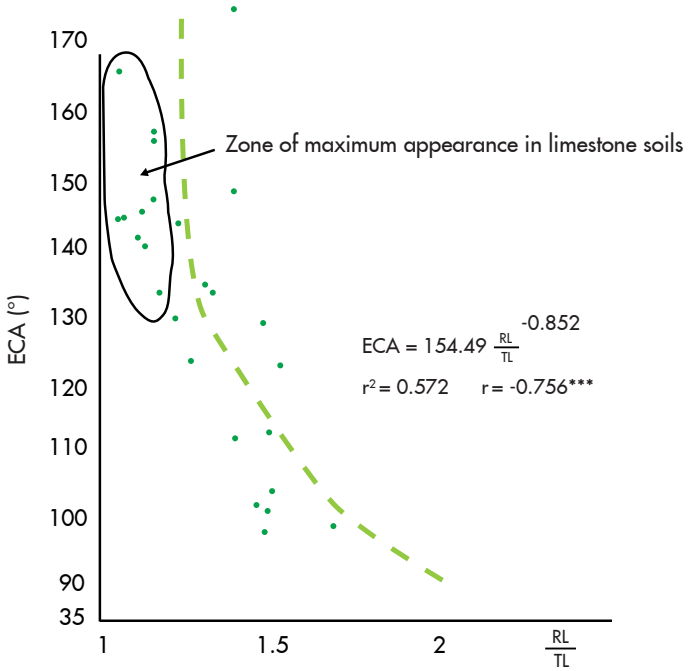


Fig. 1.1.17 Ratios between real/theoretical lengths (RL/TL) and equivalent curve angle (ECA) for studied roots (Redrawn from Morlat *et al.*, 2010) ***Highly significant

Morlat *et al.* (2010) found a better correlation between RL/TL and bulk density than between RL/TL and penetrometer resistance, probably because it integrated the nature of the soil volume such as macro and micro cracks and stone content better. The ECA was well correlated with penetrometer resistance, but better with bulk density, while ΔØ was better correlated with penetrometer resistance. The parameter ΔØ seems to be a promising index to predict the potential for root penetration.

The growth and development of vine roots are not only affected by physical and chemical soil properties, but also by nearly all cultivation practices used in the vineyard (see Chapters 4 & 5).

1.2 Root morphology

All organs and tissues in the vine grow each year as a unit and in relationship with one another. All these processes, above and below the soil surface, are dependent on the efficient functioning of the vascular system of the

vine. This system, through its structure and physiology, connects the soil with its water and nutrients with all above-ground plant parts by upward translocation of the basic building blocks and also the downward transport of photosynthetic products (Goffinet, 1999). Also, hormones migrate through the vascular system to stimulate changes in organ and tissue growth. These transport systems are greatly dependent on the morphology of the root system. Clearly, knowledge of root morphology and anatomy is necessary to understand the growth and development processes of the vine to enable improved management of vine behaviour.

According to Perold (1926) and Russell (1977), each vine root is characterised by the following zones:

1. The root growth tip. This is the youngest part of the root and consists of meristematic cells and is only 2 - 5 mm long (Pratt, 1974; Swanepoel & De Villiers, 1988). These cells contain starch up to approximately 3 mm from the growth tip (Pratt, 1974) and are exclusively for the formation of new cell tissue and are thus responsible for the elongation of the root. It is protected by a so-called calyptra, which guards the soft growth tip meristem and is 2.25 - 5.85 mm long (Britz, 1968). The size of the calyptra stays relatively constant through the root growth period because new cells are constantly formed to replace those that are rubbed off in the soil (Russell, 1977). The calyptra is also responsible for the excretion of a mucus gel and it produces a growth inhibitor which controls the downward turning of the growth tip. According to Russell (1977), this inhibitor is most probably abscisic acid, which inhibits cell elongation at the underside of the root, just behind the cell division zone, to control geotropism.

   Russell (1977) reported that Schwarz postulated in 1883 that nearly all root tips, including those of root hairs, are enveloped by a viscose material. Using an electron microscope, H. Jenny and K. Grossenbacher identified and named this material as mucus gel in 1963 (Fig. 1.2.1; Fig. 1.3.1). Mucus gel not only originates as a passive leakage of the contents of root cells, but also as an excretion from the Golgi apparatus of the outer cells of the calyptra (Russell, 1977). It facilitates the penetration of the root tip through soil particles and serves as a household for numerous symbiotic organisms of the rhizosphere (Fig. 1.2.1). The gel also ensures an intimate contact with soil particles, thus facilitating the absorption of water and nutrients (Russell, 1977).

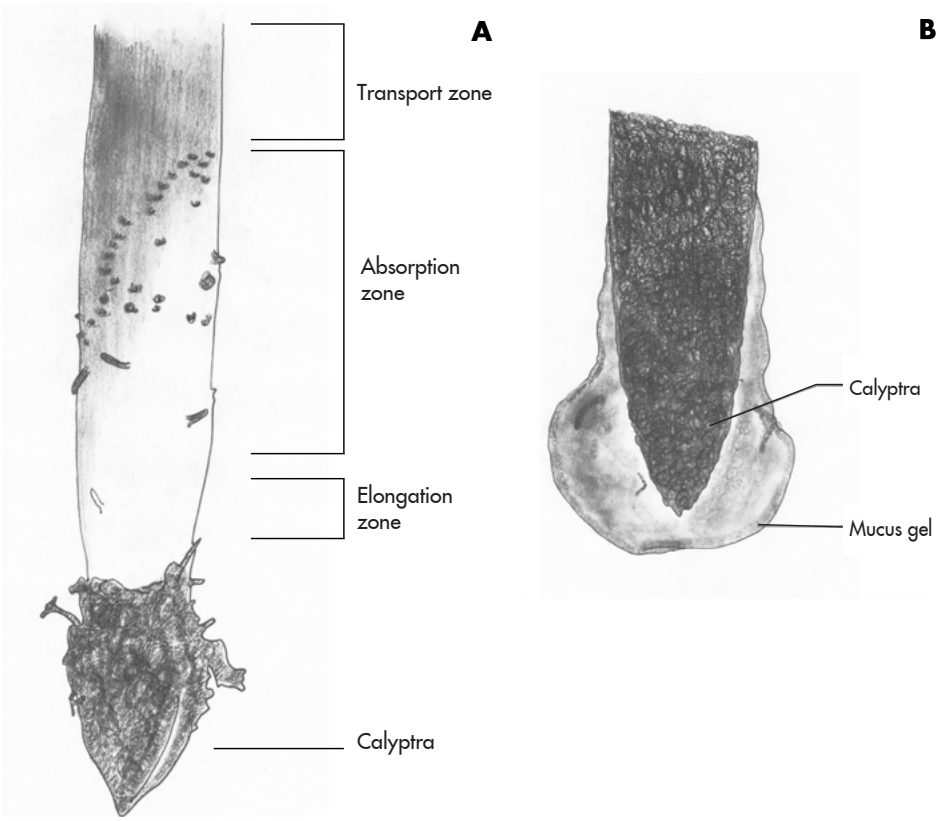


Fig. 1.2.1 External view of vine root tips. A: Without mucus gel. B: With mucus gel. (Drawn from Russell, 1977)

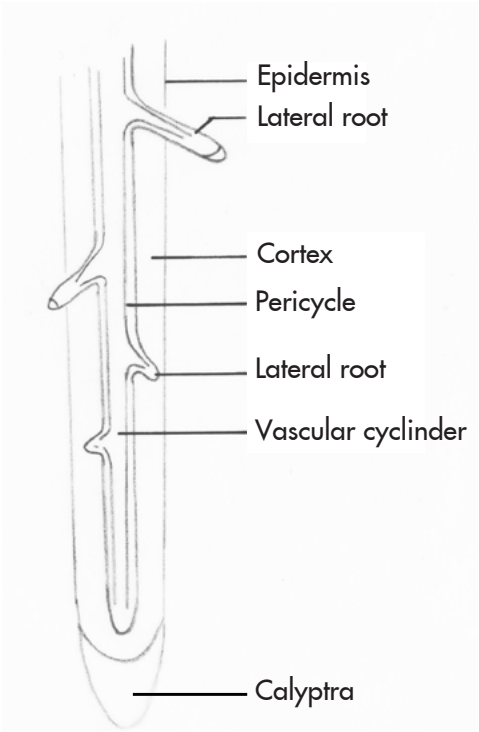
2. The cell elongation zone. This is directly behind the root growth tip (behind the calyptra) and also only a few mm long (depending on the cultivar). Here, newly formed cells elongate and develop into different tissues. The absorption zone, also known as the cell differentiation zone, follows directly on the elongation zone and is approximately 100 mm long (Pratt, 1974). It is characterised by a light yellow colour and is covered by numerous root hairs which developed from the epidermis cells.

   Root hairs have thin cell walls and big vacuoles. Individual hairs have a diameter of 12 - 15 μm, are 140 - 365 μm long (Mullins, *et al.*, 1974) and can reach a density of 300 - 400 hairs per mm^2 (Pratt, 1974). Winkler *et al.* (1974) reported a root hair density of 180 - 476 per cm root length, depending on soil pH. They live for a few days only and are continuously replaced with new hairs forming close to the root tip. In so doing, the zone of root hairs is maintained in the absorption

zone at a constant distance from the root tip. Soil pH affects the production of root hairs, and Winkler (1962) found 2.5 times more hairs at pH 5.7 than at pH 7.5, but it had no effect on growth or nutrition. This is in accordance with the findings of Cailloux (1972), who stated that the importance of root hairs under field conditions is frequently overemphasised. The main advantage of root hairs concerns their excretions (gel) which assist with mineral absorption and serve as a stimulant for rhizosphere organisms. Here, the most water and nutrients are absorbed from the soil.

3. Transport zone. This is the rest of the root and stretches from just behind the absorption zone to where it originates from other roots or the trunk (Perold, 1926; Ribereau-Gayon & Peynaud, 1971). Contrary to the absorption zone, this part of the root is brown in colour as a result of cork formation and is easily recognisable. This discolouring is related to an increase in pigmentation which may be the result of the condensation of tannins (Comas *et al.*, 2000). This browning is coupled with the death of mycorrhiza and cortex cells and is a natural process (Richards & Considine, 1981). The transport zone consists of the phloem on the outside of the cambium ring, and xylem on the inside. The xylem serves as a channel through which water and nutrients from the soil are transported upwards to the above-ground plant parts. The phloem serves as the channel through which photosynthetic products are transported downwards from the leaves to the permanent parts of the vine.

   The development of lateral roots was investigated by various researchers (Richards, 1983). Lateral root development takes place above the root hair zone, where root primordia are initiated in the pericycle and grow through the cortex to the outside (Fig. 1.2.2A). These root tips are smaller than those of the mother roots, but have similar structure and organisation (Winkler, 1962). The cracks in the epidermis caused by the emerging lateral roots are important inlets where water can flow freely into the mother roots (Fig 1.2.2B).



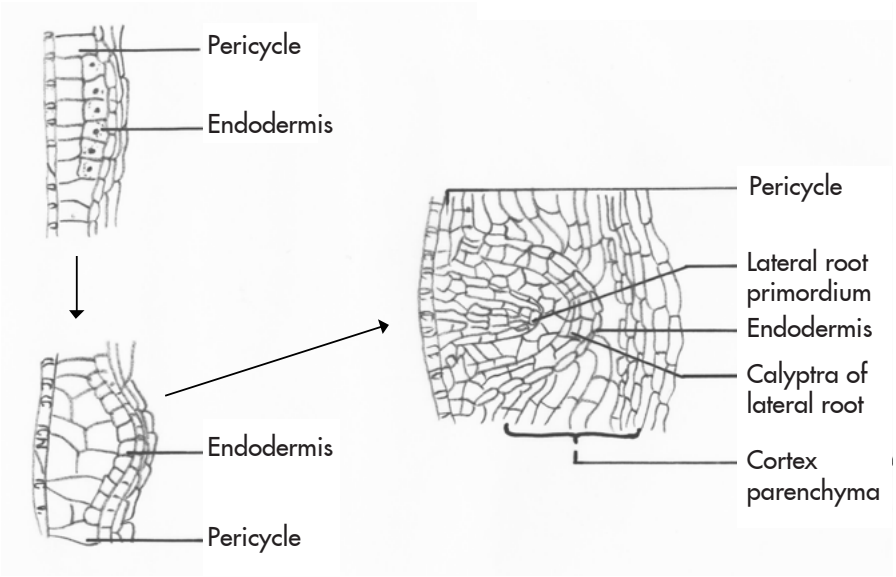


Fig. 1.2.2 A Origin of lateral roots (Redrawn from Pratt, 1974)

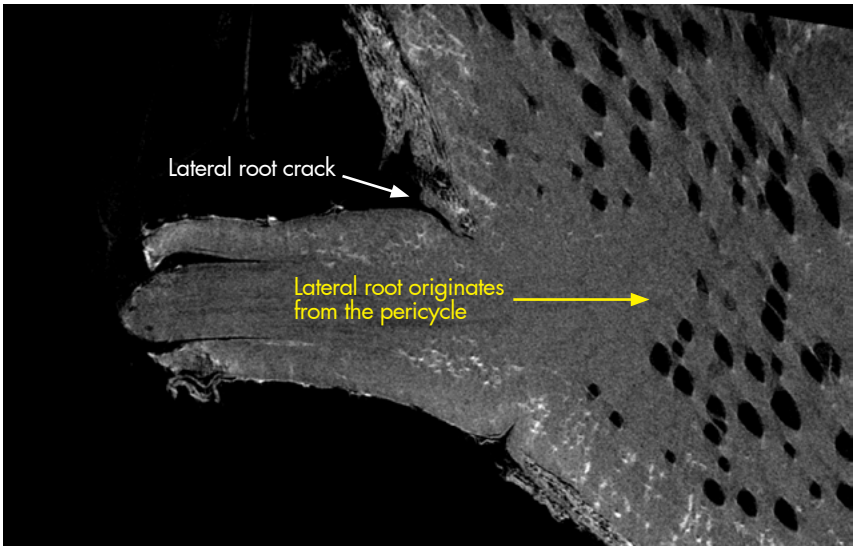


Fig. 1.2.2 B Origin of lateral roots as scanned by a Computer Tomography (CT) Scanner, Central Analytical Facilities, Stellenbosch University. (Picture: A. du Plessis, E. Archer & A. Strever, 2017)

1.3 Root anatomy

The structure of a vine root is not uniform over its total length, therefore it must be studied at different positions (Archer, 1981) (also see Fig. 1.3.1). The most important tissues in the root are the xylem and phloem. The xylem (inside the cambium ring) broadly consists of:

1. Large open pores called xylem vats. These are dead, empty vats stacked end-to-end on one another, allowing efficient sap flow (water, nutrients and hormones) upwards through the vine. This sap flow is capillary in nature and is sustained by root pressure at the beginning of the season, and later, when sufficient leaves are present, by the suction power of transpiration. At the end of the growth season these vats are blocked by thylose to enable over wintering.
2. Xylem fibres with hard, lignified cell walls to strengthen the tissue.
3. Living xylem cells in the xylem rays, storing carbohydrates to be used later as nutrition for development. It also serves as storage site for the waste products of metabolism (Goffinet, 1999).

The xylem is composed of different xylem elements which work together to facilitate the upwards transport of water and nutrients and they are: narrow and wide fibre cells, tracheids, fibre tracheids, true fibres, axial parenchyma and ray parenchyma (Fig. 1.3.2A+B). The roots of vigorous rootstocks contain notably more xylem vats than those of lesser vigour (Beakbane & Thompson, 1939).

The xylem also functions as transport channel for different signals in the vine. These signals can be physical (pressure gradients) or chemical (hormones), carrying quick messages from one plant part to the other, thus regulating tissue growth and development as a reaction to changing environmental conditions (Rogiers, 2007).

The phloem is situated just outside the cambium ring and it uses metabolic energy for the predominant downward translocation of carbohydrates and other organic compounds (Champagnol, 1984; Goffinet, 1999). It is mainly sucrose that is translocated downwards from the leaves (Rogiers, 2007). The movement takes place through living sieve tube cells, stacked on one another to form long sieve tubes. This transport is dictated by the so-called source: sink relationship. The source can be leaves or stored carbohydrates in the permanent vine parts, while the sinks are young leaves, growing shoot and root tips or developing berries. The sieve tubes consist of highly specialised cells without which no transport of complex organic compounds in the vine is possible. For assimilates to be transported, specialised proteins are necessary for the upload and download of molecules and for this metabolic energy is needed (Rogiers, 2007). Like the xylem, the phloem consists of various different elements. Some of them are indicated in Fig. 1.3.2A+B. As the root thickens, vat cambium is initiated, forming a thin cylinder of tissue between the xylem on the inside and the phloem on the outside. Cell division of the cambium throughout the growth season is responsible for forming new xylem to the inside and new phloem to the outside (Goffinet, 1999).

The phloem also functions as a transport channel for various signals in the vine, thus enabling the plant to react to different stress factors from the environment in which it grows. It is mainly the phloem-transported signals that enable the vine to produce phenolic components that discourage insects and browser animals to keep on feeding (Rogiers, 2007). Unfavourable conditions, such as extreme heat, may cause temporary blockage of the

sieve plates of the phloem with callouses, which can disappear when conditions return to normal (McNairn & Currier, 1967). Both xylem and phloem are thus regarded as very important communication channels in the vine.

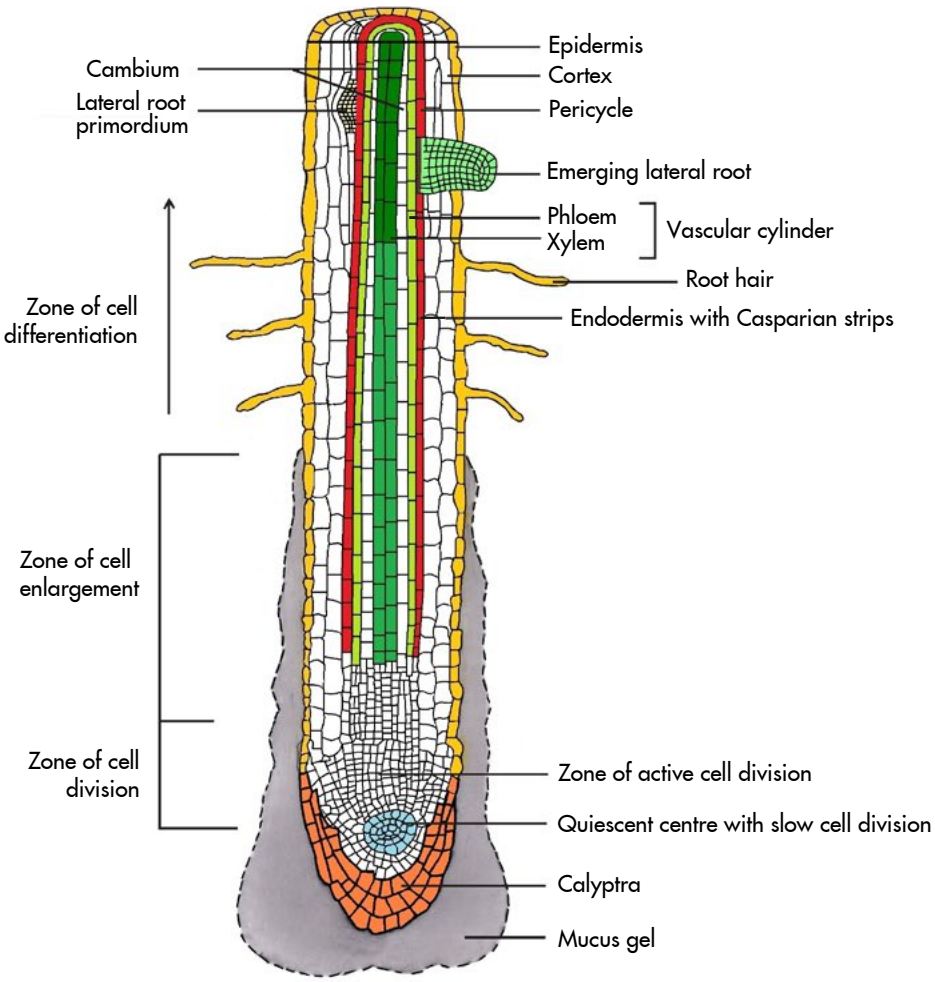


Fig. 1.3.1 Diagrammatic interior build of the root tip. (Compiled and redrawn from: Russell, 1977; Grobbelaar *et al.*, 1979 and Taiz & Ziegler, 1998)

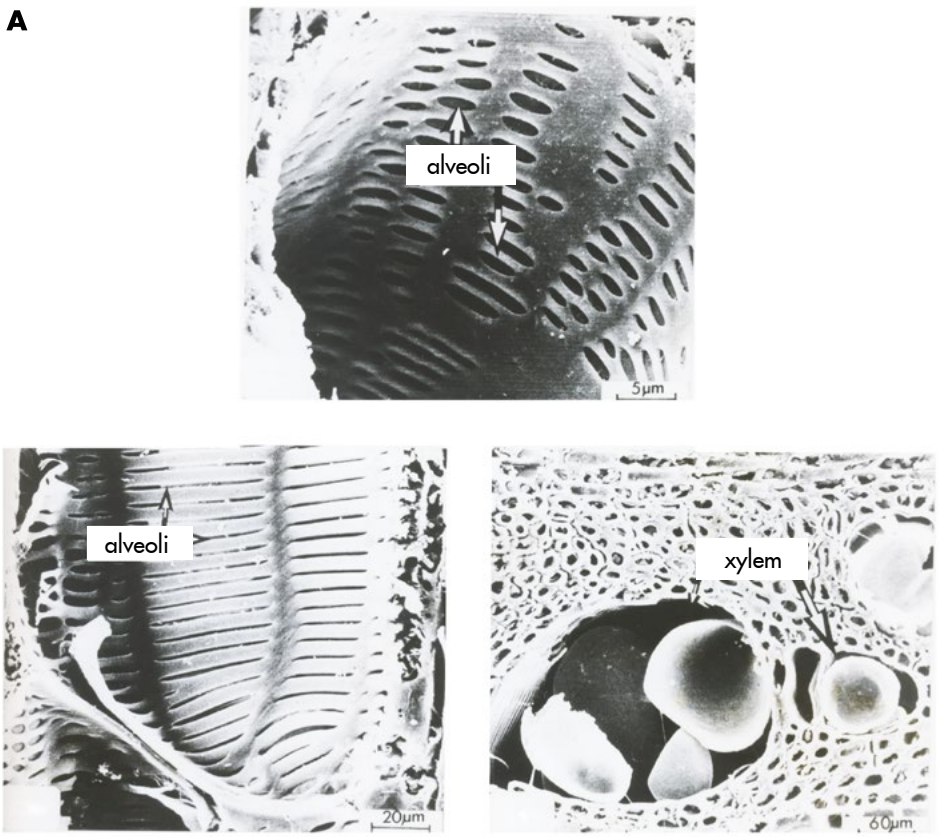


Fig. 1.3.2 A Some elements of the xylem and phloem in a secondary vine root (Swanepoel, 1983)

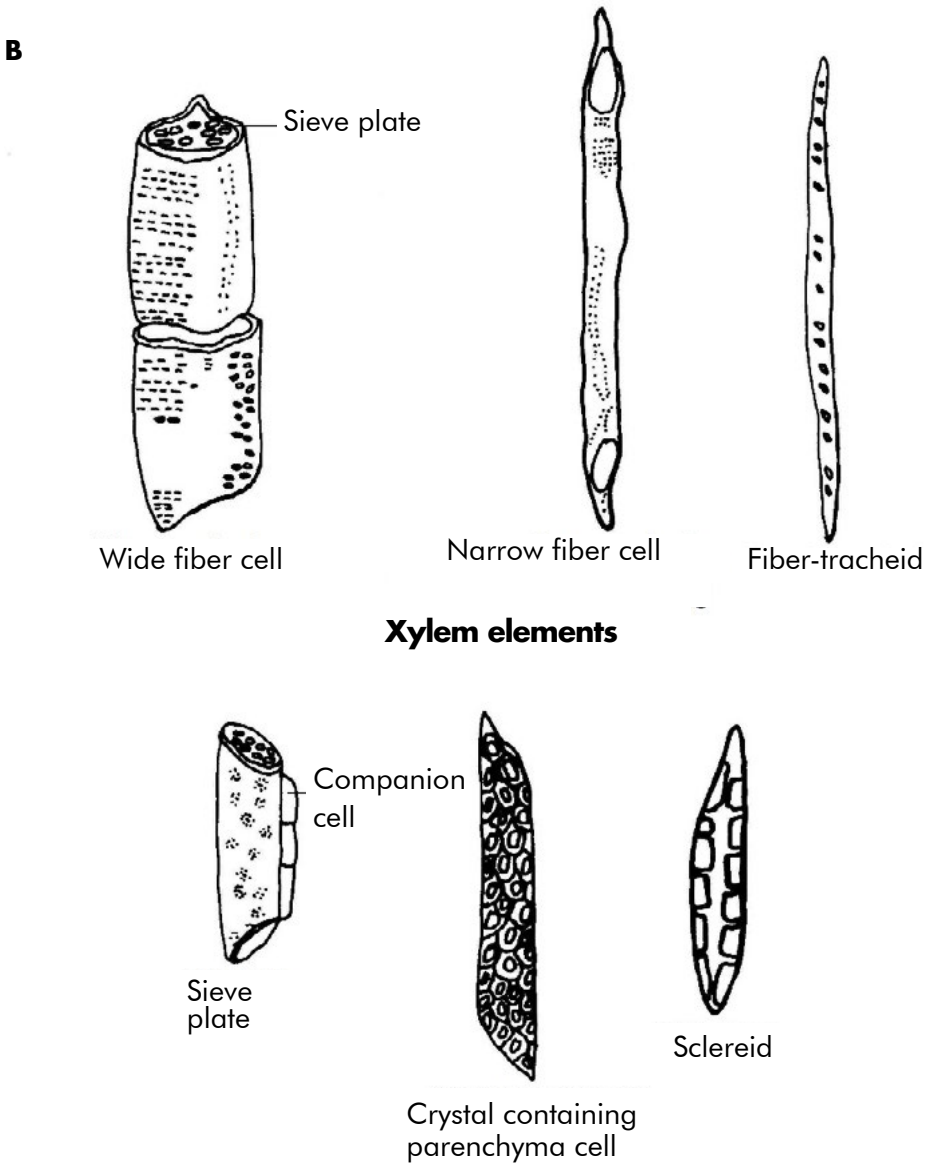


Fig. 1.3.2 B Some elements of the xylem and phloem in a secondary vine root (Compiled from Archer, 1981)

Within 10 mm from the root tip, development of conductive tissue is already clearly visible (Fig. 1.3.3). The irregularly shaped ring in the middle of Fig. 1.3.3 is the cambium initials and it enfolds the xylem, xylem fibres and xylem vats which are clearly visible (Goffinet, 1999).

The xylem is encircled by cambium initials and just on the outside thereof groups of primary phloem can be seen. Although in older root sections the phloem is primarily responsible for downward translocation, at this early stage, upward translocation of organic compounds can also take place. The original epidermis, as well as the cortex immediately on the inside, are already replaced by cork and periderm, which serve to protect the young root against soil friction.

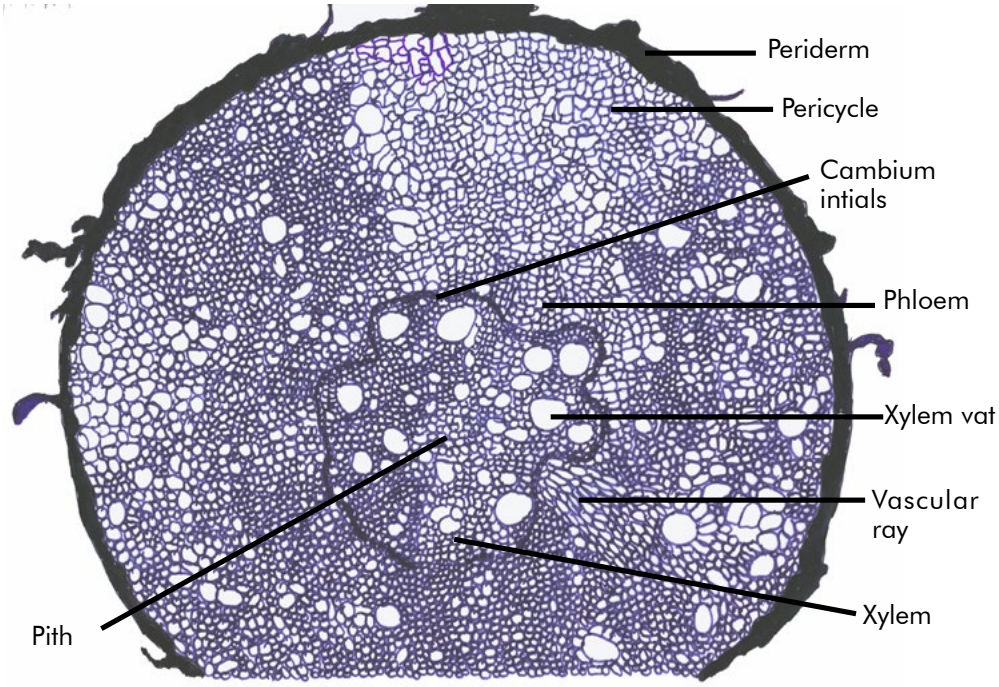


Fig. 1.3.3 Cross section of a young primary root of Richter 110, 1 cm from the tip. (Redrawn from Goffinet, 1999)

A few centimeters away from the young root tip, the primary organisation of the tissue is replaced by the development of secondary vascular tissue (Fig. 1.3.4). These tissues develop as a result of the thickening of the root, caused by cambium activity. Through active cell division, the cambium brings about new xylem elements to the inside and new phloem elements

to the outside (also see Fig 1.3.3). The new daughter cells on the xylem side have grown into vats and fibres, while enlarged xylem rays have also formed (Fig. 1.3.4). Daughter cells on the phloem side of the cambium have developed into sieve tubes, other phloem elements as well as phloem rays. Remnants of the pericycle can still be seen between the phloem and the periderm. Some vascular rays are very broad and go through to the middle of the root. They are called primary vascular rays or vascular rays of the first order because their number and placing is already fixed in the primary root organisation (Fig. 1.3.3). Vascular rays are the sites where most of the translocation exchange between xylem and phloem take place (Goffinet, 1999).

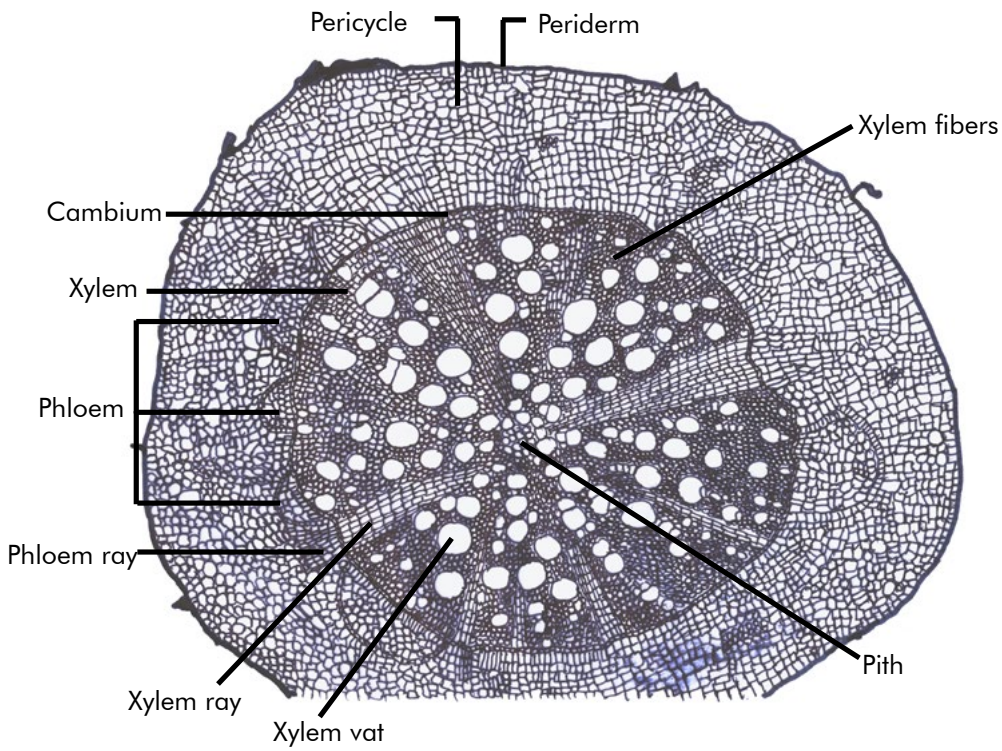


Fig. 1.3.4 Cross section through a young secondary root tip of Freedom. (Redrawn from Goffinet, 1999)

A cross section through a one-year-old root of Richter 99 (Fig. 1.3.5) shows that the xylem developed much more than the phloem in that numerous, relatively small, xylem vats and vessels had formed (Pongrácz, 1969). Phloem domes with strongly defined secondary phloem fibre strands are

clearly visible, compared to the younger root tip in Fig. 1.3.3. Vascular rays of the first, second and third order are already formed. The root is now clearly a specialised water, nutrient and carbohydrate transport organ.

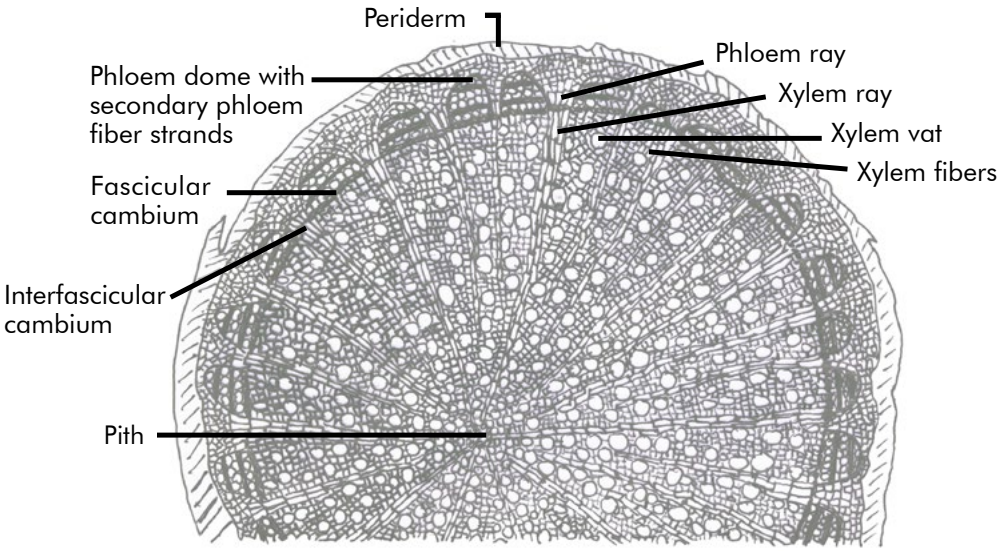


Fig. 1.3.5 Cross section through a one-year-old root of Richter 99. (Redrawn from Pongrácz, 1969)

A cross section through a one-year-old root of *Vitis vinifera* cv. Palomino (Fig. 1.3.6) shows clear differences from the traditional rootstocks. In relation to the phloem, the xylem is smaller with less, but bigger xylem vats and fibres. It makes *Vitis vinifera* more susceptible to embolism (formation of air bubbles in the xylem stream) and thus less drought tolerant than other *Vitis* species. Freeman (1983) reported that rootstocks with more and smaller xylem vats are better adapted to dryer conditions than those with less and bigger vats. The vascular rays are less but notably broader, ensuring an improved translocation communication between xylem and phloem compared to other *Vitis* species. The phloem domes are more pointed and the secondary phloem fibre strands are more poorly developed. Pongrácz (1969) found enough root anatomical evidence, together with cane morphological characteristics, that can be used to identify rootstocks during winter.

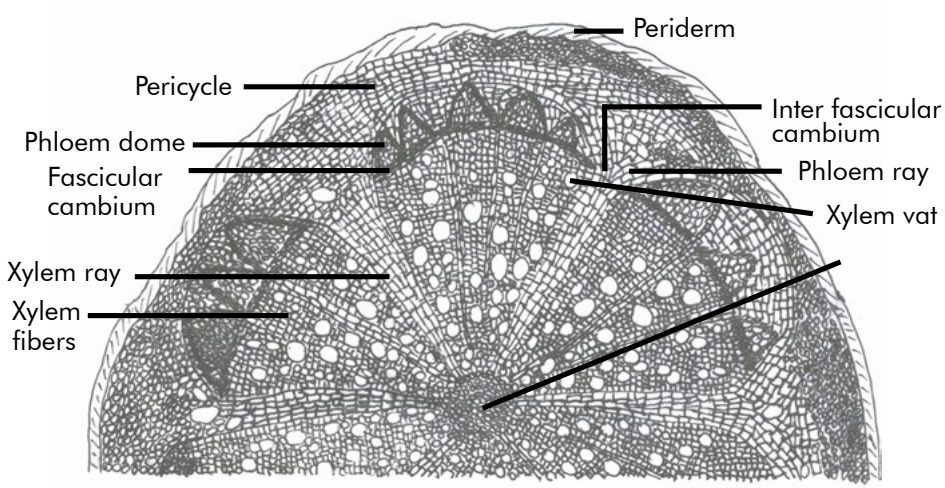
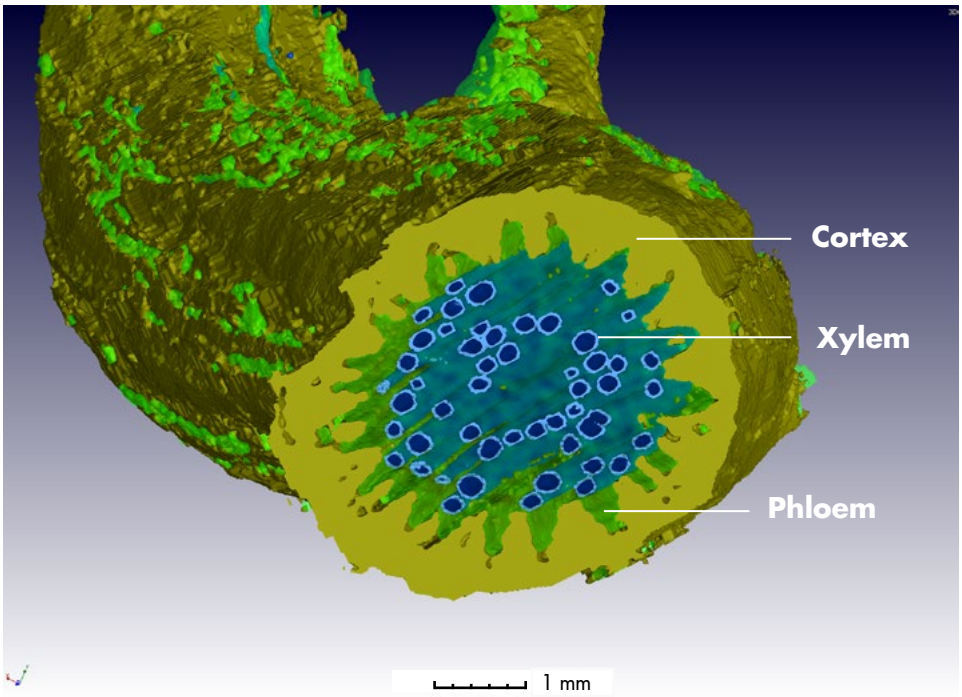


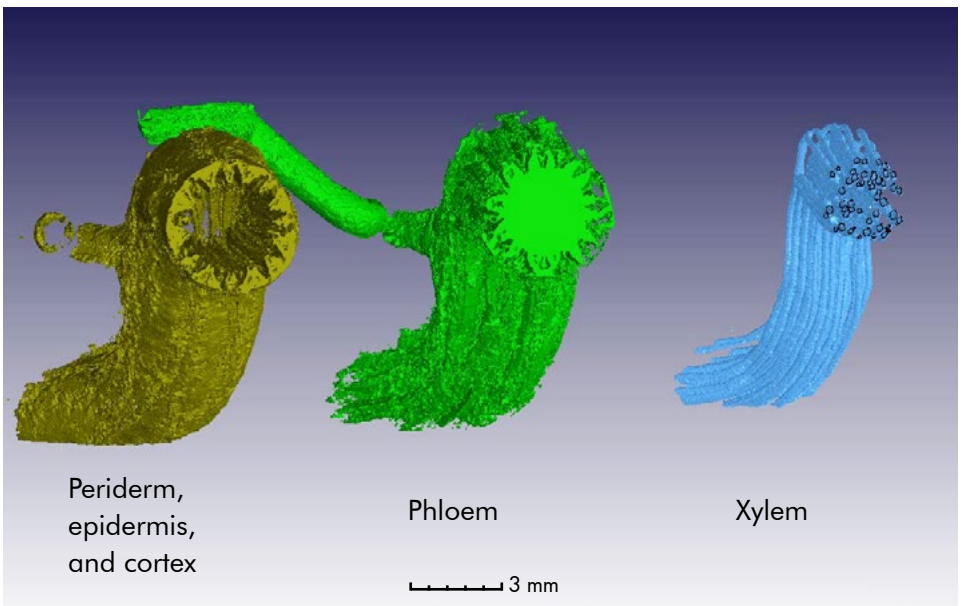
Fig. 1.3.6 Cross section through a one year old root of *Vitis vinifera* (Palomino). (Redrawn from Pongrácz, 1969)

Fig. 1.3.7A shows the main tissue types of a Richter 110 root. It is clear that the internal xylem tissue is imbedded in the surrounding phloem, which in turn, is enfolded by the outer cortex (Fig. 1.3.7B).

Although all tissues in the root are important, it is particularly the xylem which plays a cardinal role in the transport of water, nutrients and hormones. The xylem consists of hollow tubes, coupled together, enabling a direct connection between roots and aerial vine parts (Fig. 1.3.8).

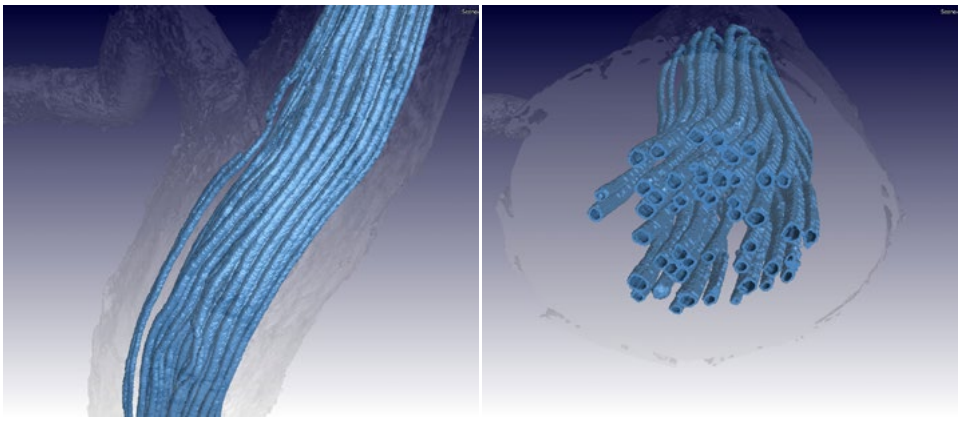


A

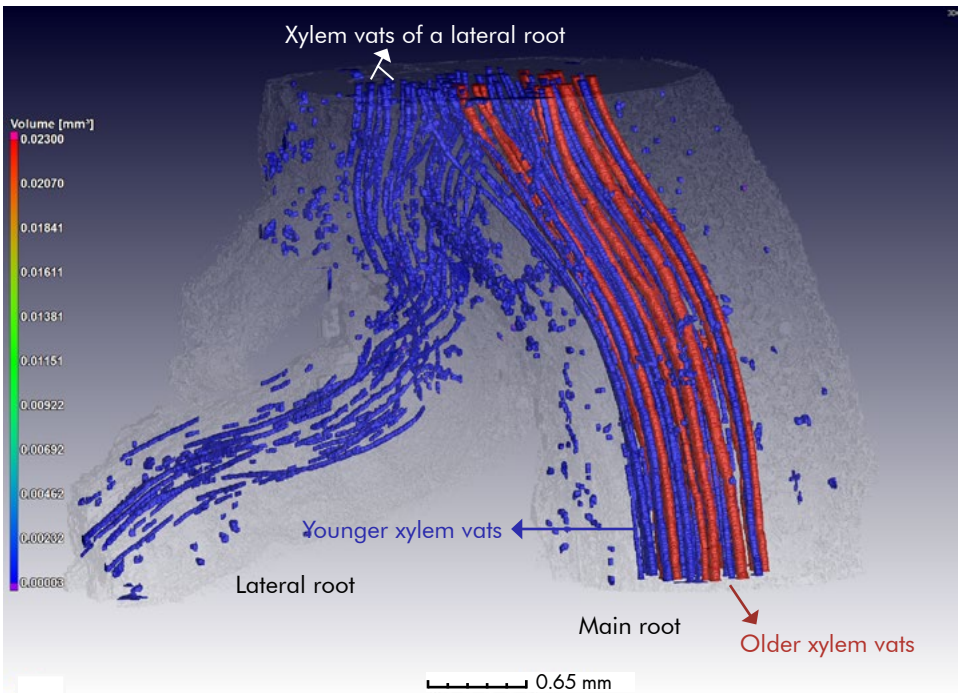


B

Fig. 1.3.7 Three main tissue types of a perennial Richter 110 root as scanned with a CT scanner.
A: cross section through an intact root.
B: Cross sections through the different tissue types
(CT scanner: A. du Plessis, E. Archer & A. Strever, 2016)



A B



C

Fig. 1.3.8 A CT-scanned image of (A) side-view, (B) end-view of xylem vats and (C) the connection of the xylem vats of a lateral root with those of the mother root of Richter 110 (CT scanner: A. du Plessis, E. Archer & A. Strever, 2017)

SUMMARY

The reaction of the vine to its surroundings is a powerful factor dictating its performance (yield and grape composition); therefore, knowledge of the root system and functions is essential. Vine root growth and expansion is dictated by soil properties, especially the physical and chemical limitations. Within the first few years after planting, vine roots colonise the soil quickly and it is especially during this phase where any limitations in the soil exert large negative effects on the eventual size and buffer capacity of the root system.

The preferred depth zone of root colonisation varies as soil nature and climate change, but it is globally situated in the top 70 cm of the soil – in cold climate countries it is shallower and in warm climate countries deeper. This preferred zone is not too shallow (desiccation) and not too deep (waterlogging).

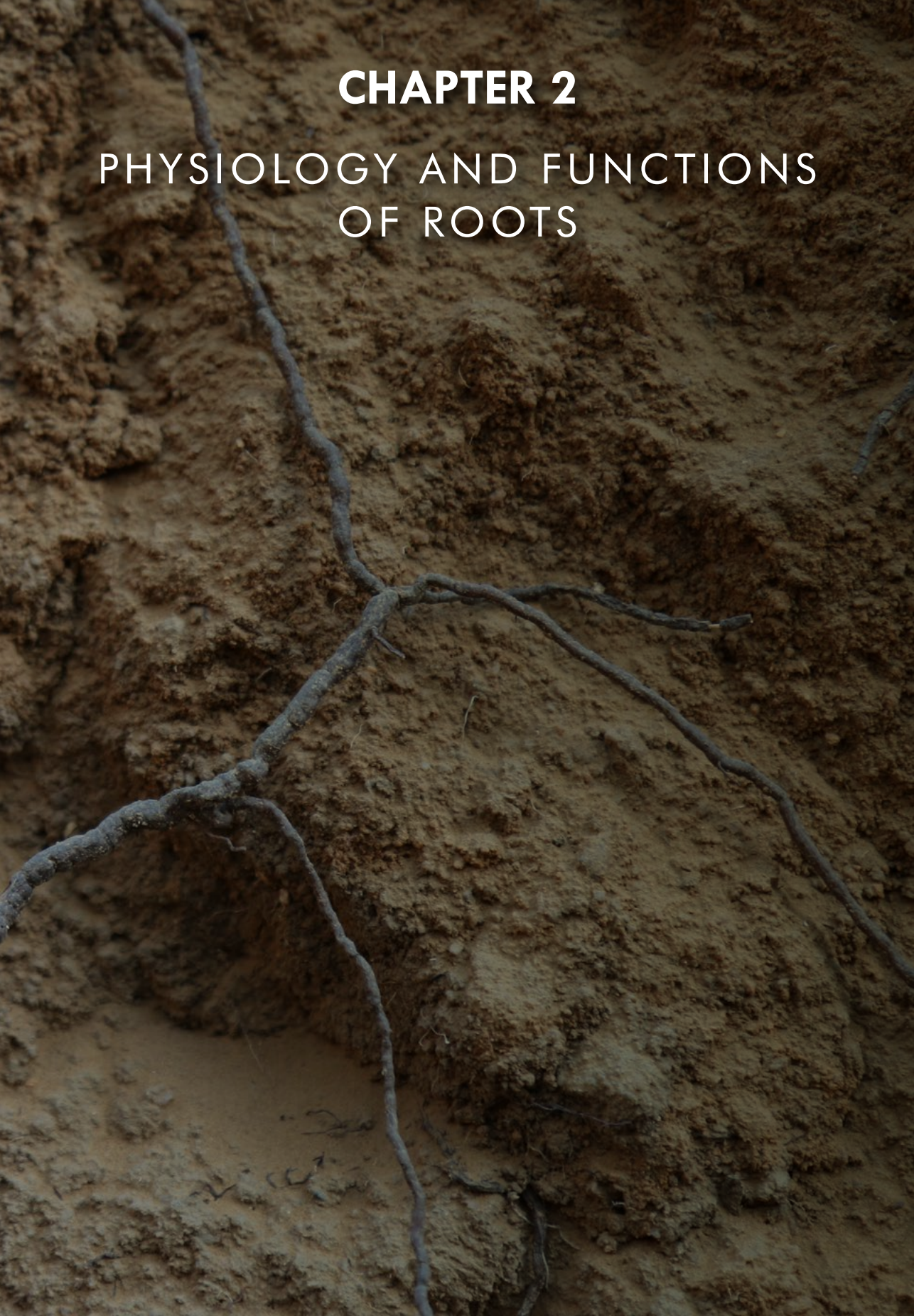
Vine root systems are characterised by shallower interception roots, consisting mainly of fine roots (< 2 mm diameter and sometimes called creeping or horizontal roots) and deeper tap roots, consisting mainly of thicker roots (> 2 mm diameter and sometimes called plunging or vertical roots). The former intercept most surface applied water and nutrients, while the latter are responsible for exploiting deep soil layers for water and nutrients, thus improving the vine's buffer capacity against unfavourable climatic conditions.

Vine roots always follow the path of least resistance and are sustained by excess photosynthetic products supplied by the canopy. In warmer (Mediterranean) climates, two main peaks of root growth occur: one at full bloom and one just after harvest. In subtropical and also cold wine climates, only one peak occurs: the former just after harvest and the latter between flowering and véraison.

A vine root is characterised by a calyptra, enveloped by mucus gel, a cell division and elongation zone, changing into a cell differentiation and eventually to a transport zone. The mucus gel houses symbiotic microbes, while it facilitates the uptake of water and nutrients.

Lateral roots originate in the pericycle of the mother root and, at emergence, form cracks in the epidermis which act as important openings for the free inflow of water and nutrients. The most important tissue types in the root are the xylem and phloem. The xylem is mainly responsible for the upward translocation of water, nutrients, hormones, etc., while the phloem is mainly responsible for the downward translocation of metabolites produced in the leaves. Xylem vats are hollow, dead tubes, allowing upward translocation by means of capillary flow and root pressure. The phloem consists of living cells in which downward translocation takes place, using metabolic energy.

There are important anatomical differences between young and old roots as well as between the roots of different rootstocks, and it is clear that this is primarily responsible for differences in the behavioural patterns of different roots.



CHAPTER 2

PHYSIOLOGY AND FUNCTIONS OF ROOTS

CHAPTER 2

PHYSIOLOGY AND FUNCTIONS OF ROOTS

2.1 Absorption and translocation of water

Plant roots originally developed to supply water and nutrients to the above-ground plant parts (Freeman, 1983). The water household in the vine is intimately linked to the soil water as well as the above-ground meso- and microclimate (Rogiers, 2007). Water loss through the canopy by means of transpiration is the driving power behind the uptake of water during the growth season. A decrease in the water potential in the leaves causes a gradient between leaves and soil so that water can flow into the roots (Mullins *et al.*, 1992). The root must be in contact with the soil particles to absorb water, except if the air space between particles is filled with water. Roots with intact cortex form the majority of total root length and are primarily responsible for the uptake of water and nutrients (Volder *et al.*, 2005). The contact surface between roots and soil is markedly increased by the network of fine roots in the upper soil layers (also known as interception roots), as well as root hairs and mycorrhiza (Taiz & Zeiger, 1998). Root hairs are microscopical protuberates of epidermis cells and occur close to the root tip, while mycorrhiza fungi colonise the roots and live in symbioses with the vine. Root hairs increase the absorption surface of roots, but it seems that this is overemphasised under field conditions (Cailloux, 1972). Their advantage is rather found in the excretions they produce, facilitating absorption of nutrients, mobilising nutrients around the roots and stimulating beneficial rhizosphere organisms.

The vine root has a strong resistance against shrinkage and this is probably the main reason why vines are more drought tolerant than most other crops (Freeman, 1983). Van Rooyen (1980) declared that the ability of the vine to withstand dry conditions can be ascribed to its ability to form deep roots, more than to an inherent insensitivity to drought.

Water moves in bulk flow around the soil particles to the roots and from the epidermis to the endodermis via three mechanisms (Fig. 2.1.1) (Taiz & Zeiger, 1998):

1. The apoplasmatic pathway (apoplast = water-filled spaces outside the cell membranes), where water moves exclusively in the cell walls into the xylem without crossing any cell membranes. This pathway is blocked by Casparian strips in the endodermis and the water is forced to move through the protoplasm of the endodermis cells, after which it moves again apoplasmatically in the vascular cylinder until it reaches the tracheid cells and vats of the xylem. This resistance of the Casparian strips to water infiltration increases the resistance of vine roots to root shrinkage (Freeman, 1983).
2. The trans-membrane pathway, is where water penetrates the cell wall from one side and leaves the cell on the other side by again penetrating the wall. It then penetrates the next cell and leaves it on the other side. This process is repeated in succeeding cells and in so doing at least two membranes in each cell are traversed via the plasmadesmata (ultramicroscopic connecting channels).
3. The symplastic pathway (symplast = protoplasm in the cell membranes), is where water moves in the network of protoplasm within the cell membranes, which are connected to one another by plasmadesmata (Mullins *et al.*, 1992). Water can also physically penetrate the corky parts of mother roots (further away from the tips) through cracks caused by emerging lateral roots (Queen, 1967; Figs 2.1.2 and 2.1.3).

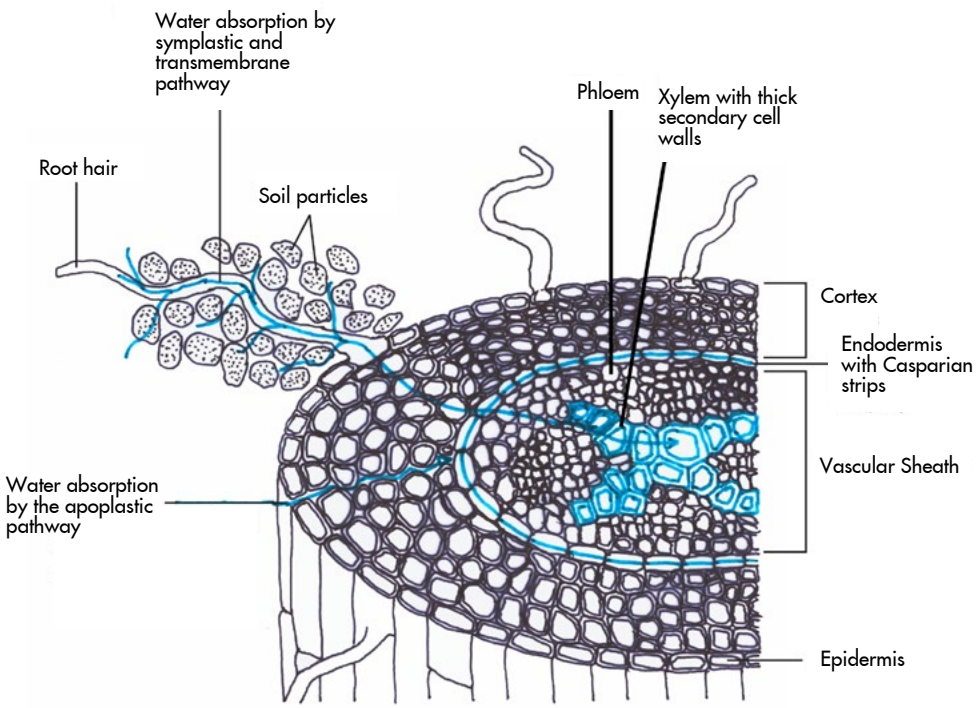


Fig. 2.1.1 Uptake of water by a root (Drawn and adapted from Taiz & Zeiger, 1998)

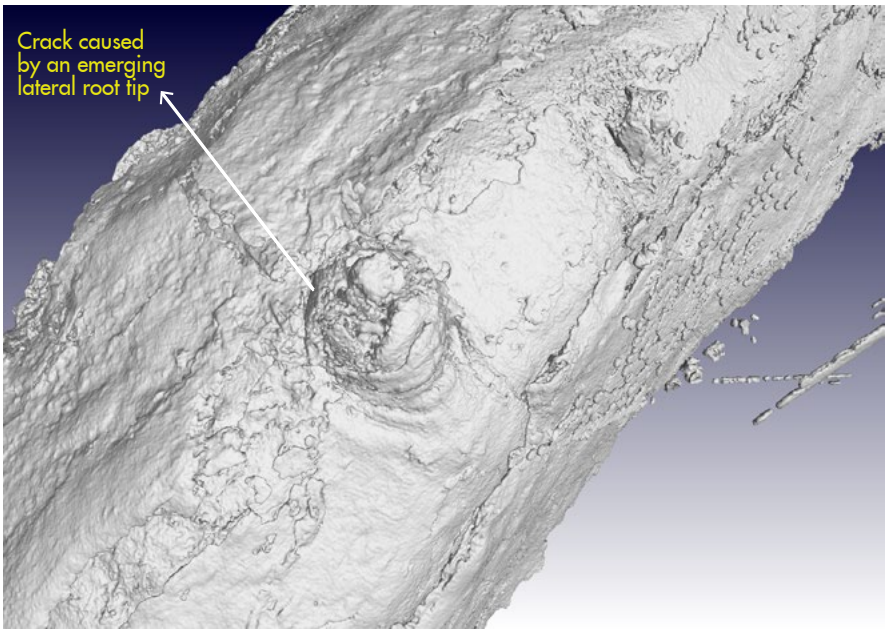


Fig. 2.1.2 Crack in the mother root caused by an emerging lateral root tip (CT scanner, A. du Plessis, E. Archer & A. Strever, 2017)

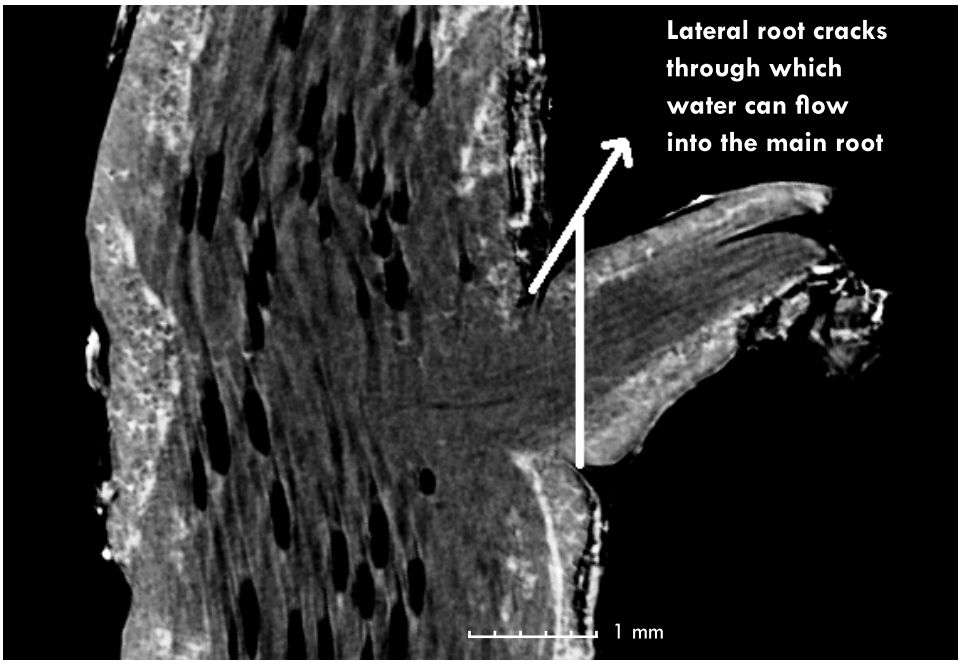


Fig. 2.1.3 Cracks caused by a lateral root through which water can enter the main root (CT scanner, A. du Plessis, E. Archer & A. Strever, 2017)

The flow of water through the vascular bundles is made possible by the strong cohesion between water molecules as well as by capillary rising. The flow speed of water in the xylem of woody plants is 1.0 to 12 mm/s (Jones, 1983). For a long time it was accepted that corked roots are impenetrable to water, but it is now known that such roots of woody species in water have a hydraulic conductivity of 40 - 70% of that of non-corked roots (Bowen, 1985). This is supported by findings that corked vine roots absorb water early in the season, before flowering, before new root growth is noted.

Although it is known that vine roots can survive in zones with serious water limitations, little attention was given to the underlying principles (Bauerle *et al.*, 2008). The vine has relatively bigger xylem vats than other plants, implicating low hydraulic resistance, thus allowing a quick redistribution of water to the roots which experience the biggest water stress (Smart *et al.*, 2005).

This whole process is named the root hydraulic conductivity and it is seriously hampered by a shortage of oxygen (wet soils) and low soil temperature. This is the reason why wilting frequently occurs in wet soils, showing the same symptoms as desiccation.

The tracheids and vats of the xylem are dead because they do not contain membranes or organelles (Taiz & Zeiger, 1998). They are like hollow tubes and are strengthened by lignified cell walls. The cell walls between piled up cells contain water permeable pits through which water can flow freely in one direction (Rogiers, 2007). The xylem is thus regarded as consisting of capillary tubes allowing upward water flow by means of pressure gradient differences. At the beginning of the season, when the soil is warming (> 6°C), the roots develop an osmotic potential because of metabolic activity, ensuring the inflow of water into the roots. Before the presence of transpiring leaves, this water is pushed up in the xylem by root pressure and becomes visible as bleeding sap at pruning wounds (Fig. 2.1.4).

Fig. 2.1.4 Root pressure causing bleeding sap at cut canes, end July/beginning August. (Picture: G. Liebenberg, Felco)

Vine roots can transport the absorbed water over a distance of 35 m, irrespective of whether the vine grows vertically or horizontally (Champagnol, 1984). As soon as sufficient transpiring leaves are present, water is pulled up in the xylem by transpiration and this tractive power keeps functioning as long as the water gradient between the air and soil is not excessive (Rogiers, 2007). If water stress in the xylem column continues to rise, the possibility for the formation of air bubbles in the water stream increases – a phenomenon called embolism. These bubbles interrupt the capillary water stream in the xylem vats and hamper water uptake. On account of the vine's genetic resistance to root shrinkage (Champagnol, 1984), it is regarded as drought tolerant, but embolism can occur during warm, dry climate conditions, especially in combination with low levels of available soil water (Rogiers, 2007).

Although it was accepted earlier that corking of the endodermis prevents water and nutrient penetration to the xylem, Kramer *et al.* (1966) and Wilson and Atkinson (1979) found that it is frequently allowed in through wounds and cracks (caused by emerging lateral roots). These findings are supported by the results of Freeman and Smart (1976). The structure of the periderm does not exclude that woody roots can absorb water and nutrients (Atkinson, 1980). Cells in the outer layers of the periderm develop cork only on the outside of their cell walls, thus not blocking the apoplastic pathway to the xylem.

SUMMARY

Effective water uptake and transport are determined by the size of the contact surface between the roots and soil. This surface is mainly determined by the network of fine intercepting roots occurring in the topsoil as well as by root hairs and mycorrhiza, while the size of the preferred zone for root colonisation also plays an important role. The better drought tolerance of the vine compared to that of other crops, is based on its resistance to root shrinkage that breaks soil contact, as well as its ability to form depth roots which can exploit the deeper, moist soil layers.

There are three ways in which water is absorbed and all three are equally important to supply water to where it is needed for growth. Additionally, free inflow of water through cracks and other wounds is also contributing to satisfy demand. All absorbed water is translocated to the xylem, so that upward translocation can take place. The flow speed of water in the xylem is 1.0 to 12.0 mm/s. The uptake of water is seriously limited by a shortage in oxygen (wetness) as well as low soil temperature and dryness, and this is why drought and waterlogged symptoms are similar.

The xylem, in which water is transported upwards, consists of hollow tubes in which water moves by means of pressure gradient differences. As soon as soil becomes warmer than 6°C, the roots develop an osmotic potential because of metabolic activity before the start of above-ground growth, and this causes the inflow of water into the roots. This water is pushed up in the xylem by root pressure and becomes visible as bleeding sap at pruning wounds. As soon as enough leaves developed, water is pulled up the xylem by transpiration. If this pulling power becomes too strong, water transport can be interrupted by the development of air bubbles (embolism).

2.2 Absorption and transport of elements

Rootstocks differ in their ability to absorb nutrient elements (Kidman *et al.*, 2014). Shiraz roots absorbed significantly more calcium (Ca) than rootstocks and gave rise to more pip containing berries, more berries per bunch and higher berry mass. Rootstock 1103 Paulsen absorbed more boron (B), and this caused less seedless berries and a smaller millerandage-index than other rootstocks. Sensitivity for zinc (Zn) deficiency was noted for 110 Richter and 140 Ruggeri and consequently more berry shatter. Rootstocks 99 Richter and Schwarzmann had the highest and 140 Ruggeri the lowest number of pollen granules on the stigma, directly related to the number of set berries (Kidman *et al.*, 2014). This indicated that 140 Ruggeri absorbed less Zn than the other rootstocks.

Some elements like B, phosphorous (P) and Ca must be in the immediate vicinity of the root to be absorbed effectively. Champagnol (1984) reported that P must be within a few millimetres from the root, while potassium (K) can migrate over centimetres and N over 10 cm distances. Root growth and branching seem to be highly dependent on P and N nutrition and provision thereof to only part of the root system is sufficient to uplift limited supply to other parts of the system. Nitrate absorption is high for recently emerged roots, but decreases notably after only a few days (Volder *et al.*, 2005). Vine roots also have the capability to prevent the transport of salts, such as Na, by storing it (Jacoby, 1964). Aluminium (Al) and copper (Cu) are also stored in the roots and, therefore, toxicities thereof are not easily detectable through leaf analyses (Delas, 1984).

The uptake of nutrient elements takes place passively and/or actively (Russell, 1977; Archer, 1996b). With passive absorption (also called mass flow or diffusion), water, with dissolved cations and anions, flows into the root and fills the intercellular spaces. An important part of this inflow takes place in the corky parts of roots through cracks in the mother root made by emerging lateral roots (Queen, 1967) (also see Fig 2.1.3). Because the cell walls of the root tissue are mainly negatively loaded, cations are absorbed faster than anions. This rapid absorption of elements lasts for approximately 30 minutes (for example after fertilization), after which it slows down markedly as the ions migrate to the xylem over the endodermis with its Casparian strips, to be translocated upwards to the aerial parts (Russell, 1977). This upward transport through the xylem is mainly passive

and takes place by means of the transpiration stream (Bollard, 1960). The transfer of ions over the endodermis to the xylem parenchyma is regulated by the neutralisation of load differences, but it is also driven by metabolic energy. This means that passive absorption is also partially aided actively. Freeman (1983) reported huge rootstock differences in the quantity of different ions taken up from the soil solution. Rootstock 1103 Paulsen, for example, absorbed significantly more iron (Fe) from the same solution than 420-A Mgt.

Active absorption of ions takes place against the concentration gradient between the soil solution and the plant sap (also gradient differences between cells) and is driven by metabolic energy obtained from hydrolyses of ATP. In this process, ions are carried over and through the cell membranes to the transpiration stream in the xylem by so-called carrier molecules (Bollard, 1960; Russell, 1977; Taiz & Zeiger, 1998). With vines there are mainly two carrier molecules: a lipid named lesitin and the cytochrome system (Archer, 1996b).

Van Zyl (1984) proposed a root index (RI) to evaluate the functional efficiency of a root system. According to this, RI = number of roots < 2 mm diameter ÷ number of roots ≥ 2 mm diameter. Normally, a high RI reflects favourable soil conditions, allowing better root colonisation of the available soil volume. If the soil is homogeneous and favourable to root penetration, RI can be used to evaluate differences in root efficiency between rootstocks (Swanepoel & Southey, 1989). Morlat (2010) also used a so-called root distribution index (RDI, also see Fig 1.1.16) to typify soil utilisation by root systems and found that the presence of fine roots is dictated by soil properties.

Conradie (1980) found no significant N-absorption before budding, and until flowering the N accumulated by new growth was supplied by the permanent vine parts, especially the roots. The roots also contributed important amounts of N for new growth during the period from flowering to the end of fast shoot growth, which means that until then, a regular decrease in root N occurred. From this stage to véraison, roots showed an increase in N for the first time. From véraison to harvest, N uptake ceased, but the bunches kept on accumulating N, which meant that it was sourced from the roots and leaves. After harvest, N was actively absorbed, of which most was partitioned to the permanent parts, especially the roots, where

the N content was doubled. Roots continued to accumulate N until leaf fall, even though active root growth, as indicated by root mass, stopped five weeks after harvest.

According to Möhr (1996), the relative importance of absorbing and extension roots is not clearly understood. Water is absorbed by both corked and non-corked roots as new roots are absent during the stage of quick shoot growth. In Mediterranean (warm) climate, Conradie (1980) found that vine growth until flowering is dependent on N reserves accumulated after the previous harvest, while post-harvest N absorption in moderate climate is less important. Möhr (1996) reported that P. Weissenbach, W.E. Heller and P. Perret in 1993 found a strong correlation between nitrate content of bleeding sap and that of the soil solution, indicating that it was absorbed from the soil before the start of shoot growth. On the contrary, Löhnertz (1988, 1989) found that nitrates were not notably absorbed from the soil before the 5 - 6 leaf stage, with a strong increase in the shoots two weeks before flowering.

Möhr (1996) reported a general appearance of lime induced Fe chlorosis before flowering in cold areas on wet, compact, calcareous soil and ascribed this to the quick change from cold, rainy to warm, dry climatic conditions, inducing rapid shoot growth. Iron is absorbed by root tips which are few during this period. He referred here to the work of Perret and Koblet (1988) who, under similar conditions, found the root tips to be inactivated by bi-carbonates and other detrimental ingredients. After flowering, the growth of root tips accelerated and it possibly explained why the leaves then turned green again.

SUMMARY

Absorption of nutrient elements happens passively and/or actively. With passive absorption the dissolved ions flow from the soil solution into the roots by means of pressure gradient differences. An important part of this inflow takes place in the corked root parts as well as through cracks in the epidermis of mother roots, caused by emerging lateral roots. Cations are absorbed faster than anions because the cell walls of root tissue are mainly negatively charged.

Active absorption takes place against concentration gradients and is driven by metabolic energy. Carrier molecules are used to transport the ions through cell membranes into the xylem.

There are important differences between rootstocks in their ability to absorb different ions, and this is accentuated by differences between cultivars in the ratio of fine: thick roots. There are also differences in the quantities of nutrient elements absorbed through the season that are driven *inter alia*, by different phenological stages.

2.3 Storage of reserve nutrients

The storage of carbohydrate reserves (mainly starch) is less in older roots than in the trunk (Winkler & Williams, 1945). This storage is mainly in the root bark and is used mostly for new root growth, with the aid of enzyme activity, when the leaves are still absent during the early season. The main advantage of larger root reserves is a bigger capacity to bring about bunch ripening the following season, and in this respect warmer climate conditions with irrigation have a notable advantage over cooler climate areas (Holzapfel, 2004). Part of the photosynthetic products made by the leaves are used for various above-ground growth processes, but in balanced vines a larger part is translocated downwards in the phloem where it is either used or stored as starch (Bouard & Pouget, 1971). The form in which carbohydrates is transported, is sugar, and the most important form is sucrose (glucose and fructose are also transported). The speed of downward translocation is 30 - 40 cm per hour (Bouard & Pouget, 1971).

Although all organs and other parts of the vine can act as storage sites, the highest percentage of carbohydrate reserves is found in the roots (Loescher *et al.*, (1990). The partitioning of carbohydrates to vine roots depends on the relative strength of the sink, compared to that of the other organs of the vine (Tromp, 1983). At the beginning of the growth season, > 80% of all starch and ±75% of all N in the vine is found in the roots (Bates *et al.*, 2002). This storage of starch, amino acids (especially arginine) and citric acid takes place especially during late summer and fall, but it can continue until just before budding (Nasser & Kliewer, 1966). Conradie (1992) also found that 60% of total N reserves in the vine at the beginning of new growth is derived from N absorbed post-harvest. The quantity of K in roots is less than N, but is normally more in the trunk and cordons. Only a small part of K is mobilised from the roots (Araujo & Williams, 1988).

The woody parts of the vine root system have a great capacity to store carbohydrates, which is then used by different organs of the vine (Bennett *et al.*, 2002). Hunter *et al.* (1995) found that starch is the main form of carbohydrate stored in the roots and that it is independent of root diameter. They also found that the synthesis of starch was independent of root age. At the beginning of the following growth season, the stored starch is mobilised and translocated from the roots through the xylem to the aerial parts at a speed of 15 - 20 cm/hour (Bouard & Pouget, 1971). The quantity

of these root reserves changes dramatically during the year. It decreases rapidly during budding and early shoot and bunch growth, then increases late in the growth season, normally after vegetative growth and bunch ripening have stopped (Loescher *et al.*, 1990).

The reserve pool in the permanent vine parts not only plays an important role in all growth and ripening processes, but is also of cardinal importance for protection against cold damage (Bouard & Pouget, 1971; Araujo & Williams, 1988; Loescher *et al.*, 1990; Bates *et al.*, 2002). The budding process, as well as shoot and root growth, taps important quantities of mobilised starch, after which initial shoot growth, until just before flowering, further drains reserve nutrients. According to Bates *et al.* (2002), up to 78% of stored root starch is used for this purpose. Although early season fine root growth is a big sink for stored N (Bates *et al.*, 2002), they quickly become a source of absorbed N after flowering (Conradie, 1992) when they supply up to 84% of the needs for growth in spring. After that, they contribute greatly to laying down the new reserve pool. Accordingly, Araujo and Williams (1988) found that root-stored N is mainly used for new root growth and that it is not the main source for other above-ground growth processes of the vine. The quantity of N that is stored in vine roots is directly related to the quantity and timing of N fertilisation and it is especially fertilisation in the fall that plays a decisive role (Tromp, 1983).

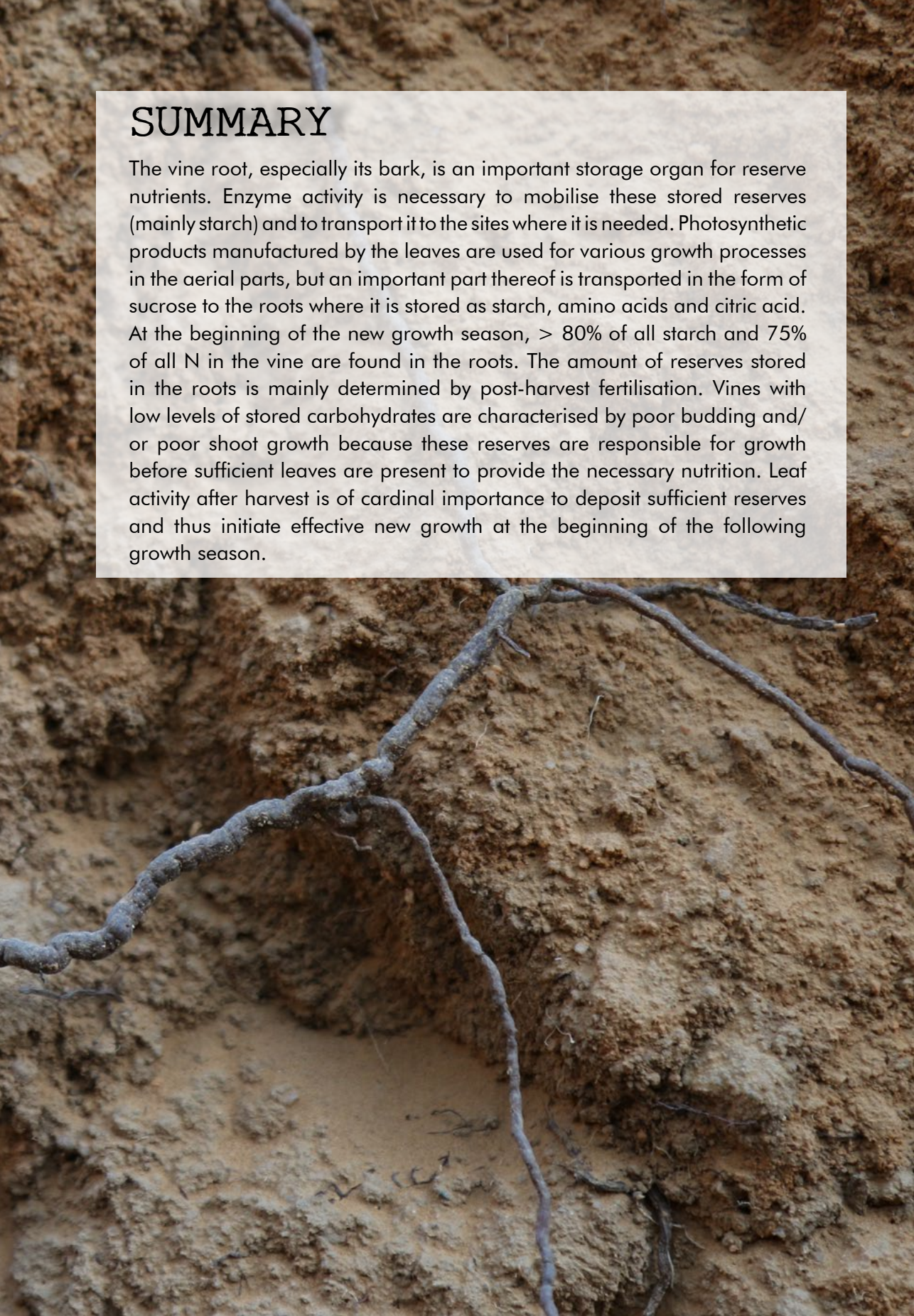
The reserves reach a low point late in summer. Vines with relatively little carbohydrate reserves at the beginning of the new growth season are characterised by poor budding and/or poor shoot growth (Branas, 1974). Sufficient reserves are necessary for early growth the following season to ensure that enough leaves are available in time for the vine to be self-sufficient (Mandel *et al.* (2001). The build-up of reserves late in the growth season is very sensitive to stress factors such as drought, waterlogging, over-cropping, poor cultural practices, etc. Periodic water stress causes up to 17% less reserves being released by respiration in the roots of maple trees during the total growth season (Burton *et al.*, 1988). This respiration was exponentially positively correlated to soil temperature and rectilinear negatively correlated with soil water shortage and root N concentration. Such conditions, coupled with exhaustion of reserves, are very detrimental to vine performance during the following growth season (Loescher *et al.*, 1990). Supporting this, Mandel *et al.* 2001) declared that the length and quality of the post-harvest growth period, untill leaf fall, are extremely important for

root growth and nutrient absorption. Warmer areas, normally, have a better post-harvest growth period than cooler areas, therefore the starch reserves are higher in the case of the former. The production of carbohydrates during this period is necessary to replenish the reserve pool in the canes, cordon arms, trunks and roots of the vine. Buffered root systems prevent unnecessary leaf fall and are therefore necessary for a good reserve balance. Therefore, practices such as mechanical harvesting must be managed correctly to prevent excessive loss of leaves.

Vine roots not only store N-compounds in winter, but also synthesise various amino acids and amides during the growth season (Nassar & Kliewer, 1966). It is clear that a well distributed and big enough root system is of cardinal importance for the yearly growth processes of the vine. The fine: thick root ratio plays an important role in vine performance. Archer and Hunter (2005/6) found that better buffered vineyards are characterised by a fine: thick root ratio of > 5, while poorly buffered vineyards showed a ratio of approximately 2. Abundant fine roots are therefore of great importance.

According to Champagnol (1984), over-cropping or leaf loss during the early years after planting will lead to delay in root growth because of an inadequate provision of sugar. Black leaf ('brunissure', a late season K deficiency symptom) or over-cropping decrease the deposit of starch, thus seriously limiting root expansion with consequent damage to the ability of roots to ensure proper water and nutrient absorption and to be resistant against drought. In accordance, Comas *et al.* (2005) found for Concord vines that over-cropping resulted in low starch content in woody roots (2 - 7 mm diameter). Over-cropping of young vines, especially on dry hills, is seriously detrimental to their future. During spring it is desirable that all factors affecting root physiology should be optimal for vegetative growth.

The results of Araujo and Williams (1988), on the other hand, did not fully support the role of roots as main storing organs providing N to the rest of the vine. According to them, N from other permanent parts of the vine provided 14 - 26% of the need for shoot growth shortly after budding.



SUMMARY

The vine root, especially its bark, is an important storage organ for reserve nutrients. Enzyme activity is necessary to mobilise these stored reserves (mainly starch) and to transport it to the sites where it is needed. Photosynthetic products manufactured by the leaves are used for various growth processes in the aerial parts, but an important part thereof is transported in the form of sucrose to the roots where it is stored as starch, amino acids and citric acid. At the beginning of the new growth season, > 80% of all starch and 75% of all N in the vine are found in the roots. The amount of reserves stored in the roots is mainly determined by post-harvest fertilisation. Vines with low levels of stored carbohydrates are characterised by poor budding and/or poor shoot growth because these reserves are responsible for growth before sufficient leaves are present to provide the necessary nutrition. Leaf activity after harvest is of cardinal importance to deposit sufficient reserves and thus initiate effective new growth at the beginning of the following growth season.

2.4 Physiology of roots

Vine roots have, over and above water and nutrient absorption, also the important function of producing hormones, which are translocated to the aerial parts where they affect the nature and rate of canopy growth (Torrey, 1976). These hormones are chemical messengers, managing the vine's reaction to the environment. With vines there are five hormone groups: auxins, gibberellic acids (GA), cytokinins, abscisic acids (ABA) and ethylene (Torrey, 1976; Taiz & Zeiger, 1998).

In vines, hormones never function alone, but always in relation to one another. There are three growth hormones (auxin, gibberellic acid, and cytokinins) and two ageing (ripening) hormones (abscisic acid and ethylene). All growth, development and ripening processes in the vine are the result of variable ratios in which these hormones occur to one another. These ratios are mainly determined by the natural and/or man-made variations in above-ground and subterranean environmental factors. It is especially the variable subterranean conditions (waterlogging, desiccation, salinity, nutrient deficiencies, root damage such as Al-toxicity, nematodes, phylloxera, untimely root pruning, etc.), which change these hormone ratios, thus determining the reactions of the aerial parts of the vine. This is ascribed to the fact that roots and root systems play a cardinal role in the hormone physiology of the vine.

Although the root tips of *Vitis* do not serve as production centres of auxin, the full-grown root tissue plays an important role. According to Bouard and Pouget (1971), only traces of auxin are produced in the growth tips and cambium meristems of vine roots. Auxin is produced more in the aerial than in the subterranean parts of the vine and is translocated to the roots where it regulates important functions. At low concentration, auxin promotes cell, shoot and root elongation, but at high concentration it induces the formation of ethylene, which suppresses root growth. Auxin promotes the synthesis of new cell wall material by activating certain enzymes (Taiz & Zeiger, 1998), thus controlling photo-, gravi- and thygmotropism.

Auxin regulates apical dominance by increasing the sink of the shoot growth tip for cytokinins (growth stimulant), while it stimulates the build-up of ABA (growth suppressor) in the lateral buds of the shoot. Auxin promotes the formation of adventitious and lateral roots by stimulating active cell division

at various spots in the pericycle just above the hair root zone to eventually form root primordia. This function is commercially used in grafting to aid cuttings in forming roots. Approximately 15 days before budding, a notable increase of auxin occurs in the buds, more so with cultivars which bud easily than with those budding with difficulty (Bouard & Pouget, 1971). Auxin retards the abscission of leaves and fruit by suppressing the function of ethylene and it induces the differentiation of vascular tissues in young organs, in callus tissue as well as below the shoot growth tip (Devlin, 1966; Torrey, 1967; Bidwell, 1974; Taiz & Zeiger, 1998).

More than 110 gibberellic acids (GAs) have been identified in plants, but most of them are inactive precursors or transition forms of only four or five active GAs. The roots are important organs in which the biosynthesis of GA takes place (Skene, 1967; Russell, 1977; Freeman, 1983). They are synthesised in their inactive forms and transported to different sites in the plant where they are then converted to the active forms to perform specific functions. For example GA 12 (inactive) are synthesised in small quantities in vine roots and translocated to specific sites, where they are transformed to GA 3 (active) to fulfil specific functions. GA stimulates internode lengthening, especially in shady canopies. It promotes berry set as well as rachis growth of seedless grapes, thus providing more space for berry growth (bigger berries) through cell division and enlargement (Taiz & Zeiger, 1998).

Torrey (1967) and Skene (1967) found GA activity in the xylem sap of *Vitis* and declared that it plays an important role in the lengthening of root cells. This GA is produced within the first 4 mm zone of root tips, while very little or nothing is found in the immediate proximal tissue. Some of this GA is immediately translocated via the xylem sap to the aerial parts, where it is transformed to the active form to affect cell division and elongation (Torrey, 1967). The biosynthesis of GA is suppressed by water logging (Russell, 1977).

The root is a very important centre for the biosynthesis of cytokinins (Bouard & Pouget, 1971; Russell, 1977; Jooste, 1983; Taiz & Zeiger, 1998). Field *et al.* (2009) found that the xylem sap at budding contained four main classes of cytokinins and that those originating from roots, were obtained from mobilised reserves. Zeatin is the most important cytokinin found in vines and there are mainly two forms: zeatin glycoside and zeatin riboside. In the glycoside form, zeatin is stored as part of reserves and in the riboside form it is translocated from the roots to the rest of the plant (Torrey, 1967). The

form in which cytokinins are synthesised, is dependent on root temperature (Skene & Kerridge, 1967). Stress factors like water shortage, excessive salt, heat and waterlogging, suppress the biosynthesis of cytokinins in root tips, while shortages in especially N and K result in a noticeable decrease in cytokinin levels. Cytokinin levels are highest in spring and decrease to zero in the fall and winter. This is in accordance with the results of Jooste (1983), who found that vine roots started producing cytokinins at soil temperature of 10°C, but that the transport thereof in the xylem is limited at that stage. He also found large differences in the ability of different cultivars to produce cytokinins in their roots. Rupestris du Lot produced significantly more cytokinins than 420-A Mgt, while ungrafted Chenin blanc synthesised significantly more than ungrafted Sultanina. Jooste (1983) related this directly to the occurrence of the growth arrestment phenomenon of vines with low levels of cytokinin.

Cytokinin stimulates cell division and is primarily responsible for the growth of the vine. It plays an important role in the reaction of the plant to NO_3^- nutrition, especially concerning leaf growth (Rahayu *et al.*, 2005). It is very important for cell division during the induction of flower cluster primordia in the green buds and also for the development of male and female flower parts. It is also responsible for the differentiation of chloroplasts which, in turn, are essential for photosynthesis. It plays a role in leaf ageing and abscission in that it counteracts and thus delays the effect of ethylene. It plays a role in the breaking of dormancy and, together with auxin, in apical dominance. Cytokinin is also responsible for the formation and budding of lateral buds and the subsequent growth of lateral shoots. It has a great effect on the synthesis of protein and the type of protein formed (Devlin, 1966; Torrey, 1967; Bidwell, 1974; Taiz & Zeiger, 1998).

Abscisic acid (ABA) is a 15-C terpenoid compound and its biosynthesis takes place in all cells containing chloroplasts and/or amyloplasts. It is synthesised in the calyptra (Russell, 1977), but the chloroplasts in leaves are also important production sites (Taiz & Zeiger, 1988). It is translocated in both the xylem and phloem and it regulates stomata closure in reaction to water stress. There are two sources:

1. An early warning from root ABA which is quickly transported via alkaline (Ca-rich) xylem sap to alkalise the cytosol of the guard cells. It depolarises the plasma membrane of the guard cells, causing wilting which, in turn, causes the guard cells to close.

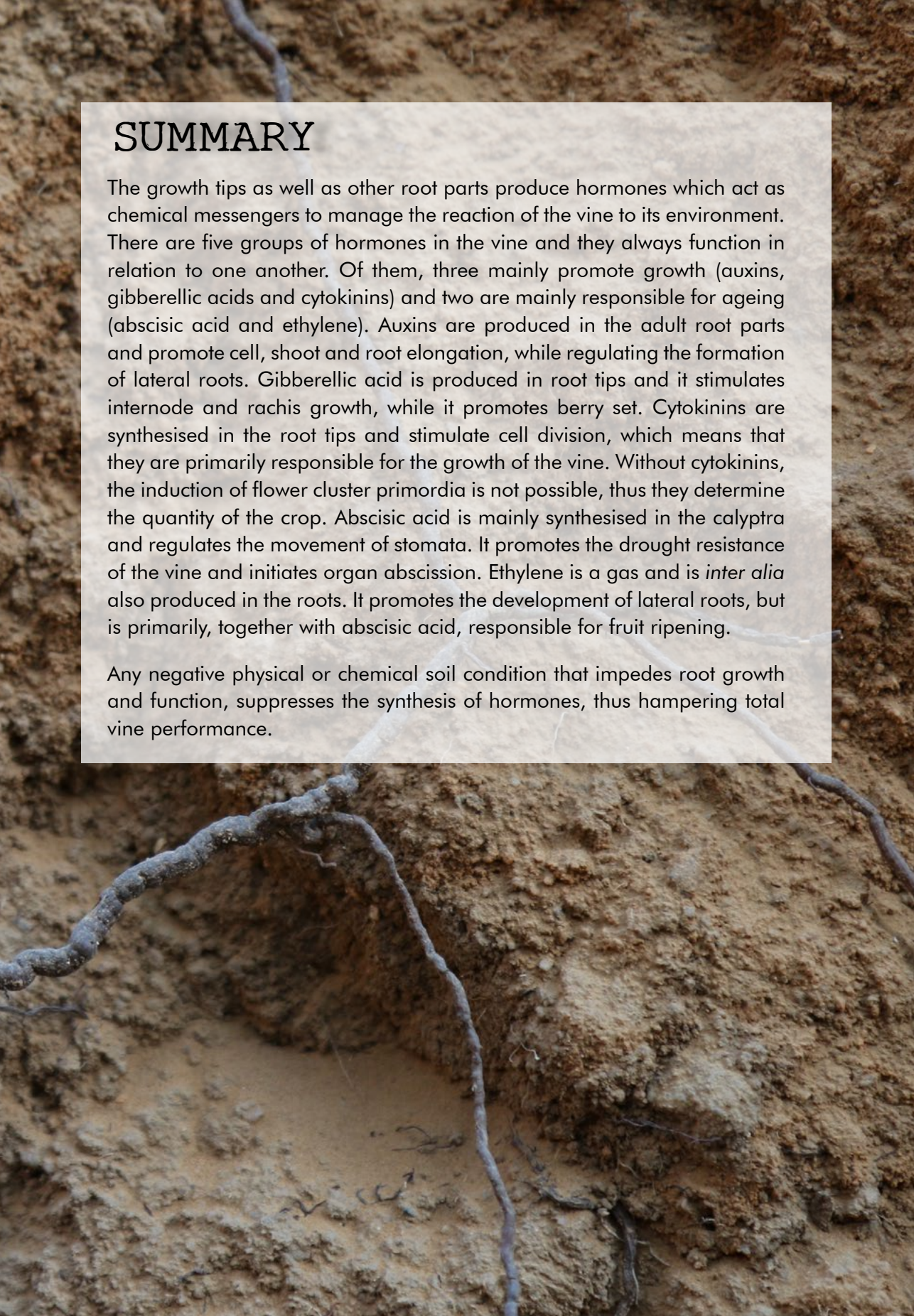
2. ABA is translocated from the chloroplasts in the mesophyll cells of the leaf to the guard cells of the stomata and it has the same effect as in 1.

1+2 are hydro-active closures (enough water in the plant).

In specific relation to GA and cytokinin, ABA is responsible for bud dormancy. It also promotes root growth and limits shoot growth under dry conditions, thus providing a mechanism to the vine to combat water stress. ABA initiates leaf and fruit abscission and aids ethylene to promote final leaf and fruit drop. Under stress conditions, it stimulates the formation of cell wall protein to protect the cell wall membranes against desiccation, thus promoting the vine's resistance against drought (Devlin, 1966; Torrey, 1967; Bidwell, 1974; Taiz & Zeiger, 1998). The biosynthesis of ABA is promoted by drought, waterlogging, nutrient shortages and salinity (Russell, 1977).

Ethylene is a gas and is synthesised in all plant parts, including roots, as a by-product of plant metabolic processes. It inhibits root elongation, but promotes lateral root development and is, together with ABA, responsible for fruit ripening. It stimulates the enzyme responsible for the breakdown of the cell walls, thus promoting fruit softening. Ethylene plays an important role in all abscission and ageing processes and it promotes the formation of root hairs. Any form of wounding (pruning, root pruning, pest and disease damage, browser animal damage) stimulates the biosynthesis of ethylene, similar to stress factors such as water-logging, frost, heat, drought (Devlin, 1966; Torrey, 1967; Bidwell, 1974; Taiz & Zeiger, 1998).

Vine roots are the main source of citric acid, from where it is transported to the aerial parts to be oxidised to malic acid via the Krebs cycle (Ribébereau-Gayon & Ribébereau-Gayon, 1971). Hunter *et al.* (1995) also found that citric acid is by far the most important organic acid occurring in vine roots and that it is independent of root diameter classes.



SUMMARY

The growth tips as well as other root parts produce hormones which act as chemical messengers to manage the reaction of the vine to its environment. There are five groups of hormones in the vine and they always function in relation to one another. Of them, three mainly promote growth (auxins, gibberellic acids and cytokinins) and two are mainly responsible for ageing (abscisic acid and ethylene). Auxins are produced in the adult root parts and promote cell, shoot and root elongation, while regulating the formation of lateral roots. Gibberellic acid is produced in root tips and it stimulates internode and rachis growth, while it promotes berry set. Cytokinins are synthesised in the root tips and stimulate cell division, which means that they are primarily responsible for the growth of the vine. Without cytokinins, the induction of flower cluster primordia is not possible, thus they determine the quantity of the crop. Abscisic acid is mainly synthesised in the calyptra and regulates the movement of stomata. It promotes the drought resistance of the vine and initiates organ abscission. Ethylene is a gas and is *inter alia* also produced in the roots. It promotes the development of lateral roots, but is primarily, together with abscisic acid, responsible for fruit ripening.

Any negative physical or chemical soil condition that impedes root growth and function, suppresses the synthesis of hormones, thus hampering total vine performance.

2.5 The role of mycorrhiza

Root excretions in the mucus gel, as well as in the surrounding soil, provide nutrition to a whole range of organisms living in close proximity to the roots. These excretions contain carbohydrates, amino acids, organic acids, enzymes and a whole range of other compounds, such as biotin, tiamin, niacin, inositol, etc. (Russell, 1977). It also contains other unidentified compounds which can stimulate or suppress the growth of fungi, bacteria and nematodes (Hooker *et al.*, 1994). The organic material annually derived from dead root material is regarded as an ideal humus for various rhizosphere organisms.

Of these rhizosphere organisms, mycorrhizae form an important part, and there are two types, *viz.* ectotrophic (external) and endotrophic (internal) mycorrhizae. The latter is also named vesicular-arbuscular mycorrhizal fungi. Literally mycorrhiza means root fungus and, according to Schreiner (2005), there are at least 37 different species, having a wide range of affinities for different host plants. Barnard already reported in 1932 that endotrophic mycorrhiza is commonly associated with Sultanina roots and that it is possibly related to the occurrence of bleeding sap.

These fungi live in symbiosis with the vine root (Schubert, 1985; Trouvelot *et al.*, 2015) where, in exchange for carbohydrates, they absorb water and nutrients from the soil and supply them to the vine (Schreiner, 2005). Ectotrophic mycorrhizae increase the efficiency of nutrient uptake from the soil and endotrophic mycorrhizae play a cardinal role in the exchange of these nutrients into the cortex cells of roots (Possingham & Groot-Obbink, 1971; Schreiner, 2005; Trouvelot *et al.*, 2015). In the cortex cells of roots, both vesicular and arbuscular structures are formed, giving rise to the name vesicular-arbuscular mycorrhiza (VAM) (Fig. 2.5.1).

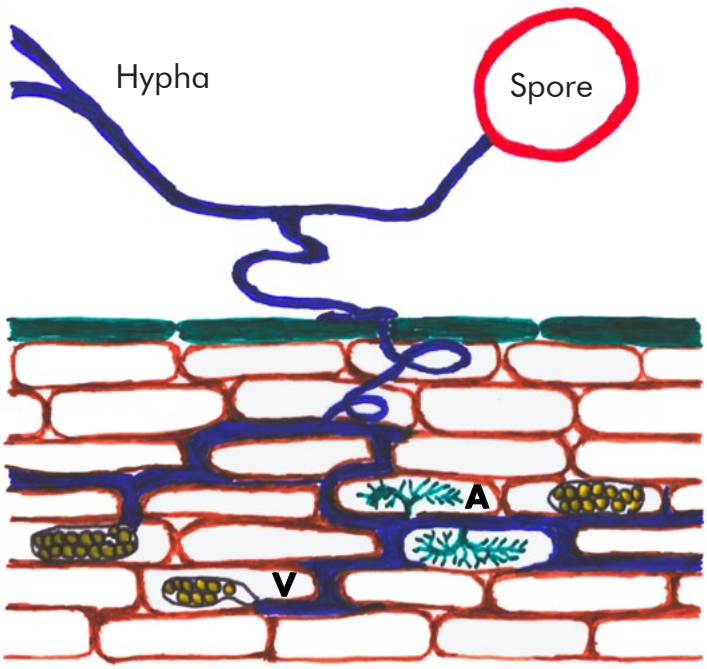


Fig. 2.5.1 Schematic presentation of vesicular and arbuscular mycorrhiza in the cortex cells of vine roots; V: Vesicular structures. A: Arbuscular structures. (Redrawn from Schubert, 1985)

Although ectotrophic mycorrhizae facilitate the uptake of various macro and micro elements, it is especially with the absorption of phosphate where they benefit the vine. Phosphate diffuses very slowly in the soil and frequently becomes out of reach of the roots because it is replenished slowly in the soil solution. The relatively long hyphae of mycorrhizae (frequently 20 mm long) can penetrate small pores between soil particles where root hairs cannot, thus easily absorb P ions and release it into the root (Russell, 1977; Trouvelot *et al.*, 2015). The finest vine root has a diameter of 500 to 1000 times greater than that of a mycorrhiza hypha (Schreiner, 2005).

With vines, high soil fertility levels, especially P and N or P fertilisation, decrease the colonisation of roots by vesicular-arbuscular mycorrhizae (VAM). Urea also suppresses VAM root colonisation and sporulation. VAM colonisation, and thus P uptake, can decrease in soils with pH(water) of 5.0 - 5.5 (Schreiner, 2005). The physical, chemical and biological composition of soil to be planted can be critical regarding the efficiency

of mycorrhiza inoculation. Mycorrhizae are absent from roots in very dry, saline or flooded soils or where soil fertility is either extremely high or low (Taiz & Zeiger, 1998). For their needs, VAM can receive 4 - 20% of the plant's photosynthetically bounded C, so that an initial negative reaction to VAM inoculation is possible until a plateau of mycorrhizal development is reached, resulting in an increase in plant growth. Plants can reach optimal growth after colonisation by indigenous fungal populations, so that artificial inoculation holds no advantage. A preliminary study of this indigenous inoculum is thus essential to determine if VAM inoculation is appropriate. There is evidence that VAM improves water uptake by roots as well as Fe absorption in calcareous soils in the case of lime sensitive rootstocks. It increases the resistance to salinity and heavy metals such as Cu, as well as to pests and diseases. Soil fumigation kills VAM, and in such cases post-fumigation inoculation with VAM can greatly improve the survival rate and growth of new plantings. Currently there are no quick and reliable methods to identify and monitor VAM in ecosystems, and its involvement in regulating hormonal functions in the vine must still be investigated.

Little is known about the rate of mycorrhizae colonisation during the first days and weeks of the life of roots, but typically a part of such symbioses frequently dies within three to four weeks (Anderson *et al.*, 2003). It is presumed that the part of the fine root system that dies quickly mostly includes those that are less vigorous and that the vigorous roots are quickly colonised by mycorrhizae. The internal structures of mycorrhizal fungi, as well as cortex cells, frequently die as browning increases (Richards & Considine, 1981; Comas *et al.*, 2000).

The surface of roots are covered with mycorrhiza hyphae that can spread up to 20 mm in the surrounding soil and especially improve P absorption (Gebbing *et al.*, 1977; Bonfante-Fasolo, 1978; Taiz & Zeiger, 1998; Trouvelot *et al.*, 2015). According to these researchers, mycorrhizae occur naturally widespread in soils and artificial inoculation in vineyard soils is frequently unnecessary. Surveys by Meyer and Woolridge (2008a & b) in nurseries and by Meyer and Woolridge (2009a & b) in commercial vineyards showed that naturally indigenous mycorrhiza fungi occur widespread in the winelands of South Africa. Meyer *et al.* (2004) found that inoculation with commercial VAM had very little effect on the number of spores in the soil because of very strong competition by natural mycorrhizae. This is in accordance with the results obtained by Schubert and Cravero (1985). They

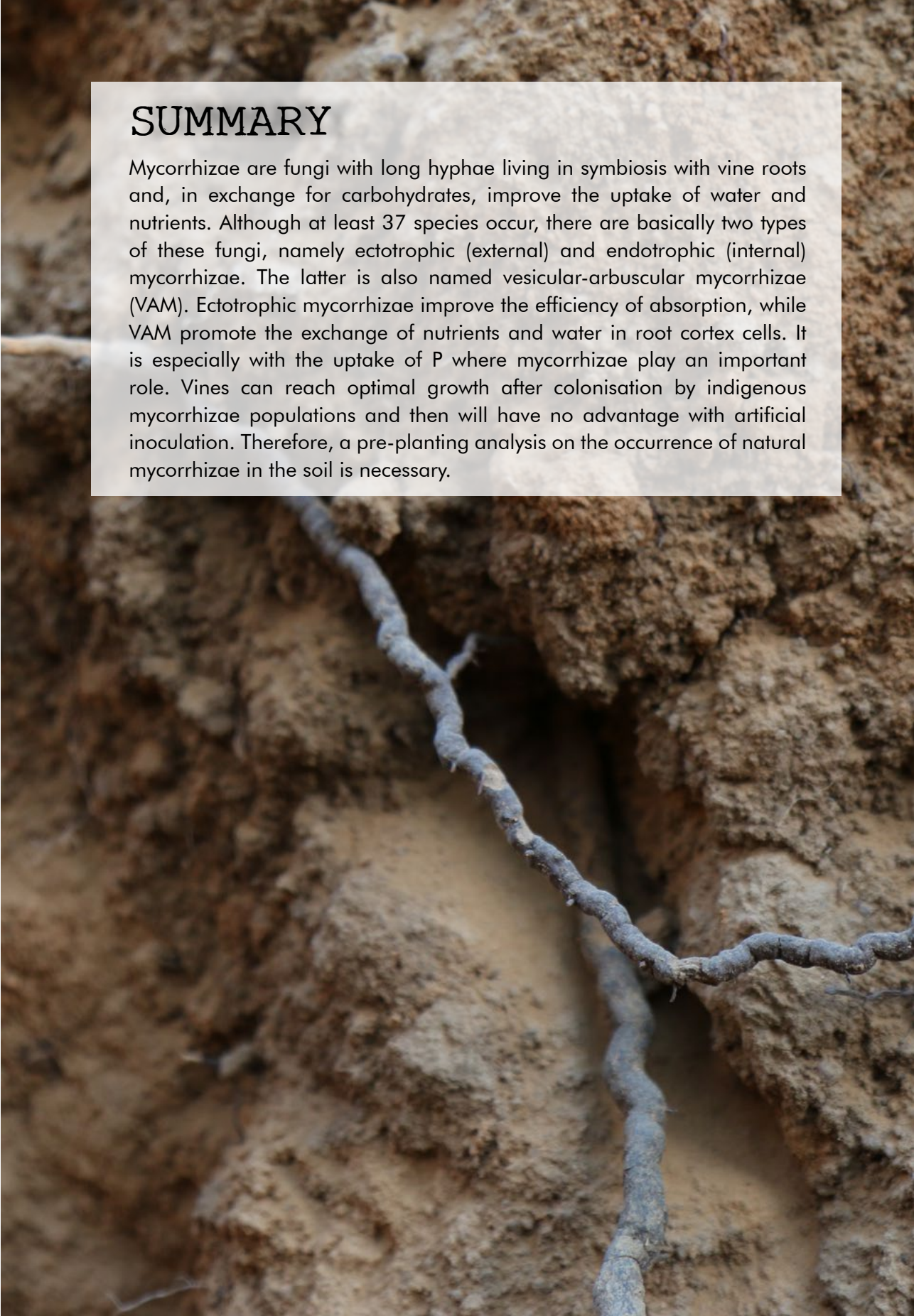
found no notable growth improvement of young vines with inoculation and ascribed this *inter alia* to the high P content of the soil before planting. Endotrophic mycorrhizae increased P absorption by vine roots drastically, but had no notable effect on the uptake of Ca, Mg, K and Na (Bartschi & Garrec, 1980).

Sap flow in spring starts before the formation of new roots (Barnard, 1932), but the mechanism by which such quick water absorption can take place was not understood at that stage. It is possible that mycorrhizae can be strongly involved in this phenomenon.

With one-year-old Sauvignon blanc/99 Richter vines in sand culture, Van Rooyen *et al*. (2004) found no effect of VAM on growth or on N and P nutrition, but a significant increase in nett photosynthetic gas exchange, stomata conductance, leaf water potential and transpiration rate, indicating improved plant water status and a potential decrease in transplant shock. This effect must still be further investigated under field conditions.

Ambrosini *et al*. (2015) found that two of six inoculated VAM species increased the root mass of 1103 Paulsen plants in 300 ml plastic tubes with Cu contaminated soil (46.2 ppm, HCL extraction), but that it had no effect on plant height, chlorophyll content or cane mass. The Cu content of the roots was increased but not in the aerial parts, and the P content of the roots was positively correlated with root mass. The percentage mycorrhizae colonisation was species bound, and the success thereof evidently determined the increase in dry mass of shoots. In this and other similar studies this was negative.

Working with five rootstocks, two scion cultivars and three VAM cultures in pots in a P poor medium, Linderman & Davis (2001) found a dramatic improvement in shoot growth. Except for SO4, root growth was also improved. They are of the opinion that vines planted in VAM poor soil caused by fumigation or terracing (exposing poor soil), will be highly reactive to VAM inoculation.



SUMMARY

Mycorrhizae are fungi with long hyphae living in symbiosis with vine roots and, in exchange for carbohydrates, improve the uptake of water and nutrients. Although at least 37 species occur, there are basically two types of these fungi, namely ectotrophic (external) and endotrophic (internal) mycorrhizae. The latter is also named vesicular-arbuscular mycorrhizae (VAM). Ectotrophic mycorrhizae improve the efficiency of absorption, while VAM promote the exchange of nutrients and water in root cortex cells. It is especially with the uptake of P where mycorrhizae play an important role. Vines can reach optimal growth after colonisation by indigenous mycorrhizae populations and then will have no advantage with artificial inoculation. Therefore, a pre-planting analysis on the occurrence of natural mycorrhizae in the soil is necessary.

2.6 Relation with wine character

The distribution of vine roots plays an essential role in the character of the grapes and wine obtained from a vineyard. Observations over a 10 year period in Bordeaux vineyards show that the distribution of roots is mainly dictated by chemical and especially physical soil properties (Seguin, 1972). Seguin (1970) found in the 'grand crus' vineyards of Bordeaux that the vertical layers of roots related to chemical and physical soil properties (especially permeability) and dictated the water supply to the vine. This determined to a large extent the cracking of berries and infection by Botrytis and had a decisive effect on the chemical composition, as well as on the organoleptic characteristics of the must. In the Loire valley, Morlat and Jacquet (1993) found general good correlations between number of roots and vigour. Yield and total quality were dependent on a healthy root system and this forces the producer to use the best applicable agronomic and viticultural practices to ensure the best possible developed root system.

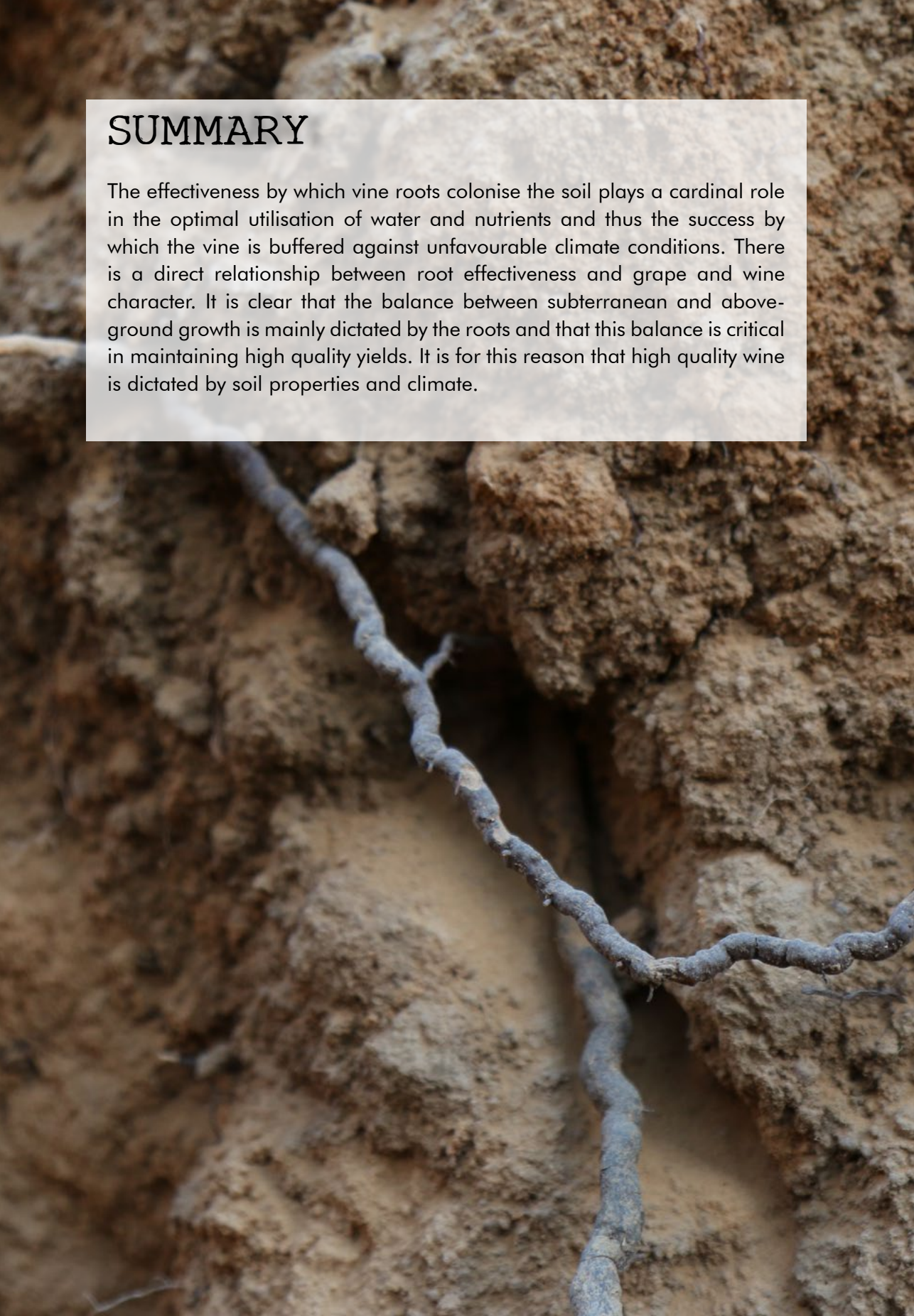
Roots adapt to specific soil properties to obtain a vine/soil balance which in turn affects grape and wine quality (Tomasi *et al.*, 2015). Similarly, Pellegrino *et al.* (2004) and Van Leeuwen *et al.* (2009) found that most variations between soil units related to differences in the water regime, which could be explained by factors such as soil depth, texture and water supply, affecting soil water capacity. In this regard, the capacity of the vine to extract soil water, as affected by root density and distribution, played an important role. This is in accordance with the findings of Archer and Hunter (2005/6) under South African conditions. Good, consistent wine quality was obtained on soils with sufficient water content through the growth season or where insufficient rainfall was compensated for by well-developed root systems which could utilise all available soil water. Soils with limited root density and distribution caused an imbalance between vegetative and reproductive growth, which led to poor grape and wine quality in dry years. Archer and Hunter (2005/6) expressed the quality of the root system as the ratio between the number of roots < 0.5 mm diameter/m^2 to the number of thicker roots/m^2. Average ratios of 5.25 for high quality and 2.0 for low quality vineyards were found. Vineyards with well distributed root systems with abundant < 0.5 mm diameter roots reacted well on limited rain and

could maintain good grape quality. The distribution and quality of the root system was positively correlated with the presence of lateral shoots and thus active leaves (Archer & Hunter, 2005/6).

These results confirm that models used to evaluate grape and wine reactions to climate and soil, must also include an analysis of the root system. According to Hunter (1998a), it is still unclear how differences in the size of the root system affect grape composition and wine quality.

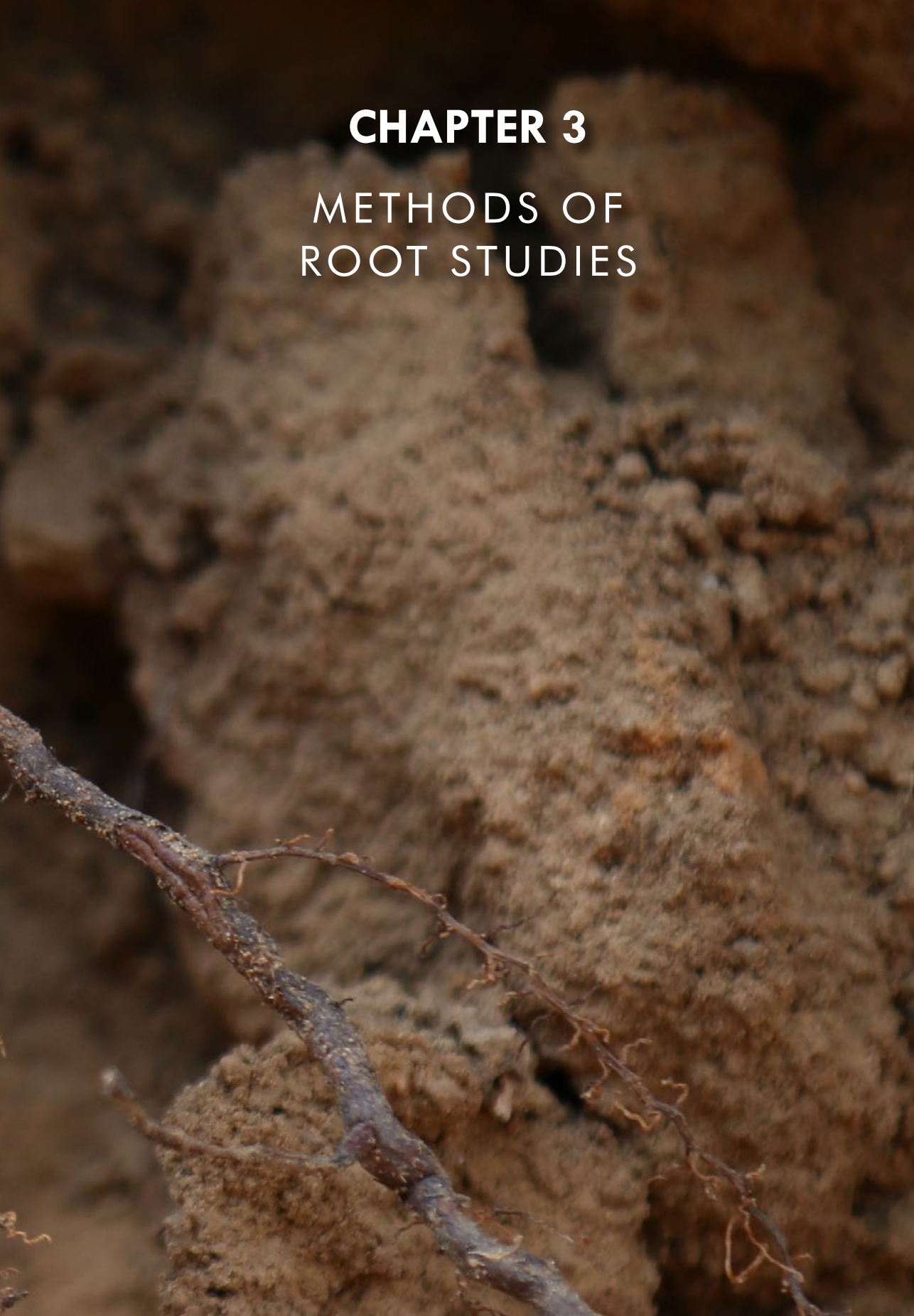
Champagnol (1984) stated that a large harvest can be obtained if the vigour provided a big enough canopy. On the other hand, ripening of a quality crop can only be obtained if root physiology is stressed to curb vigour, but still allows less but regular water supply. This can only be reached in less fertile soils with deep root systems. Morlat (1989) found that the vine root system is notably affected by soil properties and that it is benefited by a favourable succession of physical/chemical properties with few limitations. Vine vigour relates to the size of the root system, as was also found by Hidalgo and Candela (1969), but on its own there is no direct relation to wine typicity. Other factors, in relation to the root system, also play a role (Morlat, 1989).

Morlat *et al.* (2010) found that the calcareous clay-loam soils of the Loire valley have little limitation on root development and resulting utilisation of the soil volume, compared to stony sand soil on sandstone where roots are shallow and poorly distributed. These differences reflect in aerial vine parts and during dry periods this leads to disrupted physiology on sand soil. In such situations the wine from the clay-loam soil shows superior quality in spite of increased vigour and yield and less sunlight in the bunch zone.



SUMMARY

The effectiveness by which vine roots colonise the soil plays a cardinal role in the optimal utilisation of water and nutrients and thus the success by which the vine is buffered against unfavourable climate conditions. There is a direct relationship between root effectiveness and grape and wine character. It is clear that the balance between subterranean and above-ground growth is mainly dictated by the roots and that this balance is critical in maintaining high quality yields. It is for this reason that high quality wine is dictated by soil properties and climate.



CHAPTER 3

METHODS OF ROOT STUDIES

CHAPTER 3

METHODS OF ROOT STUDIES

3.1 Background

Under field conditions, root studies are still the stepchild of science (Böhm, 1979). Known methods are time consuming and laborious and accuracy of results is not always good, which discourages many researchers from doing such studies. The aim of root ecology is investigations into the effect of environmental factors on root development and can be described as root geography or rhizography. The most important ecological factors are bulk density, soil strength, water regime, soil air and nutrients. The other aspect of root research is root physiology, where for example problems with cell division in root apexes or the transport mechanisms of ions in young roots are investigated.

Systemic root studies started in the 18th century, after which no important research was documented (Böhm, 1979). Due to increased use of mineral fertilisers during the second half of the 19th century, increasing numbers of agronomy scientists became interested in root studies by means of excavating and washing roots out of profile walls. It was the American plant ecologist, JE Weaver, who, in the 20th century, developed the simple garden tool excavation method to a recognised scientific technique. This became the predominant method of root studies over the world until the middle 20th century. At the same time started the use of containers for root studies and observation of roots behind glass panels, with two small root laboratories that were built in Germany at the start of the 20th century. Also at the end of the 19th century, further progress was made in America by covering large monoliths with wire frames, through which wire staves were pushed, followed by washing the soil out so that the roots could be observed in nearly the same natural position. This method was improved on with the classical needle board method, which was also used on a large scale in Russia by leading root scientists there (Böhm, 1979).

Le Roux (1941) also referred to the trail blazing work of Weaver, who was of the opinion that the functioning of above-ground plant parts were mainly determined by the activity of the root system and that knowledge of this is of utmost importance. Le Roux (1941) also referred to another prominent researcher of East Malling, WS Rogers, who also emphasised the complete understanding of the nature of the plant root and the effect of external factors thereon, but that knowledge thereof was still inadequate due to the difficult degree of investigations on large root systems. In contrast to this, J.O. Veach and N.L. Partridge in 1932 claimed that from a tree growth and production point of view, the lateral and depth distribution of roots is relatively unimportant, on condition that there are sufficient stocks of water and minerals available (Le Roux, 1941).

Root studies are difficult because roots are not easily visible in the soil. They can easily be damaged and are difficult to measure due to the large quantities and variation thereof (Richards, 1983). Nevertheless, root studies are essential because roots cater for the above-ground water and nutritional needs of the plant and synthesise hormones needed for the development of the shoot system.

3.2 Methods

Böhm (1979) classified the different approaches to root studies as follows:

3.2.1 Excavation (also known as 'skeleton' methods): This is the oldest method and entails the digging of a trench at the outer perimeter of the root system and deeper than the root system, followed by the careful removal of soil to expose the whole root system (dry excavation), coupled with drawing or photographing the root positions. This requires a large amount of physical work, is very time consuming and more suitable for woody roots of trees and shrubs than for grass or annual plants. A modification is the washing out of soil with water (wet excavation) or removal of soil with air pressure (Van Breda, 1937) or a vacuum. With the sector method modification, only a part of the root system is excavated. Usually a 1 - 3 meter trench is dug about 50 cm from the trunk, as deep as the root system dictates, and the soil excavated up to the trunk to expose the heart of the root system. Horizontal excavations are usually used for tree roots studies. Soil is excavated from the trunk

outward and blown or sucked out, until the main roots are exposed. A string or wire grid is placed over it to improve the drawing of the roots.

3.2.2 Monolith: Blocks of soil are removed with a spade or mechanical tools and the soil washed out. The square monolith method entails the digging of a trench of about 1 meter down to maximum root depth and the removal of monoliths (usually 1 000 cm^3) layer by layer out of the profile wall. This method does not determine the roots outside the excavation volume and also include roots from neighbouring plants.

3.2.3 Box: A square monolith is isolated around the plant with wood panels, tilted to one side and taken to a wash place where one side panel is removed, the monolith soaked in water, then angled at 10° and the soil carefully washed out. This method is more labour intensive and time consuming than the dry excavation method and therefore not much used. However, no other method retains the fine roots and even root hairs so well.

3.2.4 Cage: For three dimensional images, a monolith with a plant in the centre is made by digging trenches around the plant down to maximum root depth. A wire netting is then fitted around it and sharpened wires pushed through the net and monolith in parallel rows. The upper soil layer is removed and replaced with plaster of Paris to keep the plant upright. The soil is then washed out from above in situ. The cross wires hold the roots in position, which can then be photographed. This method is very time and labour consuming and a complete root system is seldom obtained. Fine roots do not stay in position and cling together when wet.

3.2.5 Needle board: This is probably the most general root study method that combines image presentation and quantitative measurements. A soil monolith with a representative sample of the root system is taken with the aid of a special wooden board with needles (usually in a 5 cm square pattern, 5 - 20 cm long), which retains the roots in their natural position. The needle side of the board can be painted black for better contrast for photographs or a black plastic sheet can be pushed over the needles beforehand, which is handy to eventually lift the roots out in their original positions. The needle board is pushed into the profile wall or nails driven in through holes made beforehand in the board. The soil around the

sides and bottom of the board is excavated, the sides and bottom covered with planks, the monolith removed, placed in a water bath and the soil washed out. The method is labour intensive and does not work for stony or sandy soils. Several variations of this method were used by different researchers and for different plants, but apparently not for grapes.

3.2.6 Soil auger: This is the most suitable for taking volumetric soil-roots samples and can be done with hand augers, usually with 7 mm inner diameter, in 10 cm increments, down to a depth of 1 m, with at least 5 sample positions per plant or treatment. The roots are washed out. For deeper samples, mechanical core augers can be used, where the core is sectioned and the roots washed out. The washing out of roots takes time and can be eliminated by breaking the core in about 10 cm segments and counting the roots on both exposed ends. This can be seen as a modified profile wall method, but seems to be best suited for fibrous roots like that of grass species.

3.2.7 Profile wall: This is probably one of the best ecological root study methods. Le Roux already used and reported on it for grapes in 1941 in South Africa. It was first done by Weaver in the USA (1919 - 1926), who removed a soil layer of about 10 cm from a smooth profile wall with a scraper and then made drawings of the exposed roots. Soil can also be removed with compressed air or water spray. Information obtained is primary qualitative. Quantitative data can be obtained by removing only a soil layer of about 1 cm and then counting the roots. Real acceptance of this so-called trench method came in response to intensive root studies conducted in 1932 by J. Oskamp and L.P. Batjer (Böhm, 1979) in orchards in the USA. Here, the positions of roots were mapped with the aid of wire grids placed on the profile walls, and diameter sizes indicated by corresponding dots or circles. For this, graph paper and appropriate scales were usually used. A modification on this is the foil method, by which a transparent plastic plate with a marked grid pattern is positioned on the profile wall, with a transparent plastic foil thereon and the positions and sizes of the roots then drawn directly on the foil.

3.2.8 Glass wall: According to Böhm (1979), root studies with this technique in undisturbed soil were first reported by W.B. McDougall in 1916. A modern development is the construction of underground

glass wall laboratories or rhizotrons. In the case of undisturbed soil, contact between the glass walls and soil faces were obtained by filling the about 2 cm space between the two with dried and sieved soil, obtained from and in the same order as the soil horizons concerned. Roots can be charted, but a quicker method is to trace roots on transparent plastic foil placed on the glass face. The quickest method of measuring root growth is to count the intersections of roots with the grid pattern on the glass walls (most generally 5x5 cm square). Root length per cm^2 observation surface, is designated as root intensity. In cases of good contrast between white roots and dark soil, photos can be taken and used in image analysing computer programs. Information on root growth and death with time can be recorded with cinematography. As a less expensive alternative, another technique was developed by using transparent plastic tubes with a grid system on the wall, which is placed in the soil in holes made by soil augers. Initially, intersections were counted with the aid of a mirror and light source on a steel rod that were moved up and down the plastic tube, but currently digital cameras are used. This tube method (mini-rhizotron) causes little soil disturbance and sufficient tubes allow statistical analyses of results.

3.2.9 Indirect: These are observations of changes in soil water or nutrients in different soil layers between successive observations as indication of root distribution or activity in the soil profile. Another approach to measure root activity is the use of colour compounds (dyes) and non-radioactive and radioactive markers, of which the ^{32}P isotope is the most frequently used.

3.3 Prominent studies

Interest in studies on the interaction between root and shoot systems as part of a 'whole plant' physiology approach, has increased systematically. There are few quantitative studies on root growth of grapevines under field conditions due to large labour inputs and often inaccurate measurements because of a loss of fine roots (Mullins *et al.*, 1992). Branas and Vergnes (1957) divided methods then in use to study grapevine roots in two groups. The method of 'co-ordinates' (*coordonnées*) or the excavation method of Böhm (1979) entails the determination of the spatial trajectories of all roots in three dimensions. This demands the progressive loosening of all soil in

the volume utilised by roots. At the start of the twentieth century, Degrully and Ravaz (1905) already conducted their classical study on grapevine roots by excavating roots and recording their presence with depth every 10 cm away from the vine. This was very time consuming and prevented large numbers of examples from being done. Furthermore, the results could only be expressed as horizontal and vertical projections without numerical data, which complicated the making of comparisons. This was nevertheless the only method that gave an approximate idea of the conditions under which roots distribute. In the early forties, in South Africa, Le Roux (1941) also used the method of meticulously excavating grapevine roots and creating graphical images thereof. He also used the profile wall method. The 'sampling' (*sondages*) method of Branas and Vergnes (1957) entailed the recovery and weighing of roots encountered during the excavation of successive soil layers of a given thickness. The results were figures that made comparisons possible. However, this technique causes the destruction of the vine. Branas and Vergnes (1957) used a thickness of 25 cm for the first soil layer because of the absence of roots in the first 0 - 5 cm and the soil surface relief that made a too thin first layer impractical. Subsequently, 20 cm thick layers were sampled, up to a depth of 125 cm, as there were few roots deeper than that. Roots were removed by hand in autumn, cleaned of soil and the fresh mass determined. Lots of hair roots and root tips were lost and no method could be found to overcome this.

The root investigations of Doll (1953) started with a trench of 3 m length, 60 cm wide and 1.5 m deep that stretched from a neighbouring vine row up till the vine concerned. Roots were progressively exposed with small picks, measured and traced by artists (Fig. 3.3.1).

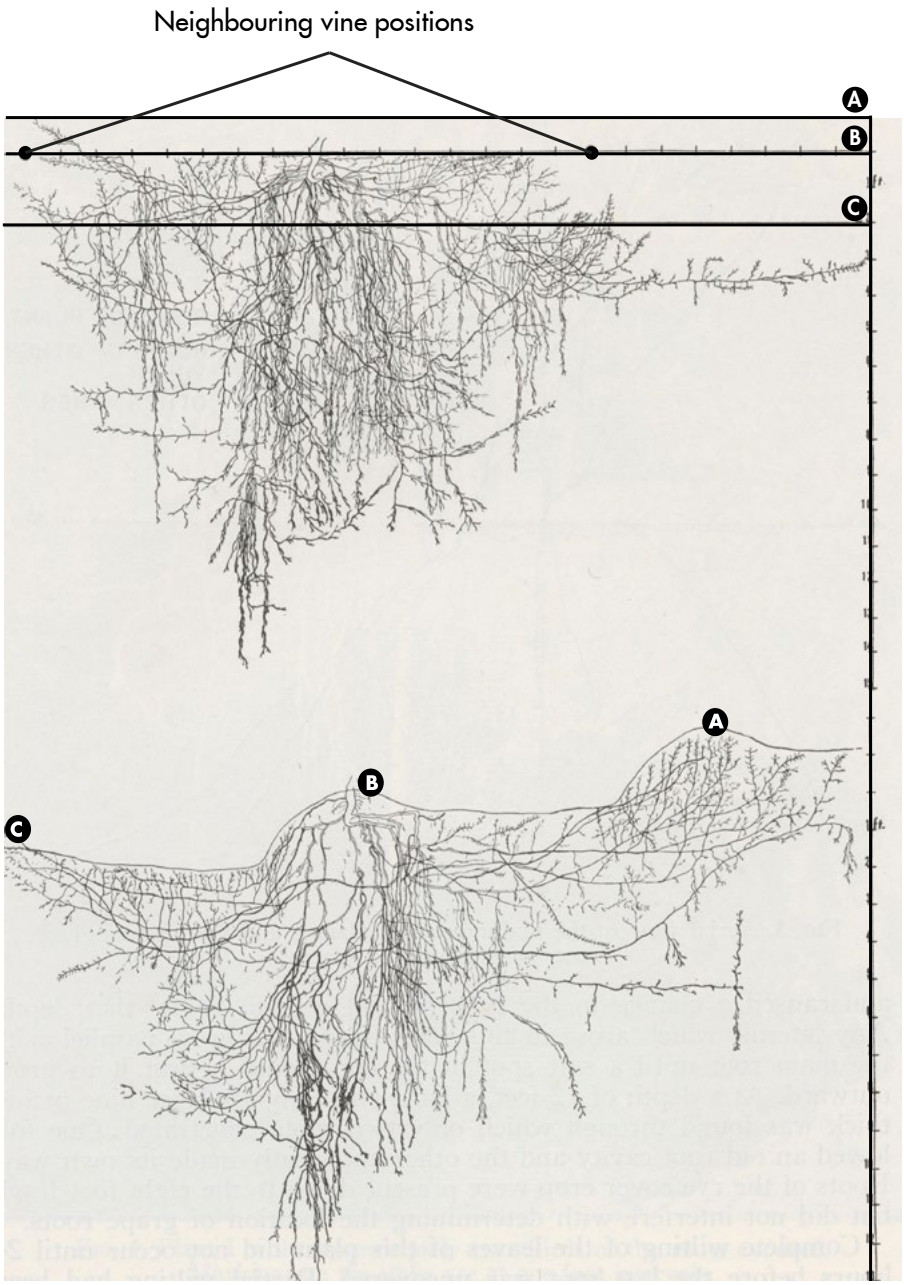


Fig. 3.3.1 Above: Frontal view of most of the exposed roots.
Below: Side view of root system.
A: The terrace above
B: The terrace on which the investigated vine was planted.
C: The terrace below the investigated vine
(Redrawn from Doll, 1954)

Schuurman and Goedewagen (1955) removed monoliths of soil and roots by means of a needle board with plastic sheet and then make a soil film with a cellulose solution of unknown composition on the exposed side of the monolith. The soil film was then removed, turned around and pasted on a board, after which the soil remaining on the needle board was washed out, the roots lifted with the plastic sheet, dried and pasted alongside the soil film, which then served as a good illustration of the effect of soil properties on root distribution.

In Spain, Hidalgo (1968) carefully excavated roots around vines up to the extremities thereof, which reached depths of 3.25 – 4.5 m, although few such cases existed naturally. Another example of this technique is the classical work on grapevine roots by Garcia de Lucan Gil de Bernabe and Gil Monreal (1982) in Jerez, Spain

In the Ivory Coast, Bonzon and Picard (1969) used three methods of root investigations on pineapples:

1. Cultural profile, where the effect of cultural methods could be observed by excavating the roots occupying a soil volume and recording, inter alia, intersections by means of horizontal segments. Not many repetitions are feasible, it is destructive and only qualitative.
2. Root profile, where a representative segment of soil with roots is taken out with a needle board with plastic sheet, the soil washed out, with or without drying, and chemical dispersion with 5% sodium chloride or sodium hexa-metaphosphate (Calgon), depending on clay content, the roots lifted out with the plastic sheet after drying and pasted on a white sheet of paper on which observations and measurements could then be made.
3. Auger samples, which are taken with special cylindrical augers and the roots in the cores washed out through a set of 16 and 14 mesh sieves. The dry mass of these roots can be determined, but is insufficient for characterising total length, mean diameter and mean specific mass. A second parameter, which only varies as a function of root length and diameter, is the diametric surface. The penetration of light through a glass plate on which the dried roots are spread out in a thin film of water, is measured with a photo-electrical planimeter, from which the diametrical surface can be calculated with a formula.

In Rumania, Kubeča (1968) investigated the root systems of 10 - year-old Italian Riesling in sandy soil with a 250 cm deep water table, for three different inter-row planting distances and three trellising systems. The roots of four vines were sieved out for all three planting distances for 20 - 40 cm, 40 - 60 cm and 60 - 80 cm depths, weighed, and lengths measured. Roots were classified as < 0.4 mm (weighed only), 0.4 - 1.0 mm, 1.0 - 2.0 mm, 2.0 - 3.0 mm and > 3 mm diameter.

Originally, for studies on the periodicity and scope of root growth, underground observation chambers were mostly used, such as that of Freeman and Smart (1976), McKenry (1984) and Van Zyl (1984). Freeman and Smart (1976) used an underground chamber of 3.6 m square and 2.0 m deep, with five water-tight 0.8 x 0.6 x 1.2 m compartments at two opposing sides, fitted with wire-grid integrated glass walls on the inside for observing root growth. Mature Shiraz vines were planted in the compartments, filled with sandy loam (85% sand) soil, and the pattern of root growth and reaction to irrigation studied over two seasons.

Van Zyl (1984b) conducted root studies in a Colombar vineyard for four soil water depletion regimes with the aid of root chambers, made of steel frames (2.5 x 1.5 m rectangle and 1 m deep), covered with wooden panels and trapdoor for access, with 30 x 30 cm grid glass side walls parallel to the vine rows, in which fine wire grids of 1.2 x 1.2 cm were integrated (Fig. 3.3.2).

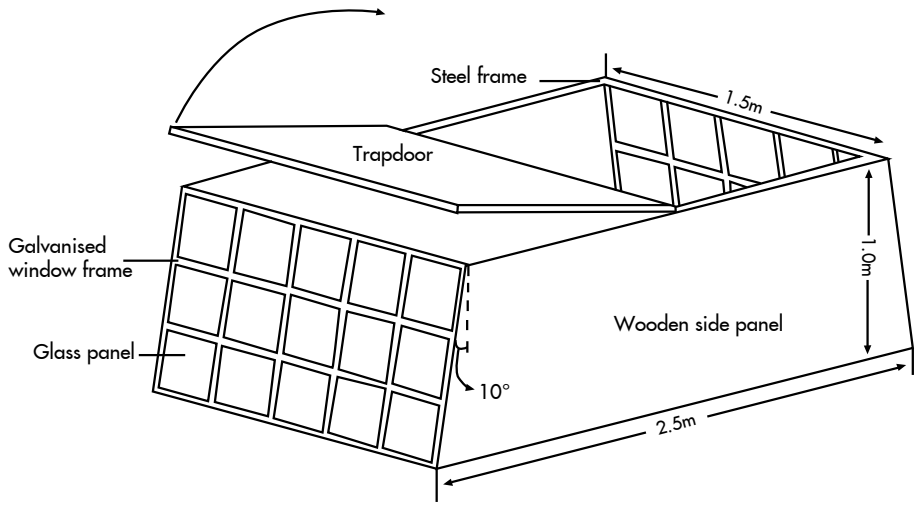


Fig. 3.3.2 Root observation chamber with glass panels for *in situ* root studies (Redrawn from Van Zyl, 1984b)

Chambers were installed between and 50 cm from two vine rows in slightly larger holes and sieved soil filled into the spaces around them according to the original horizon sequence. One year was allowed for stabilisation before commencement of root studies. Black plastic curtains were draped in front of the glass walls to eliminate light and the trapdoor only opened during weekly root studies, which were conducted over two seasons. The number of actively growing root tips against the glass walls was recorded as well as intersections of white roots with the wire grid. Root lengths were calculated using the formula of Böhm (1979): Root length (cm) = 0.786 x number of intersections x grid unit (cm).

In his studies on the effect of plastic cover strips on vine root distribution, Van der Westhuizen (1980) removed entire representative vines up to 0 - 40 cm and 40 - 80 cm depths, sieved out and weighed the roots. Van Zyl and Van Huyssteen (1980) studied vine root distribution under different trellising systems by charting the roots in the walls of profile pits dug perpendicular and parallel to the vine rows. Root thickness classes were < 0.5, 0.5 - 1.0, 1.0 - 5.0, 5.0 - 10.0 and > 10.0 mm diameter. Saayman and Van Huyssteen (1980) studied the distribution of vine roots by taking out 20 cm thick soil segments of 37.5 x 50 cm in a grid pattern around vines down to 120 cm depth and taking out the roots therein by crumbling them through a 6.5 mm sieve. Roots were divided into three classes, namely < 2 mm, 2 - 7 mm and > 7 mm diameter, dried and weighed. The distribution of roots under a vine was drawn three dimensionally on a mass/segment base with a computer program. Root studies were also done on profile walls that were dug perpendicular to vine rows for a distance of 150 cm to each side of a row. Roots were carefully exposed in the profile walls for a distance of about 5 cm, painted white and drawn on graph paper according to scale and the three thickness classes. Van Huyssteen and Weber (1980) also used profile pits with walls 0.4 m from vines to evaluate the effects of soil cultivation on vine performance. The positions and size of roots were drawn on graph paper, with size classes of < 0.5 mm, 0.5 - 1.0 mm, 1.0 - 5.0 mm and > 5 mm diameter. Van Zyl and Weber (1981) also used profile walls, 50 cm from the vine row, to record roots graphically.

Morlat and Venin (1981) used 1.5 x 0.7 m and 0.9 m deep profile pits, made 40 cm from the vine row, and counted the roots in the walls. For the tall fescue cover crop, roots were sampled in the profile wall with cylinders of known volume according to soil horizons. These roots were extracted with

successive washings and then sorted. Results were expressed as number of roots/m^2/horizon for vines and as gram roots/m^3 in the case of tall fescue. Deep plunging vine roots were counted for a determined surface of the profile pit bottom at 85 cm depth. Vine roots were classified into five classes:

1. Roots < 1 mm diameter, little suberised, with rapid replacement and very efficient in absorption of water and minerals;
2. Roots 1 - 2 mm diameter, more suberised, derived from permanent root system;
3. Roots 2 - 5 mm diameter, already much suberised and permanent;
4. Roots 5 - 10 mm diameter, with especially anchor and transport functions;
5. Roots > 10 mm diameter

An Asymmetric Index (AI) was developed for the vine root system from profile pits on opposite sides of vine rows (east and west). The AI was small for chemical weed control, but increased with the tall fescue cover crop, that indicated a less well distributed root system in the latter case. Under tall fescue, the AI was large in the upper horizon, but smaller for chemical control. This was also true for 10 - 25 cm and 25 - 50 cm deep horizons, but in the 50 - 85 cm deep soil layer, larger heterogeneity was found for chemical control. A negative correlation was observed between AI and number of roots.

To evaluate the effect of soil pH on vine performance, Conradie (1983) grew grafted Chenin blanc vines in 45 ℓ earthen pots in soil at different pHs. After four years, the vines were taken out and the soil around the roots washed out, the roots divided into medium (> 2 mm diameter) and fine roots (< 2 mm diameter), dried and weighed. For his studies on the seasonal nutrient uptake by Chenin blanc, sand culture was used in similar pots and vines destructively sampled during 14 periods (Conradie, 1980; Conradie, 1981).

Data obtained from glass houses and pot studies demand the use of young vines (McKenry, 1984). Unfortunately, it can be expected that, during the first three years, the phenology of vine roots would differ from that of established vines. McKenry (1984) used an old rootstock trial with Thompson Seedless and dug a trench from the vine row up to the middle of the between row space. Soil segments of 30 x 30 x 30 cm were taken out of the profile wall and placed in a box form 0.5 cm sieve that was placed in a larger pail and the soil washed out with a 2.8 - 4.2 kg/cm^2 water jet. Such a set of

samples was taken every 90 days. Large, dead roots were categorised as root skeletons, live roots as structural roots, which were further divided into > 2 mm diameter larger structural roots and < 2 mm also as structural roots but possessing larger degrees of branching. The category new roots represented the number of new root tips that were readily recognisable on strength of colour, periodicity and absence of cambium or lignification. This classification sufficed until mid-summer, when new growing roots started necrotising. To be counted as root tip, it must have exceeded 2 mm length, but did not need to be live at the tip. The base of the root tip that remains after breaking off, is not easily discernible from a site of root initiation, therefore the 2 mm length was arbitrarily brought in. Only root tips in the growing roots category had the classical colour and form that are associated with nutrient uptake and nematode attack. Roots were weighed after drying on blotting paper and the volume determined by water displacement in a measuring cylinder. Roots were coloured and de-coloured and the degree of decolouration measured colorimetrically, with the assumption that the larger the colour intensity of the decoloured roots, the bigger the absorption capacity thereof.

In the Bordeaux region, Soyer (1984) used the profile wall method of Morlat (1981) to study the effects of soil mulches, digging 0.9 m deep trenches 0.4 m from the vine row, sampling nine 10 cm thick soil layers and using three root thickness classes, *viz.* < 1 mm, 1 - 2 mm and anchor roots > 2 mm diameter.

Root studies on perennial plants are subject to various limitations, *viz.* large heterogeneity of root distribution, large volumes of soil involved, abundant asymmetry on both sides of the vine row, and large variation in root diameter (Morlat, 1989). In the Loire valley, he developed a non-destructive profile wall method, with levels of root counts parallel to the vine rows. Six measuring vines were selected according to the mean circumference of 100 scions and rootstocks, of which half the root system of a vine was studied by means of two trenches that were dug 20 cm from the vine and in the middle of the inter-row. The number of live roots was counted up to depths between 95 cm and 125 cm, depending on soil type. In addition, deep plunging roots were counted at a mean depth of 1 m on a horizontal plane of 15 cm wide on the bottom of the profile pit, at 20 cm from the vine and in the middle between rows. Three classes of roots were used: < 1 mm diameter (roots with absorbing hair roots, little

branching, with rapid replacement cycle and important functions of nutrition and synthesis of substances; 1 - 2 mm diameter (more suberised and part of the permanent root system); > 2 mm diameter (strongly suberised framework and permanent roots, with anchoring and transport functions) Root investigations were done before the start of the vegetative phase and results expressed as number of roots/m^2 and according to soil horizons. The same method was later used by Morlat and Jacquet (1993) with Cabernet franc/SO4 in the Loire valley.

In two investigations on root systems of Pinot noir x Richter 99 in deep-delved Glenrosa soil at different planting widths, Archer and Strauss (1985) used a root exposing technique for three-year-old vines where each root was suspended by thin sewing threads on the trellis wires or kept in place by thin wooden rods. This excavation was done to a depth of 60 cm and the roots of each planting width treatment photographed from above and from the side against a background of a 20 x 20 cm grid system. The angles of penetration at a depth of 60 cm were measured by means of thin wires and a protractor. Finally, the roots were traced life-like on paper from projections of the slide photographs. In the second study, nine years after planting, Archer (1992) used the profile wall method of Le Roux (1941) with 1.2 m deep trenches placed 50 cm from the vine row, to characterise the mature root systems o f each planting distance treatment according to different thickness classes. These classes were 0 - 0.5 mm, 0.51 - 2.0 mm, 2.1 - 5.0 mm, 5.1 - 10 mm and > 10 mm diameter.

Hunter (1998a) used the profile wall method and the root diameter classification of Richards (1982) in the same trial. Furthermore, trenches were dug on the borders of the surface allotted to a vine, up to a depth of 1.2 m. Soil was washed out around the roots and the roots supported in their original position by means of pegs, and photographs then taken. The whole vine was subsequently removed and the original root distribution recreated and photographed again at a fixed distance to obtain images of both horizontal and vertical root distribution.

Swanepoel and Southey (1989) used the profile wall method as described by Böhm (1979) and a grid of 20 x 20 cm, 1.2 m wide (inter-row vine spacing) and 1.2 m deep. They also used the root index (number of roots < 2 mm÷number of roots > 2 mm) as proposed by Van Zyl (1984).

McLean *et al.* (1992) were the first to use minirhizotron tubes in vineyards. The tubes were transparent poli-buturate with a 5 cm inner diameter, 3 mm side walls and 1.82 m long, and were placed in 45° from vertical holes made by a hydraulic soil auger (Fig. 3.3.3). Excellent rhizotron-soil contact was achieved with this and images of 2.16 cm^2 were obtained with a micro-video colour camera, taken each 1.2 cm from below. The number of roots were counted with a monitor and relayed to a computer program.

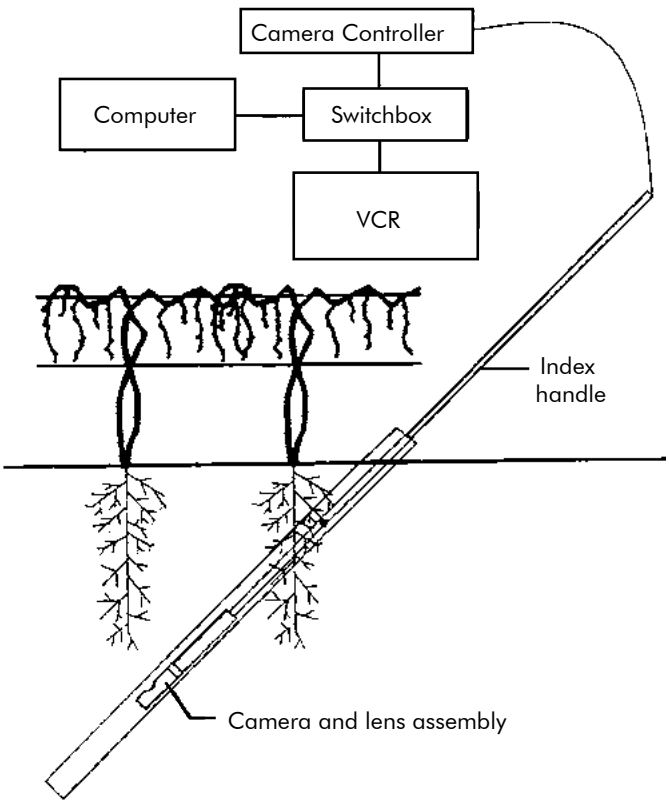


Fig. 3.3.3 Diagrammatic representation of the microvideo colour camera assembly, control system, indexing handle and minirhizotron tube at 45° below the vines (Redrawn from McLean *et al.*, 1992)

Buckland *et al.* (1993) proposed a method for calculating root length density, where root contact points are counted in specific grid surfaces in minirhizotron tubes and converted to root length density by means of a specially developed formula. This was in good agreement with auger core

samples obtained for wild cherry tree roots and better than intersection counts. This suggests that contact points are to be preferred to intersection counts for sparsely distributed root systems such as that of trees.

The investigations of Möhr (1996) in the Mosel valley are a contribution to knowledge of root growth in undisturbed vineyard soil in a temperate climate zone. Root samples were taken at 5 - 6 leaf stage, beginning of flowering, before bunch closure and at harvest. Soil monoliths (segments) of 10 x 20 cm and 20 cm thick were taken for four layers up to 100 cm deep and the roots therein washed out with the aid of a 1 mm sieve. The roots were classified as A: New roots with cortex; B: Live, brown-coloured roots with cortex, age uncertain; C: Live roots with periderm, < 2 mm diameter (fine roots); D: Live roots with periderm, 2 - 5 mm diameter (medium roots) and E: Live roots with periderm, > 5 mm diameter (thick roots). Class A roots had a wax-like, creamy-white appearance and together with Class B roots, described as 'absorbing roots'. In order to identify live roots in Class B, fresh roots were plasmolysed and coloured according to the method of Krauss and Deacon (1994). Root tips were counted and stored in a mixture of 60% ethanol and 10% acetic acid, pending further investigations. Live roots in Class C were identified by washing away the cortex on a sieve with a water jet until the periderm was visible. Roots with a light brown periderm were judged to be live. The lengths of Class E roots were measured automatically with a Comair root length scanner.

Comas *et al.* (2000) used reduction of triphenyltetrazolium chloride (colour reaction) by dehydrogenase enzymes, of which most are associated with mitochondria function, which is an established test for vitality. They found a good relationship between this and root respiration and a 77% reduction in metabolic activity of roots with browning.

Hunter and Volschenk (2001) used the profile wall technique as described by Böhm (1979) and as modified by Hunter and Le Roux (1992) for root studies on Chenin blanc/99 Richter vines at Robertson. Trenches, about 1.9 m deep, were dug 30 cm away from the vine row and parallel to it. Roots were sketched graphically down to a depth of 1.2 m and to halfway between vines in five thickness classes, *viz.* < 0.5 mm, 0.5 - 2 mm, 2 - 5 mm, 5 - 10 mm and > 10 mm diameter and categorised according to Richards (1983) as fine, extension, permanent and framework (> 5 mm diameter) roots.

Anderson *et al.* (2003) used clear, 183 cm long, butyrate tubes with 7.7 cm outer diameter, that were installed at 30° to the vertical with the aid of hardened steel tubes, an angle guide and sledge-hammer, about 50 cm from the trunk of Concord vines. Dry sieved soil was poured in around the tube sides for good contact. The tubes were etched with 127 numbered 1.0 x 1.5 cm windows on the upper side of the tube and images were obtained with a miniature video camera and processed as described by Comas *et al.* (2000). Dates on which roots were formed, became pigmented, turned black and disappear, were noted. Comas *et al.* (2005) also measured root production of Concord vines over four seasons with the aid of similarly installed 5.7 mm outer diameter minirhizotron tubes. Images were obtained every second week with a minivideo camera system. The starch content of lignified roots was determined by sampling roots of vines next to the minirhizotrons, of which the periderm was removed after drying and before grinding thereof.

Smart *et al.* (2006) studied root distribution with profile walls to typify rooting depth as determined by genotype, soil properties and environment. They used a theoretical model proposed by Gale and Grigal (1987) for trees, *viz.* $Y = (1-ß^d)$, where Y = fraction of roots from the soil surface to a depth of d cm. The median value for ß was 0.9826 (n = 240) and most profiles had values > 0.975. These values place the distribution of vine roots as of the deepest observed for plants world-wide.

Soar and Loveys (2007) used 41 mm diameter and 1 m long soil cores, mechanically drilled out at 30 cm distances from each other at 20 cm, 85 cm and 150 cm distance from the vine row (Fig. 3.3.4).

This then represented 50% of the soil volume of the vine down to a depth of 1 m. Soil cores were divided into 4 x 25 cm segments and washed through a set of four sieves of 6.4, 3.2, 1.6 and 1 mm mesh sizes. Roots on the two larger mesh sieves were gathered with tweezers and roots on the finer sieves washed over through a 2 ℓ funnel with a 5 cm, 0.5 μm sieve equipped outlet and finally onto a 200 μm filter, from which they were collected with tweezers. Washed roots were transferred to a 30% alcohol solution and stored. The roots-alcohol mixtures were poured out onto clear Perspex trays, scanned and the root images analysed with a Canadian software program (*WinRhyzo*) for length and volume. The most time consuming aspect of this

type of root investigation is the sorting, counting and measuring of the roots for a series of diameter classes. The *WinRhyzo* program makes this process rapid and dependable and includes the capacity to eliminate false values.

Bauerle *et al.* (2008) worked with transparent plastic minirhizotron tubes, angled at 30° from vertical and installed 50 cm from the trunk at both sides of strong vigour 1103 Paulsen and low vigour 101-14 Mgt vines. Continuous root images were recorded over the length of the tubes every second week during the growing season and monthly during the dormant period. Images of about 14 x 18 mm were analysed with *WinRhyzo Tron MF* software for population counts, survival and production of roots. Lehnart *et al.* (2008) used three 6 cm diameter, 130 cm long tubes per vine, installed at 90°, 60° and 45° to the soil surface and respectively 10 cm, 50 cm and 56 cm away from the vine. Roots were observed with a camera on a slide support frame every 1.35 cm down the tube, frontally and at 90° to the vine, in total 2 x 76 observations per tube each second week and for four years. Thy used the formula of Buckland *et al.* (1993) to calculate root length densities.

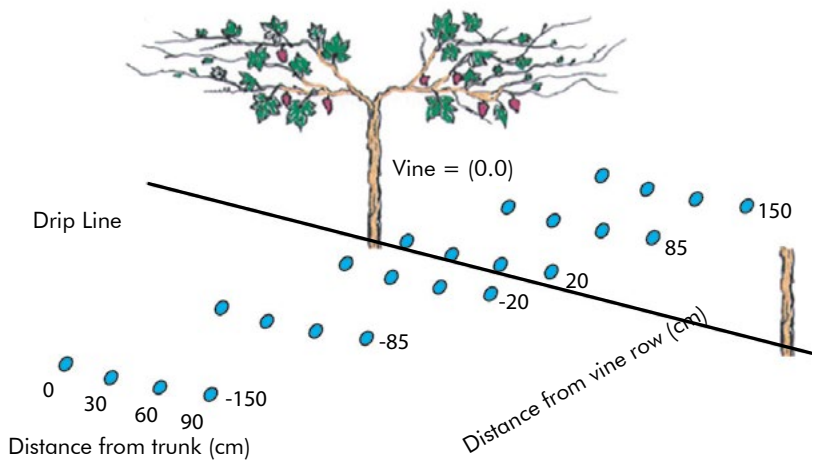


Fig. 3.3.4 Soil/root sampling pattern (Redrawn from Soar & Loveys, 2007)

Morlat (2008) used soil profiles of between-vine length, 0.9 m deep and vertical walls 0.15 m and 1 m (half the inter-row distance) from the vine row, with three holes on the right and three on the left hand side to make

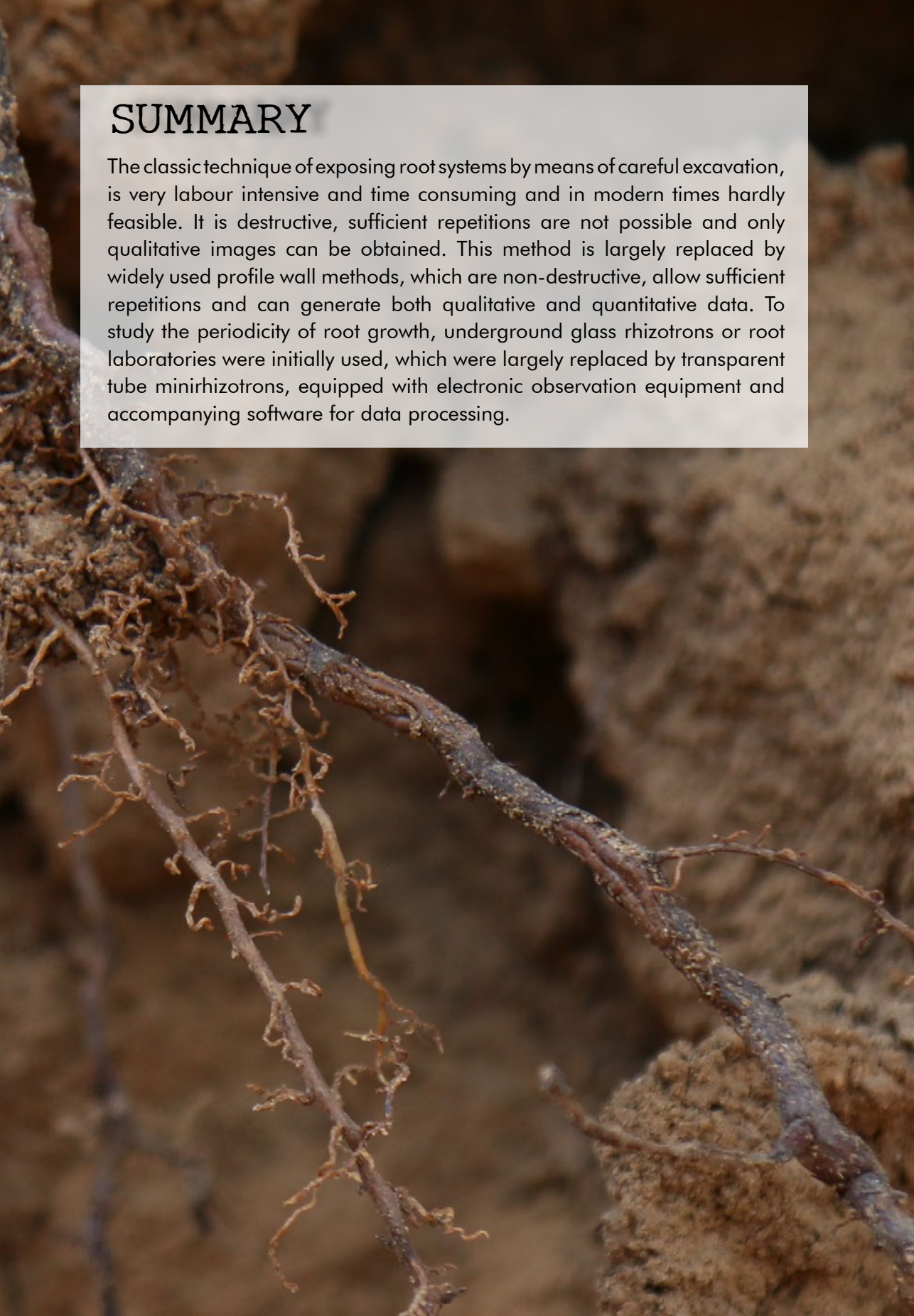
provision for root system asymmetry (Morlat & Jacquet, 2003). He counted roots on vertical faces and also deep plunging roots on a 0.15 m horizontal plane on the bottom of the hole. Morlat *et al*. (2010) used two methods of root investigation in the mid-Loire valley, *viz*. a non-destructive quantitative method of observation of roots in vertical profile walls, where roots were redrawn as accurately as possible, as well as a qualitative weighing method where roots were taken out according to soil horizons and divided into diameter classes and weighed after drying. Each trench was dug beside a vine with a trunk circumference (rootstock and scion) close to the mean of a population of 100 vines.

Tomasi *et al*. (2015) studied the root distribution of 15 - 20 year old vines in four different medium to heavy textured soils by means of the profile wall method of Böhm (1979). The inter-row spaces were permanent cover crop and the beams treated with weedicide. The profile walls were in the inter-row, 60 cm from the vine row and root distribution recorded to a depth of 100 cm and a length of 1.2 m (the between-vine distance). Root counts were done with the aid of placing a 20 x 20 cm grid against the profile wall, with the vine central. Roots were divided into < 1 mm (thin), 1-2 mm (medium) and > 2 mm diameter (lignified) classes and results expressed as number of roots/m^2.

In Hungary, Kocsis *et al*. (2016) investigated root distribution with the profile wall method (1 x 1.2 m) and studied root growth patterns with twice weekly observation by means of a microrhizotron camera system (two observation tubes per vine). Total root length and root mass were determined with *RootSnap* software.

Gaiotti *et al*. (2016) also used the profile wall method, with trenches up to 1 m deep and 45 cm and 90 cm from the vine row and classified roots as fine (< 1 mm), medium (1 - 2 mm) and thick (> 2 mm). Giese *et al*. (2016) used profile walls positioned parallel and perpendicular to the vine row for root intersection counts and sampled soil monoliths (20 x 20 x 20 cm) with a five sided steel box, from which the roots were washed for mass determination. They also took mechanical soil cores (51 cm diameter, 1.2 m long), which were laid out in plastic troughs en divided into 20 cm sections, from which roots were washed and arranged and scanned on a white surface. These images were analysed for root length and the roots subsequently dried and

weighed. The cumulative fraction of roots with soil depth was calculated with the model $Y = (1-ß^d)$, where Y = cumulative fraction of roots with depth and d = the soil depth in cm (Gale & Grigal, 1987). The estimated coefficient ß can be used as a numerical quantity that summarises the depth distribution of roots, with larger values of ß corresponding to larger proportions of roots with depth.

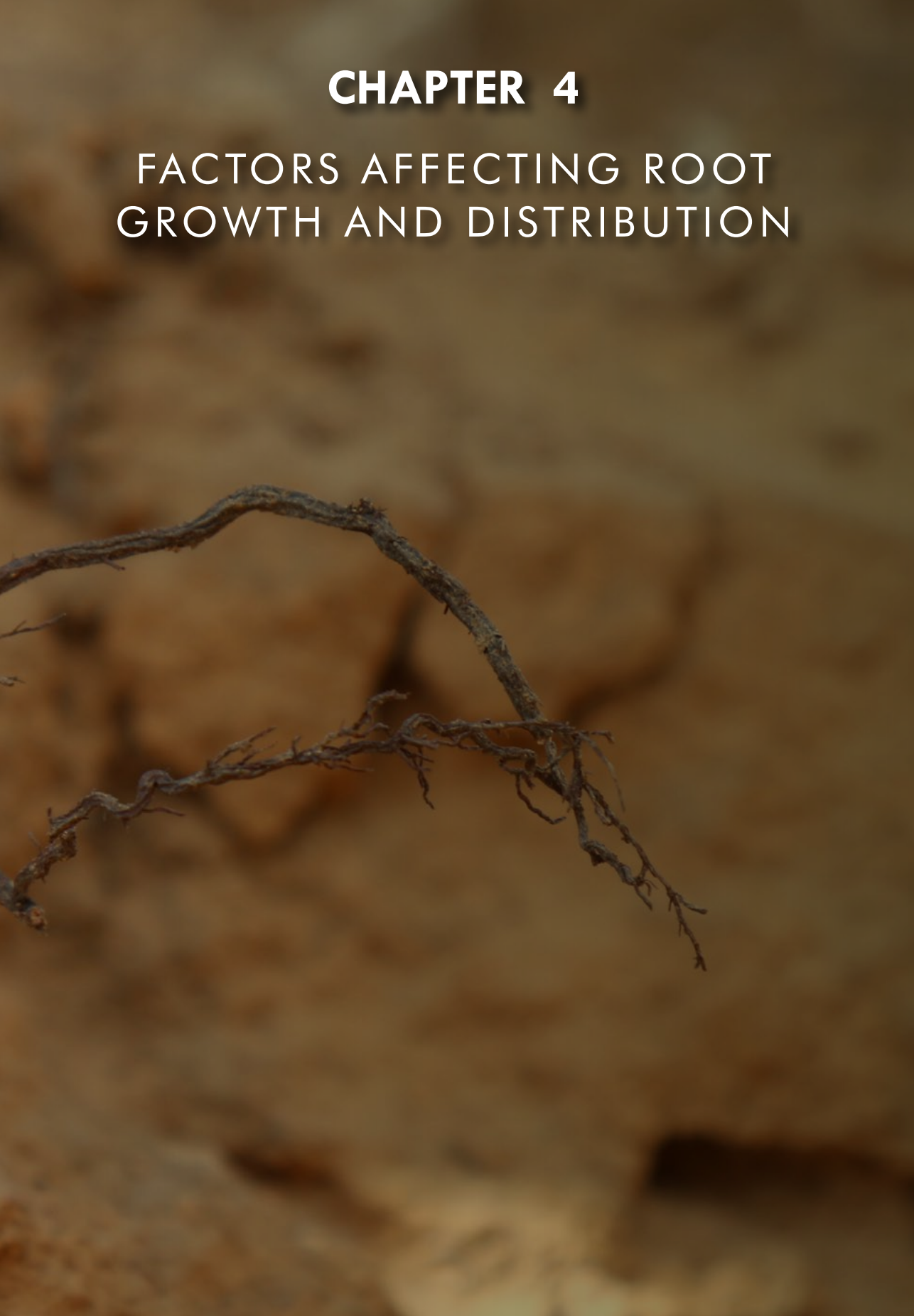


SUMMARY

The classic technique of exposing root systems by means of careful excavation, is very labour intensive and time consuming and in modern times hardly feasible. It is destructive, sufficient repetitions are not possible and only qualitative images can be obtained. This method is largely replaced by widely used profile wall methods, which are non-destructive, allow sufficient repetitions and can generate both qualitative and quantitative data. To study the periodicity of root growth, underground glass rhizotrons or root laboratories were initially used, which were largely replaced by transparent tube minirhizotrons, equipped with electronic observation equipment and accompanying software for data processing.

CHAPTER 4

FACTORS AFFECTING ROOT GROWTH AND DISTRIBUTION



CHAPTER 4

FACTORS AFFECTING ROOT GROWTH AND DISTRIBUTION

4.1 Soil type, soil physical and chemical factors

Root growth in soil is affected by geo-, chemo- and hydrotropism (Seguin, 1971). Soils that favour deep root development generate more vigorous above-ground growth than soils that allow only shallow root penetration. Reduction of the root zone by soil compaction also reduced the size of the root systems of Rupestris du Lot as well as that of Berlandieri 41B (Magriso, 1979). This caused a reduction of the above-ground growth, with an associated lower yield. Root growth was positively correlated with total porosity of the soil and the volume of air pores therein and negatively correlated with soil density. Seguin (1971) found that rooting depth varied between 40 cm to 5 - 6 m, depending on soil properties such as the location of compact horizons or hard concretion layers. Roots were often only temporarily blocked by compact horizons in that they explore the surface of the limiting layer until finding a thoroughfare (soft zone, old rotten roots, worm tunnels or natural cracks).

Davidson and Hammond (1977) found that root elongation of cotton was limited by soil strengths above 2 bar and that H. M. Taylor & H. R. Gardner reported in 1963 that there was no penetration above 26 bar. The latter came to the conclusion that soil strength, and not bulk density, is the critical factor that governs root elongation in sandy soil. Bulk density had a direct relationship with soil strength, but there was no unique relationship for all soils because grapevine roots generate different pressures to penetrate soil (Fig. 4.1.1). The effects of mechanical resistance (soil strength) and reduced aeration (soil pore size) are difficult to separate, but experiments of Gill and Miller (1956) showed that, combined, these two factors are more effective in reducing root growth than any of these alone.

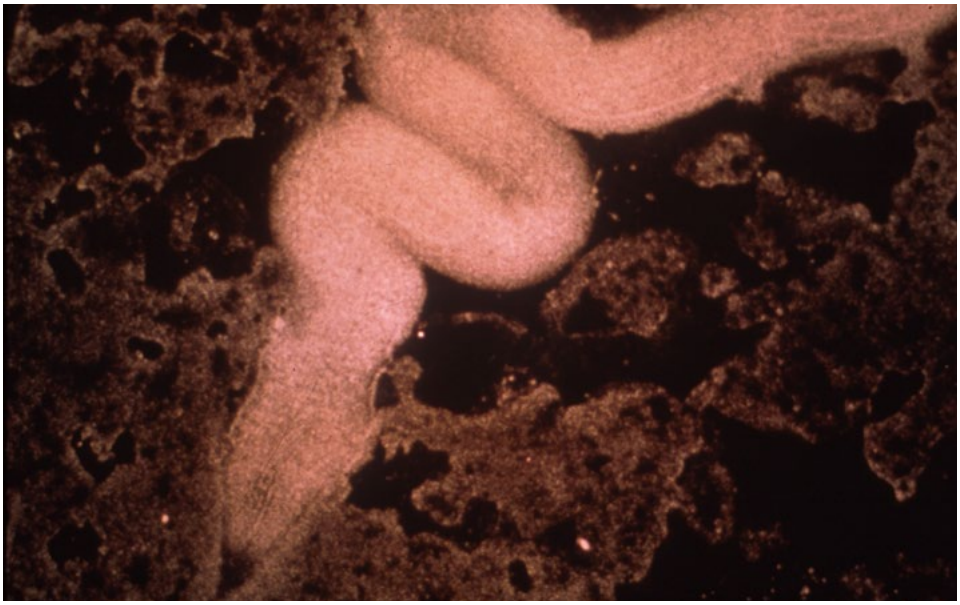


Fig. 4.1.1 Example of limited soil pore size hindering root penetration. (Picture: Viticultural & Oenological Research Institute (VORI))

Van Huyssteen (1988a) found that increasing soil compaction hampers grapevine root growth, but could not find any critical soil compaction or penetrometer values at which root growth was completely prevented. In soil preparation studies, Saayman and Van Huyssteen (1980) found that for Chenin blanc/99 Richter in the Stellenbosch area, a highly significant direct correlation between both shoot and crop mass and effective soil depth, as determined with a continuously registering penetrometer.

The grapevine has the reputation that it is a poor soils plant and can only survive in these soils because of its ability to utilise the slightest amounts of organic or mineral accumulation. This chemotropism is well demonstrated when a nutrient source, such as organic matter or clay, occurs in a zone of sparse root presence and the roots then develop on the surface of these nutrient sources and enveloped them as a dense matt of branched fine roots (Champagnol, 1984).

Branas and Vergnes (1957) found that limited soil depth does not change the zone of most roots, but does reduce the total mass of roots in all layers, especially in the most root-populated 25 - 45 cm layer (Fig. 4.1.2).

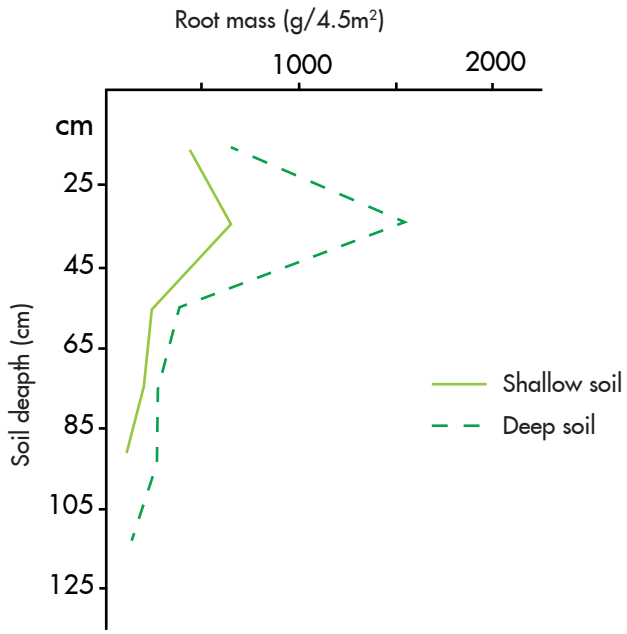


Fig. 4.1.2 Fresh mass of Rupestris du Lot roots in 4.5 m^2 plant space depths of a shallow and deep soil. (Redrawn from Branas & Vergnes, 1957)

However, the vertical root distribution in the shallow soil is more uniform and will be totally homogeneous in a limited space, such as in a container or pot. This seems to be justification of the empirical practice to remove superficial roots with cultivation after planting, preferably in spring or again during the second and third year, with the objective to encourage deeper root development.

Soil texture affects both deep penetration and root density (Nagaraja, 1987). Coarse texture caused 220 cm deep penetration and a root density of 0.4 mm roots per cm^3, while this was respecively 100 - 120 cm and 0.8 - 1 mm per cm^3 for medium texture and 60 - 120 cm and 0.7 - 1.7 mm per cm^3 for fine texture. Champagnol (1984) reported that the zone of preference in which most roots occur, is affected by soil water and soil aeration and that it varies from place to place (Table 4.1). A universal root distribution pattern is therefore an erroneous concept because of the crucial effects of soil properties on it. This is in accordance with the results of Smart *et al.* (2006), who found that, worldwide, vine roots penetrate soil deeper than most other plants. Their studies indicate that soil properties such as inpenetrable layers, stoniness and the presence of gravel lenses have a greater effect on depth

distribution of roots than genotype. Likewise, Morlat and Jacquet (1993) found that the features of the vine root system are significantly affected by soil properties. It is especially the waterholding and water supply abilities of the soil, together with soil strength, bulk density, textural differences and clay percentage, that dictate the growth, distribution and density of roots. In accordance to this, Williams and Smith (1991) also found that root distribution in the available soil volume is determined by soil properties, whereas root density is a function of the rootstock cultivar.

Table 4.1 Zones of preference for grapevine root development for different conditions (Champagnol, 1984)

Environment	Soil	Climate and rainfall	Aerated soil depth	Preferred depth (cm)
Montevideo	Very compact clay	Warm temperate (1100 mm)	Very shallow	8 - 20
Montpellier	Sandy, with bank at 1 m depth	Mediterranean (750 mm)		20 - 40
Montpellier	Compact clay-loam	Mediterranean (750 mm)		25 - 50
Madrid	Sandy loamy	Mediterranean (500 mm)		25 - 50
San Joaquin California	Sandy loam	Mediterranean		30 - 70
Jerez	Very compact clay-loam on broken rock	Mediterranean (500 mm)		40 - 70
Iowa	Permeable silt	Continental	Very deep	10 - 200

The soils that Seguin (1971) studied in the Margaux (Medoc) region, formed in quaternary gravelly sand, deposited on tertiary fertile clay and lime. The 'poor' soil was duplex, gravelly sand (1 - 4.5% clay) on clay (35%), with a 60 cm deep A and E horizons (corresponding with the Kroonstad and Estcourt soil forms of the South African Soil Classification System), while the 'normal' soil was 90 cm deep, relatively uniformly ochre coloured, gravelly loamy sand (9 - 14.5% clay) (corresponding to South African Avalon, Pinedene or Tukulu soils). Root distribution in the A and E horizons of the 'poor' soils was sparse and vertical, due to the hanging water table on the clay layer. The clay layer was marbled with ochre and greyish blue colours, with some black Fe and Mn concretions. In spite of the compact nature of

this clay layer, root distribution therein was good, with colonisation by fine roots. In the 'normal' soil, root distribution was uniform over the full depth, with fine roots more abundant from 60 cm depth. These differences in root distribution and water regime were largely reflected in wine character, with lower sugar, higher pH and malic acid in wines in the case of the shallow duplex soil.

In the Medoc more fine roots are present in soil layers with iron (Fe) in reduced form (greyish blue colours) than where Fe was oxidised and occurred as concretions (Seguin, 1971). In certain cases the hardness of the concretion layers could have been the cause, but he found that, even in cases where the Fe rich soil layer was very friable and well aerated, there was still an absence of live fine roots. According to Seguin (1971), this phenomonen merits further in depth inverstigation. This is also contradictory to what is observed under South African conditions. The presence of 'alios', or rather the more realistic term 'iron concretions' (accumilation of Fe in soil), was always regarded as a wine quality factor, but Seguin (1971) did not find it conducive to root branching and formation of fine roots. It is therefore unlikely that Fe concretions in themselves can be an advantageous factor concerning wine qualiy. It appears rather that it is the conditions in the Medoc that determine the formation of Fe concretions, *viz*. lowering of the water table during summer, that are advantageous concerning good ripening of grapes.

In the Loire valley, Morlat and Jacquet (1993) found that six soil factors explain 71% of total variation in root distribution. Available water capacity and clay content were correlated positively to root density, whereas penetrometer resistance, bulk density and hydromorphism were negatively correlated. Root distribution patterns were closely related to soil conditions, rather than to genetic aspects. A good relationship was also obtained between number of roots and above-ground growth. Yield and grape quality were found to be dependent on a viable and healthy root system.

Already in 1941 in the Western Cape, Le Roux found that bulk density and soil acidity increase with depth and that phosphorus (P) content diminishes. This had a hampering effect on grapevine root growth and soil colonisation. The number of roots correlated positively with soil fertility, and in some cases up to 91% more roots occurred in fertile than in poor soils. Soil pH also affected root hair production: in acid soil, fewer root hairs were

formed than in alkaline soil. According to Boubals (1977), winegrape roots that are much weakened by soil acidity, acquire a red appearance when bisected. This reminds of what can be observed in waterlogged soil. Roots are impaired by free metal cations like aluminium (Al), which turns roots necrotic in acid soil.

It is generally accepted that exchangeable Al in acid soil is mostly responsible for poor root growth and that it should be < 0.2 cmole/kg (Kotze, 1993; Reeve & Sumner, 1970). In France, Marcelin (1974) found that vines perform poorly in soil with pH(water) < 5.0 and that poor root growth was one of the symptoms. Conradie (1983) found that the root mass of 140 Ruggeri, 110 Richter and 99 Richter responded little to liming but that shoot mass did, whereas root mass of especially 101-14 Mgt increased significantly (Fig. 4.1.3).

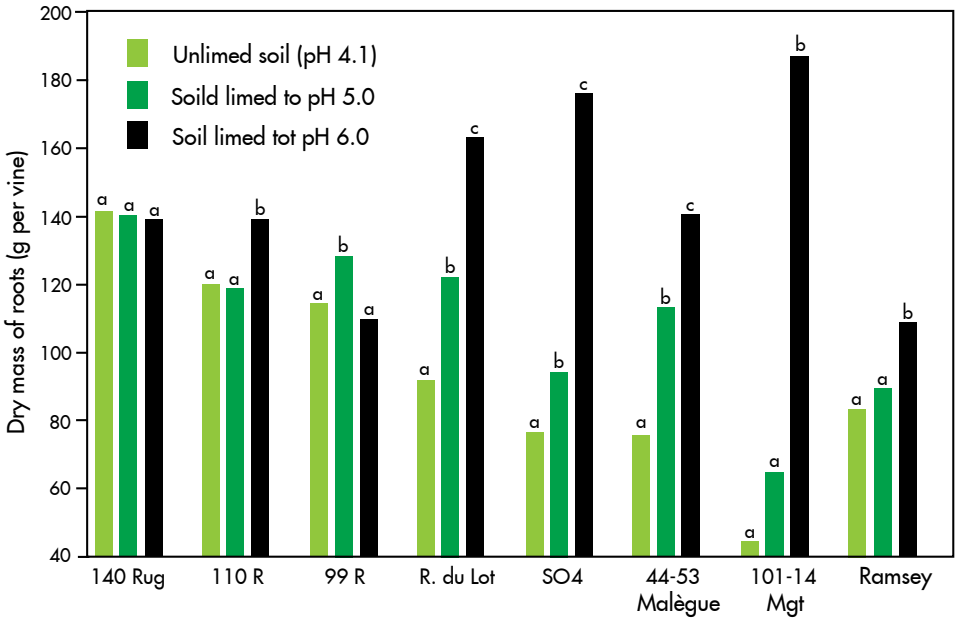


Fig. 4.1.3 Effect of soil acidity on the root growth of eight rootstock cultivars (Redrawn from Conradie, 1988)

Liming the soil to $pH_{(KCl)}$ 6, caused significant increases in fine, medium and total root mass for all rootstocks (Fig. 4.1.4)

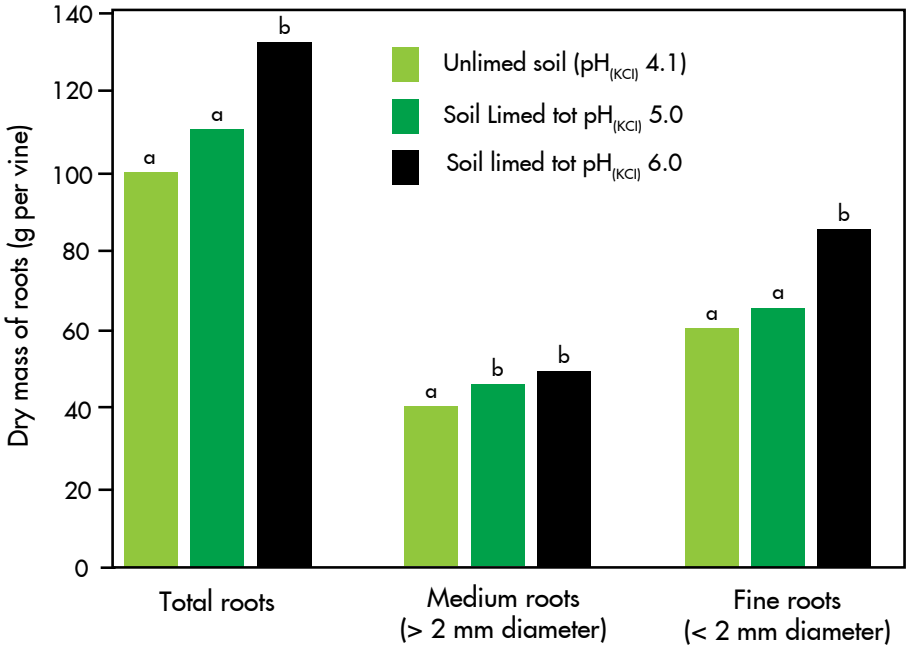


Fig. 4.1.4 Effect of soil acidity on the dry mass of total, medium and fine roots; mean for 15 rootstock cultivars (Redrawn from Conradie, 1988)

From the above, it is clear that physical and chemical properties of a soil have significant effects on the growth and functioning of grapevine roots. However, very little research brings this into relation with the implications thereof on vine performance and wine properties. As a result, Tomasi *et al*. (2015) investigated the root distibution of 15 -20 year old vines in four medium to heavy textured soils with the profile wall method of Böhm (1979). There was a permanent sward in the working rows, whereas the berms were treated with weedicide. Soil and accompanying root distribution did not have a significant effect on total soluble solids of musts, but did affect total titratable acids, time of ripening, bunch mass and yield:shoot mass ratio. Soil units had a highly significant effect on the total number and distribution of roots for all diameter classes (< 1 mm (thin), 1 - 2 mm (medium) and > 2 mm (lignified). Fine roots were 73% of total roots and mostly present in the upper 40 cm soil. Medium roots were 20% of total roots and localised in the upper 60 cm soil layers, whereas lignified roots occurred mainly between 20 cm and 40 cm depths, but mostly deeper than the fine roots. Their findings that grapevine roots adapt to specific soil properties, such

as water retention capacity, in order to obtain a vineyard:soil equilibrium that affects grape and wine quality, were supported by the findings of Van Leeuwen *et al.* (2009) and Pelligrino *et al.* 2004).

Tomasi *et al.* (2015) found that most variation between soil units was related to differences in water regime, that could be explained by factors such as soil depth, texture, water supply and the ability of the vine to extract water. Good and consequent wine quality were observed only for soils with sufficient water content throughout the growing season, or where defficient rain was compensated for by a well developed root system that can utilise all available soil water. Soils with limited root density and distribution caused an imbalance between vegetative and reproductive growth, that lead to poor grape and wine quality in dry years. This important principle of a balance between all winegrape growth patterns and organs, was also demonstrated by Archer and Hunter (2004/5). Furthermore, Archer and Hunter (2005/6) found a clear positive relationship between root system composition and wine quality in that it was especially the fine roots that determine wine quality during warm, dry summers. They emphasised the importance of efficient physical and chemical soil preparation before planting, as well as the making of good planting holes during planting (Archer & Hunter, 2010). These results confirm that models used to evaluate grape and wine reaction to climate and soil, should also include an analysis of the root system.

Seguin and Compagnon (1970) found that rooting depth was of crucial importance for the occurrence of grey rot in Merlot on the gravelly sandy soils of the Bordeaux area. Rooting was deep in well-drained soil, with fewer roots in the surface layers. Therefore, rain during ripening had a greater effect on water uptake of shallow-rooted vines because the whole rooting volume is suddenly saturated with water and luxury water uptake then caused cracking of berries and Botrytis infection.

The differences in performance of Chenin blanc, as induced by different rootstocks (see also Tables 4.3.2, 4.3.3 and 4.3.3), were investigated in three different localities in South Africa (Southey & Archer, 1988). In Vredendal (Olifants River), the genetic root distribution characteristics of six rootstocks in a sandy silt soil, classified as Dundee soil form (McVicar *et al.*, 1977), were totally overshadowed by soil physical properties. This alluvial soil had a silt layer at different depths as a result of ancient flooding and for all

rootstocks, most roots were concentrated in this layer. The depth of the silt layer differed between rootstocks and caused 101-14 Mgt (with a reputation of being shallow rooted), to have a considerably deeper root penetration than 3306 Couderc (with a reputation for deeper rooting) (Fig. 4.1.5). About 70% of the 3306 Couderc roots and 80% of the 101-14 Mgt roots were concentrated in this silt layer. The root mass per unit soil volume differed drastically between rootstocks, with 1.512 kg for 101-14 Mgt and only 0.391 kg for 333 EM.

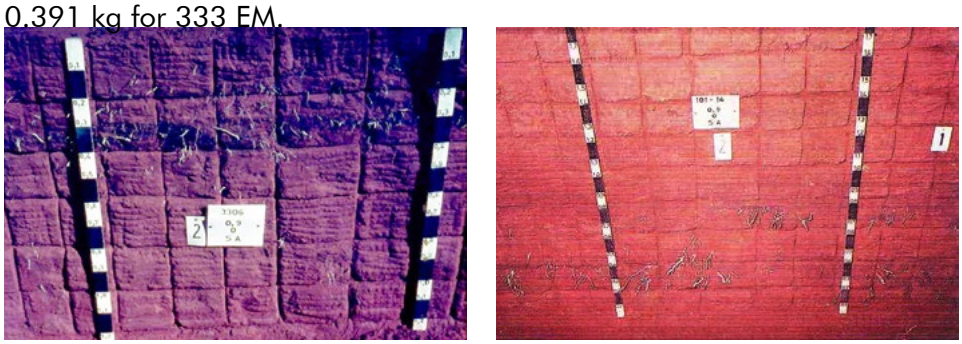


Fig. 4.1.5 Root distribution is strongly dictated by soil physical properties. Left: Roots of 3306 Couderc concentrated mostly in a silt layer at 200 - 400 mm. Right: Roots of 101-14 Mgt concentrated mostly in silt layers at 800 - 1000 mm and 1400 - 1600 mm depths. Grid size: 200 x 200 mm (Southey & Archer, 1988)

SUMMARY

Grapevine roots have a preference for growing in soil zones with the least hindrance. This hindrance is normally of a physical nature, but chemical limitations (toxic levels or deficiencies) can also play a large role. World-wide, grapevine roots penetrate soils deeper than most other woody plants. For each situation, grapevine roots have a zone of preference that varies in depth depending on changes in soil properties. In this regard, it is especially the water holding and water supply ability, soil strength, bulk density, textural differences and clay percentage of the soil that play a role, whereas soil pH and P content are often also determining factors.

There is a balance between above-ground and underground growth, which is mainly determined by rootgrowth. The larger (more intensive) the root growth, the larger the above-ground growth and *vice versa*. A well buffered root system with a high ratio of fine to thick roots is responsible for balanced above-ground growth, that impacts directly and positively on grape and wine character.

4.2 Soil and root temperature

In general, the temperature limits for root growth of woody plants are 5 - 35°C, with the optimum temperature for grapevine roots close to 30°C (Woodham & Alexander, 1966). Sultanina roots started growing actively at 10°C and continued growing up to 30°C. From 11 - 30°C, the dry mass of roots increased almost three-fold and was linked to stronger shoot growth and better fruit set. This is in accordance to the findings of Jooste (1983) for ungrafted vines in pots, that, in general, the highest rate of root mass increase occurred at 20°C, but that cultivar differences do occur (Fig. 4.2.1 & 4.2.2). Contrary to other cultivars, Rupestris du Lot still showed a strong increase in root growth rate from 20°C to 30°C. Graham *et al.* (2002) found that cold soil temperature in spring retarded bud burst and budding percentage, as well as root mass.

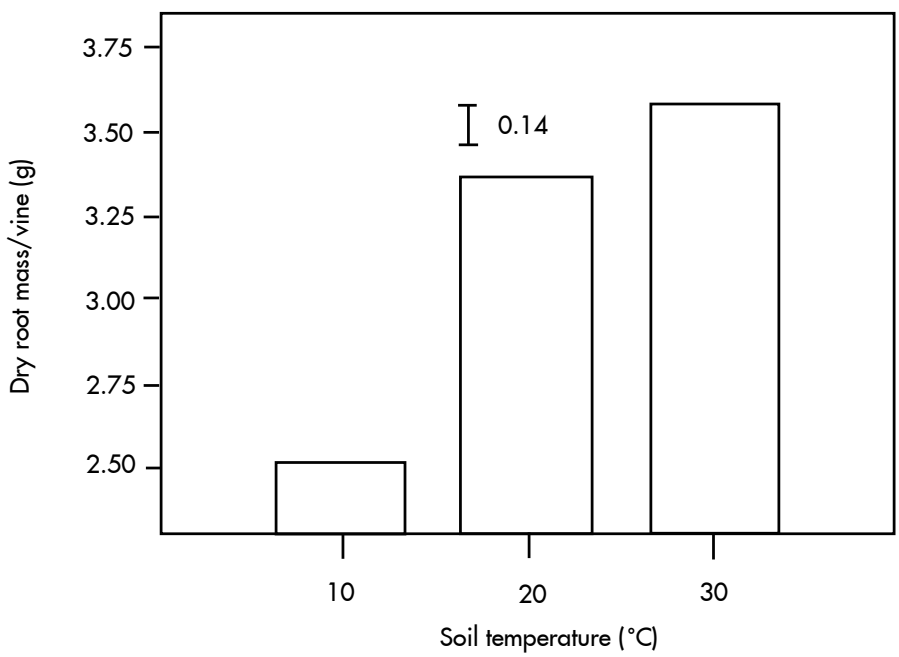


Fig. 4.2.1 Effect of soil temperature on the root mass of *Vitis*. Vertical bar = SSD ($P \leq 0.05$). (Redrawn from Jooste, 1983)

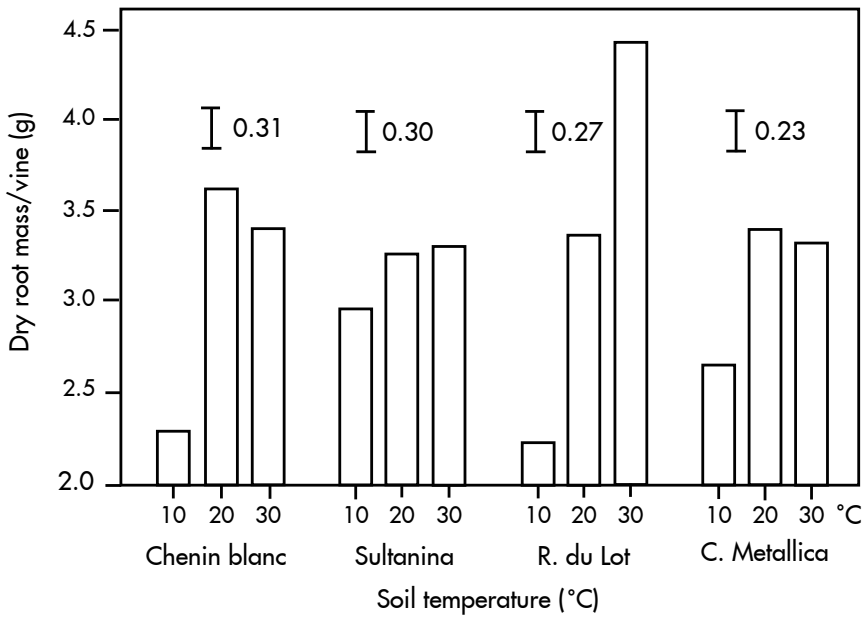


Fig. 4.2.2 Effect of soil temperature and cultivar on root mass of grapevines. Vertical bar: = SSD ($P \leq 0.05$). (Redrawn from Jooste, 1983)

According to Rogers (1939), W. A. Cannon already determined in 1925 that the ideal soil temperature for root growth was 20 - 31°C. Vascenko (1966) found that most roots occur in the soil layer with optimum temperature and that the wide temperature fluctuation in the topsoil hinders the development of fine roots. In this context, soil colour, soil cover and shading by foliage play a large role. Dark-coloured and red (iron oxides) soils heat faster and retain their temperatures longer than lighter coloured soils (Seguin, 1971).

Clarke *et al.* (2015) found that soil temperature was directly correlated to fine root length and branching, but inversely correlated to starch content. Root branching was also inversely correlated to starch content, which indicated that high soil temperatures caused more rapid mobilisation of reserve nutrients in spring. It also caused accelerated nitrogen repartition to the above-ground growth, as well as a higher element content of leaf petioles at fruit set and at harvest, except for Mg, Na and B. Warmer soil and accompanying better root growth were reflected in enhanced shoot growth and leaf surface, but lower starch contents. Soil degree-days are, therefore, a good predictor of the scope of root growth and starch degradation between bud burst and fruit set. Soil warming in spring initiated starch and N mobilisation, which were advantageous to both new

root and shoot growth (Clarke *et al.*, 2015). Higher soil temperatures after bud burst caused more fine root development and branching, which were advantageous to water and nutrient uptake. Initial foliage development is therefore predominantly supported by N derived from reserves, with N uptake from the soil an additional source under warm rootzone conditions. Warm soil caused increased stomata conductance and thus increased photosynthesis rates, that turns shoots into positive exporters which promote the recharge of carbohydrates and root growth.

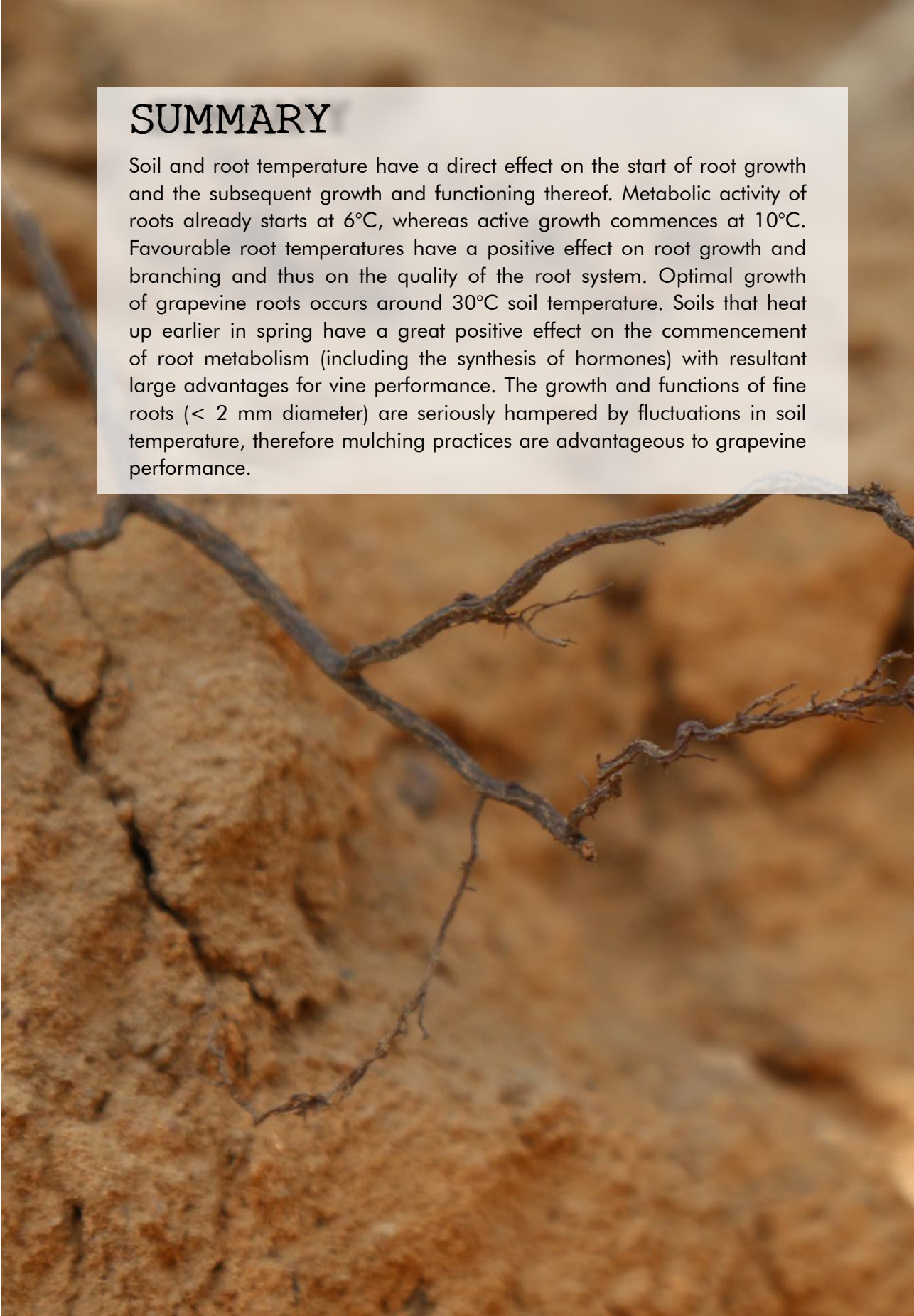
Warmer soil and therefore, root temperatures, cause a more rapid mobilisation of root starch in spring, which not only brings foreward phenological stadia, but also cause a larger biomass (longer shoots, bigger leaves) (Rogiers & Clarke, 2014). Root temperature of 30°C caused significantly more and deeper roots as well as stronger shoot growth than at 20°C (Skene & Kerridge, 1967). This has practical implications in that soil temperature fluctuation in a vineyard causes greater variation in above-ground growth, with a negative effect on homogeneity of shoot growth and therefore uniformity of grape composition. The colour of the material used as soil cover on the berms also has important implications in that darker colours have a positive impact on the temperature of the topsoil, which can promote early season fine root activity.

Kliewer (1975) worked with root temperatures of 11, 15, 20, 25, 30 and 35°C and found that bud burst and flowering were three to eight days earlier at 25 - 30°C than at 11 - 15°C. The total shoot growth was at a maximum at 30°C, as well as the total number of leaves and leaf surface per vine. The mean shoot length, dry mass per trunk length unit, leaf surface, and leaf and bunch dry mass, were significantly less at 35°C than at lower root temperatures. The number of berries per vine that had set, did not differ, but were significantly higher per bunch at 11°C than at temperatures above 30°C. He ascribed these differences to earlier root activity at medium high tempertures that not only improved water and nutrient uptake, but were also advantageous to hormone production.

Field, *et al.* (2009) found that soil temperature plays an important role in the mobilisation and use of root carbohydrate reserves from bud burst to flowering. During this period, both xylem sap flow and the cytokinin composition of the sap were dictated by soil temperature. In contrast with the results of other researchers, Field *et al.* (2009) found no differences in

time of bud burst for soil temperatures of 13°C and 23°C and stated that bud burst is rather affected by apical dominance and the number of buds per vine.

Pituc (1966) found that the roots of grapevines that were planted on terraces grew away from the terrace wall and ascribed this to the high soil temperatures of the walls. Local observations indicate that soils that reach temperatures of 10–12°C faster, caused earlier bud burst, faster growth and a larger crop, due to earlier root activity, than cooler soils. Zelleke and Kliewer (1980) found that higher soil temperature (25°C vs. 12°C) brought the date of bud burst foreward with 17 days. Budding percentage and shoot growth were also significantly better at higher soil temperatures.



SUMMARY

Soil and root temperature have a direct effect on the start of root growth and the subsequent growth and functioning thereof. Metabolic activity of roots already starts at 6°C, whereas active growth commences at 10°C. Favourable root temperatures have a positive effect on root growth and branching and thus on the quality of the root system. Optimal growth of grapevine roots occurs around 30°C soil temperature. Soils that heat up earlier in spring have a great positive effect on the commencement of root metabolism (including the synthesis of hormones) with resultant large advantages for vine performance. The growth and functions of fine roots (< 2 mm diameter) are seriously hampered by fluctuations in soil temperature, therefore mulching practices are advantageous to grapevine performance.

4.3 Genetics

Branas and Vergnes (1957) found that 110 Richter utilised shallow soil better than Rupestris du Lot, with 323 g per 4.5 m^2 fresh mass roots, against only 160 g per 4.5 m^2 for Rupestris du Lot, but that 110 Richter had more shallow roots in wet soil, indicating that it was more sensitive to wetness.

In a study on one-year-old ungrafted rootstocks, Pongrácz (1968) found that the growth habit of the root systems of 23 cultivars were greatly affected by the nature of the soil. Still, *Vitis riparia* and its related descendants produced shallower but denser root systems. These roots were thin, yellowish in colour, with a smooth surface. *Vitis rupestris* and its related descendants had deeper root systems, reddish-brown in colour. These root systems also were dense but of medium thickness. *Vitis Berlandieri* and its related descendants had deep, less dense, thick, greyish-brown and poorly branched root systems characterised by rough surfaces.

Branas and Vergnes (1957) found large differences between the root mass of rootstocks over 0 - 125 cm soil depth and classified rootstocks accordingly, with Rupestris du Lot as reference. Rootstocks with root mass less than that of Rupestris du Lot are Riparia Gloire de Montpellier, 3309 Couderc, Kober 5BB, 161-49 Couderc, 216-3 Castel, 1616 Couderc, 106-8 M.G., 44-53 Malèque, 196-17 Castel, 3306 Couderc. Rootstocks with root mass comparable to that of Rupestris du Lot are 99 Richter, SO4. Rootstocks with root mass greater than that of Rupestris du Lot are 110 Richter, 41B Mgt, 333 Ecole de Montpellier, 420 A Mgt, Grezot 1. The root mass of Riparia Gloire de Montpellier was 0.56 of that of Rupestris du Lot, but more uniformly distributed with depth. Branas and Vergnes (1957) defined evenness of root distribution as: Root mass in the 25 - 45 cm maximum root density soil layer ÷ Total root mass up to a soil depth of 125 cm. This ratio was 0.51 for Riparia Gloire de Montpellier, against 0.37 for Rupestris du Lot. With the latter as reference, rootstocks were classified as follows: Even distribution was found in Riparia Gloire de Montpellier, 99 Richter, 106-8 M.G., 41 B Mgt, 333 Ecole de Montpellier, 44-53 Malèque, 110 Richter, 196-17 Castel, 161-49 Couderc. Moderate distribution was found in Rupestris du Lot, SO4, Riparia Gloire de Montpellier, Grezot 1, 161-49 Couderc. 3306 Couderc. Uneven distribution was found in 216-3 Castel, 3309 Couderc, Kober 5 BB, 99 Richter, 110 Richter, 420 A Mgt, 44-53 Malèque. (Rootstock that occurs in more than one class is due to soil differences that affected root growth in the upper or deeper soil layers).

The portion of roots in the surface layers was expressed by Branas and Vergnes (1957) as: Root mass in the 0 - 25 cm soil layer ÷ Total root mass in 0 - 125 cm soil depth. With Rupestris du Lot as reference, rootstocks were classified as high: SO4, 106-8 M.G., 41 B Mgt, 333 Ecole de Montpellier, 110 Richter, 420 A Mgt; medium: Rupestris du Lot, Riparia Gloire de Montpellier, Grezot 1, Kober 5 BB, 44-53 Malèque, 196-17 Castel; and low: 99 Richter, 116-3 Castel, 3306 Couderc, 1616 Couderc, 44-53 Malèque, 161-49 Couderc.

The portion of roots in the subsoil was expressed as: Root mass in the 45 - 125 cm soil layer ÷ Total root mass in 0 - 125 cm soil depth. According to this, the classification was high: Riparia Gloire de Montpellier, 44-53 Malèque, 1616 Couderc, and 3306 Couderc; medium: Rupestris du Lot, 99 Richter, 3309 Couderc, 41 B Mgt, 333 Ecole de Montpellier and 196-17 Castel; and low: SO4, 216-3 Castel, 106-8 M.G., Kober 5 BB, 99 Richter, 420 A Mgt and 161-49 Couderc.

Branas and Vergnes (1957) found that root mass was not always in relation to above-ground growth, because rootstocks with a small root mass (amongst others Riparia Gloire de Montpellier, 3309 Couderc) can have great vigour, even more than that of cultivars with large root masses (amongst others 420 A Mgt, 333 Ecole de Montpellier). When roots are thin, there are more functional root tips than in the case of thick roots, and it can be expected that they are more effective. Rootstocks with the same root mass do not necessarily communicate their capacity to the scion because of different functionalities and graft combination interactions.

Oslobeanu (1968) found that the total number of lateral roots per vine was determined by the rootstock cultivar. Stoev and Rangelov (1969) could show that the total root mass, as well as the depth and distribution thereof, was less for Muscat rouge grafted onto Rupestris du Lot than when grafted onto 41 B Mgt or on its own roots. The depth and horizontal distribution of roots in the same soil and the same planting distances are affected by the scion cultivar (Daulta & Chauhan, 1979). Between five cultivars, the widest horizontal distribution was 1.92 m (for Anab-e-Shahi) and the least was 0.93 m (for Gold). The largest number of roots at 30 cm distance from the trunk was 26 (for Thompson Seedless) and the smallest number was 5 (for Cardinal). This shows that genetics dictate root distribution only when soil properties are similar.

Tardáguila *et al*. (1995) found that differences in root growth and distribution patterns between rootstocks were the main cause for differences in dry mass division between the organs of the grapevine. There were also differences in the concentrations of mineral nutrients, with 101-14 Mgt having the lowest and 41 B Mgt, together with 420 A Mgt, the highest N concentrations in their roots.

According to Erlenwein (1965), the affinity between scion and rootstock affects root growth and its distribution. Combinations with weaker affinity have thinner rootstocks with weaker root systems than those with better affinity. It is particularly the root growth peak in autumn that is impaired by poor affinity (Semina, 1965).

Le Roux (1941) investigated the roots of seven rootstock cultivars grafted with three scion cultivars with, amongst others, the profile wall method that was described decades later by Böhm (1979). Examples of Le Roux's work are shown in Figures 4.3.1, 4.3.2 and 4.3.3. It is evident that the distance from the vine where the root study was done, had a great effect on the root distribution image acquired. Slightly further from the vine, a more intensive distribution was encountered than closer to the vine. This finding contributed lagely to the 40 - 50 cm standardisation of the distance from the vine for such root studies.

Jacquez showed a well distributed root system that penetrated relatively deeply in the non-irrigated soil, which was described as fertile by Le Roux (1941). However, no roots were present in the upper 15 cm soil depth in this clean cultivated vineyard (Fig. 4.3.1).

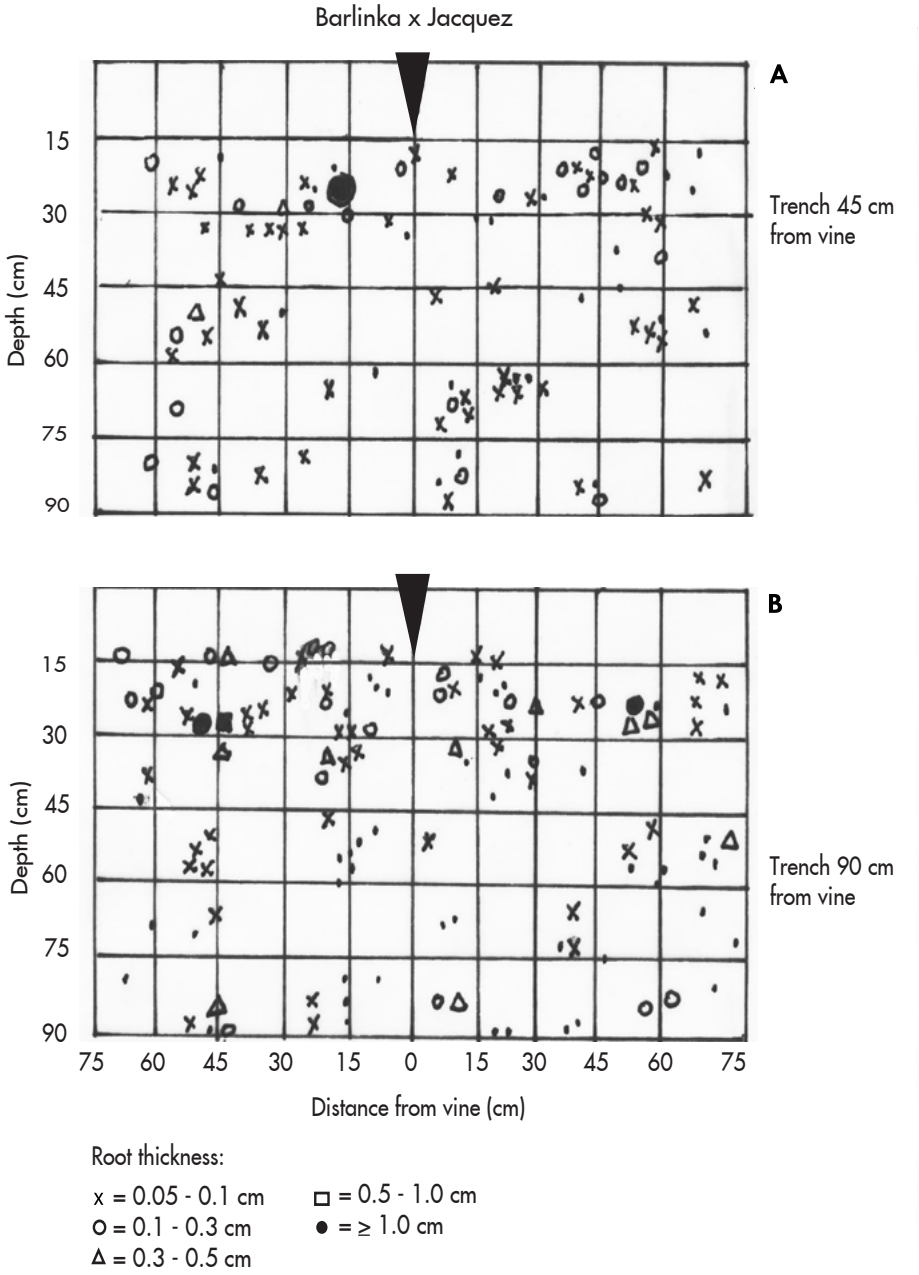


Fig. 4.3.1 Root distribution of Barlinka/Jacquez at Welgevallen Experimental Farm, Stellenbosch. (Redrawn from Le Roux, 1941)
Note the better distribution further away from the vine.

Le Roux (1941) also found that the physical nature of the soil plays a dominant role, compared to that of genetics, regarding the root distribution pattern of rootstocks. Fig. 4.3.2 clearly shows how a hard, barely penetratable soil layer can restrict roots to the softer surface layer.

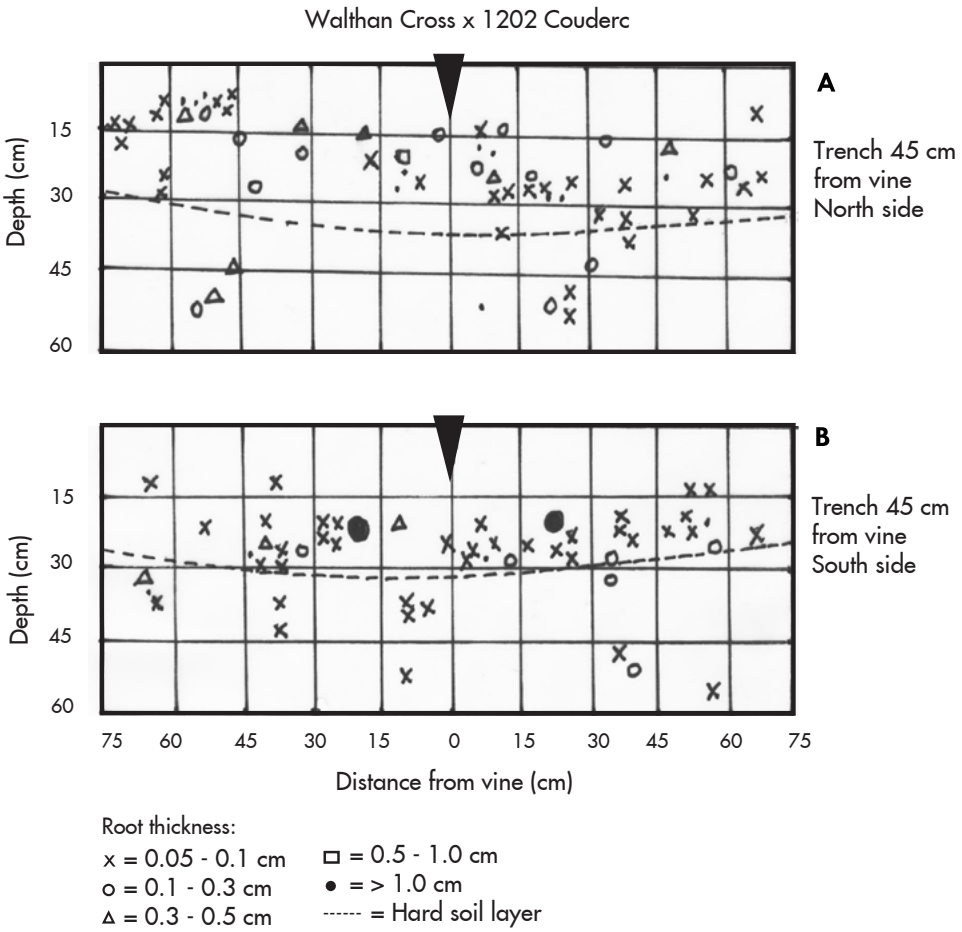


Fig. 4.3.2 Root distribution of Waltham Cross/1202 Couderc at Welgevallen Experimentat Farm, Stellenbosch. Note the impact of the hard soil layer on the depth penetration of roots. (Redrawn from Le Roux, 1941)

The rootstock 333 Ecole de Montpellier clearly showed a deeper tap root penetratiom than the other rootstocks (Fig. 4.3.3) and Le Roux (1941) described this as part of the nature of the rootstock. This rootstock also had more roots in the upper 15 cm soil depth than the other rootstocks, which had the same soil volume at their disposal.

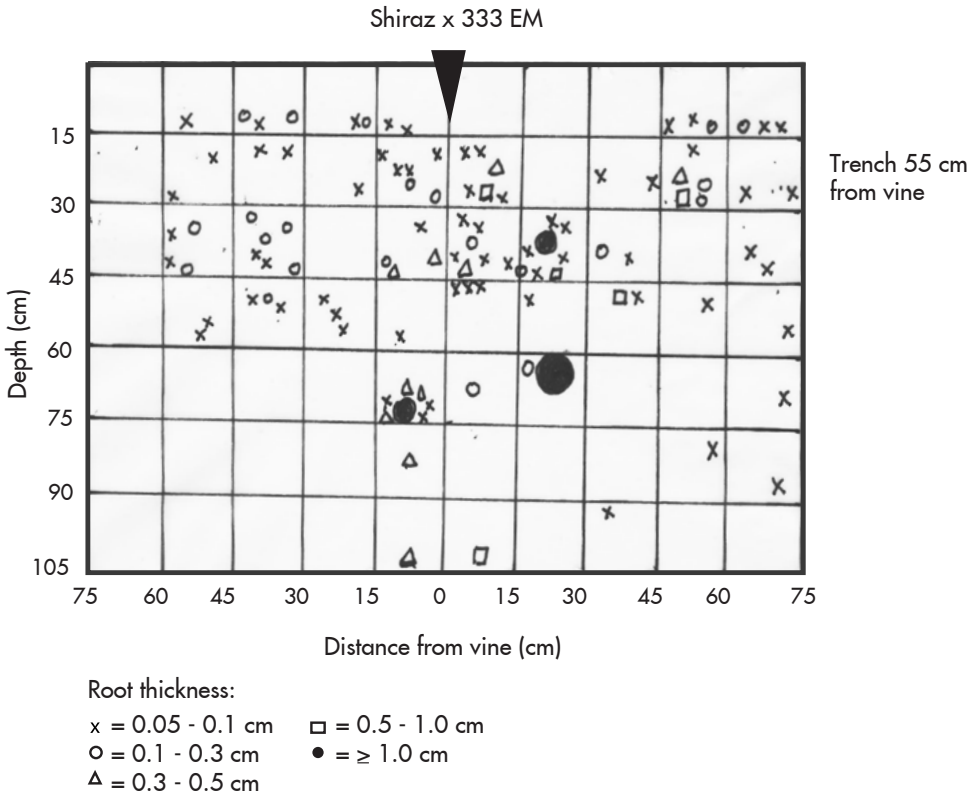


Fig. 4.3.3 Root distribution of Shiraz/333 EM at Welgevallen Experimental Farm, Stellenbosch. (Redrawn from Le Roux, 1941)

The framework roots of Jacquez were mainly present in the upper soil layers, with 70% fine roots in the top 45 cm soil layer, but with almost no roots in the 15 cm surface zone (see Fig. 4.3.1). The rootstocks 333 EM and 1202 Couderc had a deeper tap root system than Jacquez. Although the latter showed less root branching, its fine roots were much shallower than that of the other rootstocks. Riparia Gloire de Montpellier had a very frail root system, with tap roots thinner and less fleshy than was the case for the other rootstocks. This rootstock allowed more roots from neighbouring vines in its colonilisation zone, which was a sign of its low vigour. Apart from Riparia Gloire de Montpellier, the framework roots of 101-14 Mgt were more weakly develloped than that of the other rootstocks and struggled in compact soil layers. A very weak fine root system was encountered for 420 A Mgt. Rupestris du Lot had very weak depth penetration but up to 6 m long framework roots were encountered in the upper 45 cm soil depth (Le Roux, 1941).

In a study on Chenin blanc, grafted onto eight different rootstocks, grown in a red, sandy Hutton soil form (MacVicar *et al*, 1977) in the Lutzville area (Olifants River), experimental vines were selected according to trunk circumference and shoot mass to be representative of each graft combination (Southey & Archer, 1988). The roots were investigated, using the profile wall method (Böhm, 1979). The roots of all rootstocks investigated, penetrated the soil to a depth of 1.5 m, except for that of 3306 Couderc, where no roots deeper than 1.25 m were found due to a hard, compact soil layer. Except for Ramsey, most roots, especially fine roots, were present in the deeper (> 75 cm) soil layers (Fig. 4.3.4 A, B, C and D). This was ascribed to the more sandy nature (rapid drying out after irrigation) and higher temperatures of the topsoil. The deeper soil layers thus had a more advantageous environment for root growth. Similar findings were also made by Van Zyl and Weber (1981).

However, root density differed largely between rootstocks, with that of Ramsey the highest and Teleki 5BB the lowest (Fig. 4.3.4 A, B, C & D). In agreement with this, McKenry (1984) and Ngarajah (1987) found that Ramsey had a considerably larger and deeper root system, with thicker roots, than that of Thompson Seedless. The examples in the figures are arranged according to root densities, with that of Teleki 5BB the lowest and Ransey the highest. These root distribution patterns were related to the growth and yield performance of Chenin blanc on the different rootstocks (see Table 4.3.2). Coupled to this, the efficiency of roots was significantly impaired by infection with nematodes (Southey & Archer, 1988).

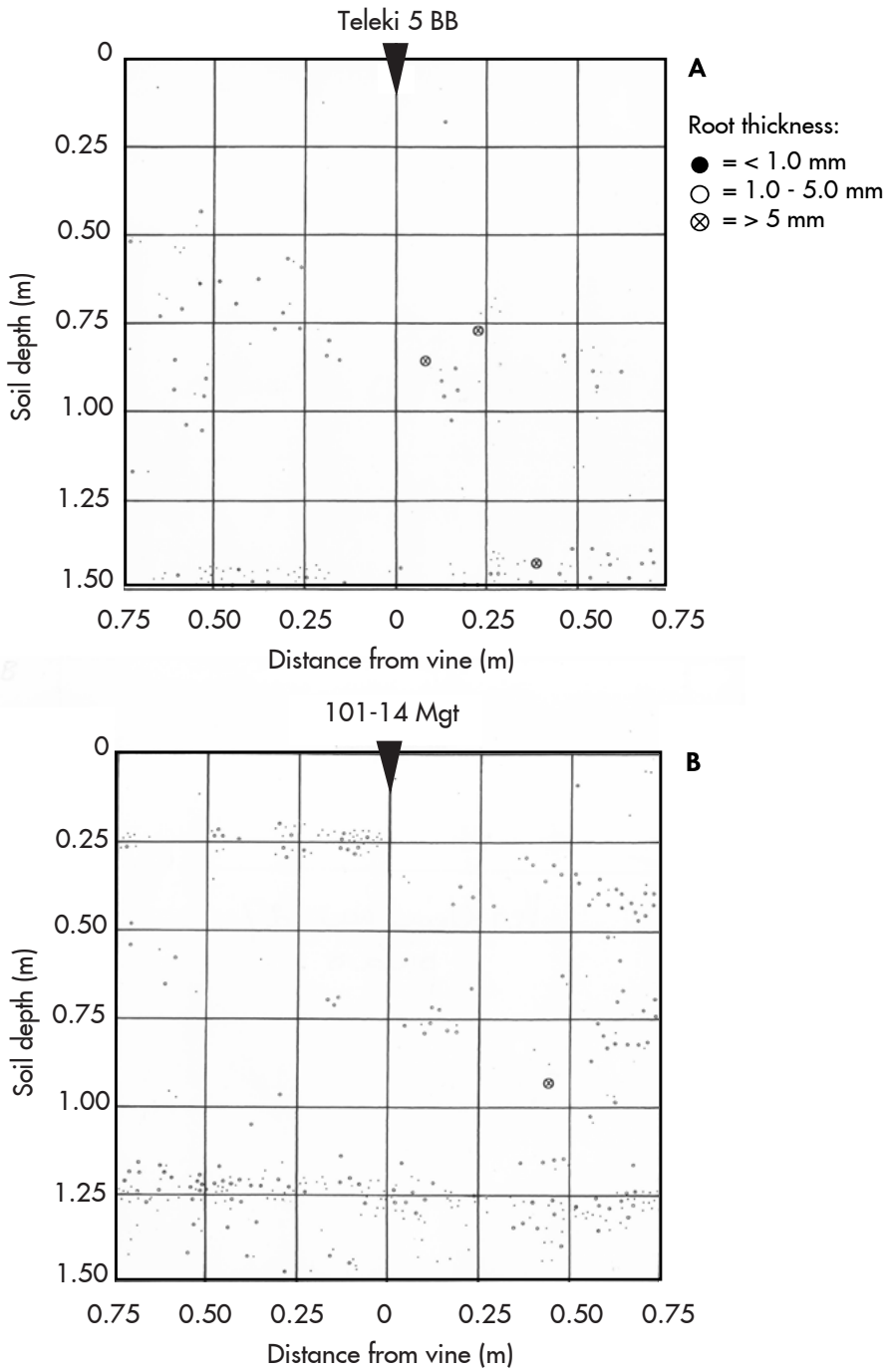


Fig. 4.3.4 A+B Root distribution of Chenin blanc, grafted on Teleki 5BB (A), 101-14 Mgt (B) in a sandy Hutton soil form, Lutzville. Grid size: 20 cm x 20 cm. (Southey & Archer, 1988)

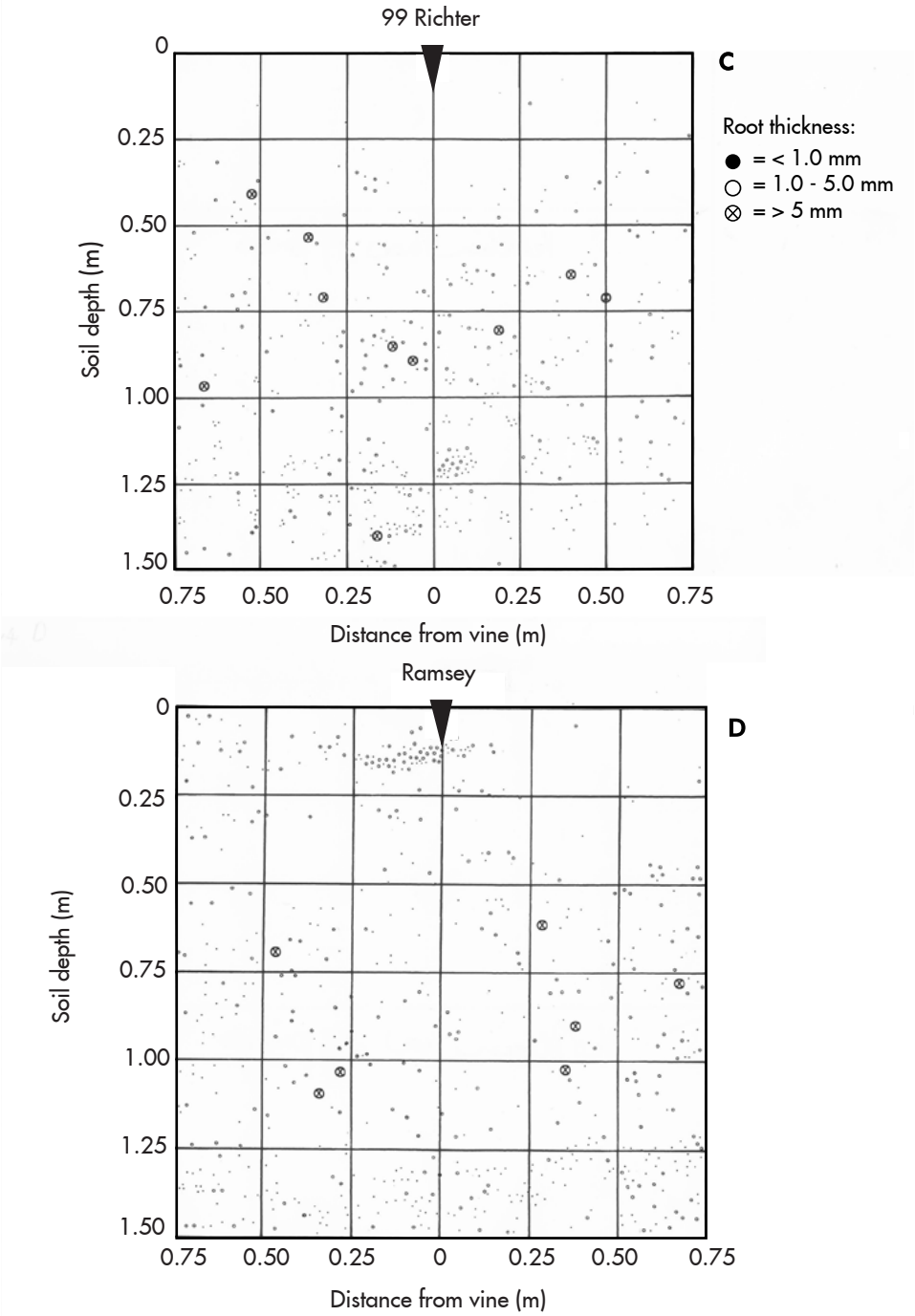


Fig. 4.3.4 C+D Root distribution of Chenin blanc, grafted on 99 Richter (C) and Ramsey (D) in a sandy Hutton soil form, Lutzville. Grid size: 20 cm x 20 cm. (Southey & Archer, 1988)

In a study on Chenin blanc grafted on six different rootstocks and grown in a Clovelly soil form (McVicar *et al*., 1977) in the Stellenbosch area under dryland conditions, Southey and Archer (1988) also found large differences in depth distribution of roots and root density (Fig. 4.3.5). The soil was characterised by a massive (structureless) subsoil at about 1 m depth, that affected the depth distribution of roots of all rootstocks. Nevertheless, the roots of 140 Ruggeri, 110 Richter and 1103 Paulsen could succeed in penetrating this soil layer through cracks (Fig. 4.3.5), whereas the roots of 101-14 Mgt and USVIT 16-13-23 could not. These observations are in accordance with that of Saayman and Van Huyssteen (1981), who found that the subsoil layers of this soil type is not conducive to depth penetration of grapevine roots, due to soil density and acidity. The high root density and good depth distribution of 140 Ruggeri, and to a lesser extent that of 110 Richter and 1103 Paulsen, explained why these rootstocks are widely regarded as drought resistant.

Under intensive irrigation, Swanepoel and Southey (1989) found that the roots of 13/5 Berlandieri, 101-14 Mgt and 1103 Paulsen colonised dark, humid silt soils much better than those of 140 Ruggeri and US 12-6-8. They ascribed this to weaker wetness tolerance of the latter two rootstocks. These researchers found that root density, root index (Van Zyl, 1984) and number of fine roots (≤ 2 mm diameter) contributed significantly to yield ($p \leq 0.05$; $r^2 = 0.91$). The larger number of fine roots per m^2 profile wall that were found for 13/5 Berlandieri, 101-14 Mgt and 1103 Paulsen, induced better shoot growth and yield (Table 4.3.1).

Table 4.3.1 Root distribution and vine performance for different rootstocks on a dark, silt soil (adapted from Swanepoel & Southey, 1989)

Rootstock	Number of roots/m²	*Root index	Number of fine roots (< 2 mm)	Vine performance (kg/vine)	
				Cane mass	Yield
13/5 Berlandieri	2069	39.6	1792	3.6	18.2
101-14 Mgt	1604	27.1	1210	2.6	13.8
775 Paulsen	1006	44.7	839	2.3	17.0
1103 Paulsen	2660	41.9	2199	2.1	21.1
99 Richter	1138	28.9	833	1.6	13.1
110 Richter	1468	29.9	1103	2.7	14.9
140 Ruggeri	635	20.2	483	0.7	10.0
US 12-6-8	813	38.7	695	0.4	4.4
US 16-13-26	1062	18.3	760	1.4	14.4

*Number of roots < 2 mm ÷ Number of roots ≥ 2 mm

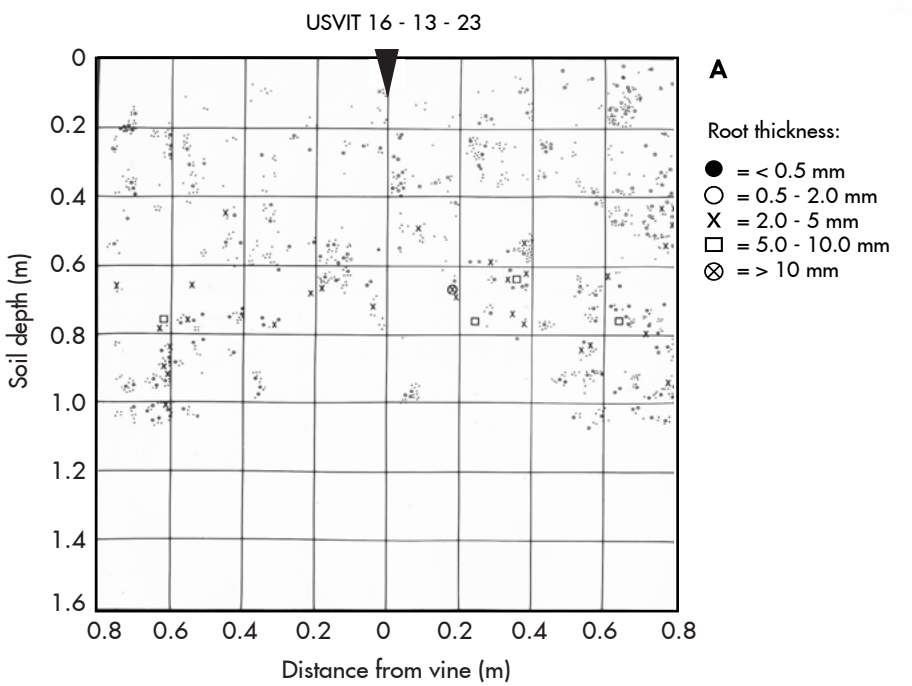


Fig. 4.3.5 A Root distribution of USVIT 16-13-23 (A), grafted with Chenin blanc and grown in a Clovelly soil, Stellenbosch. Grid size: 20 cm x 20 cm.

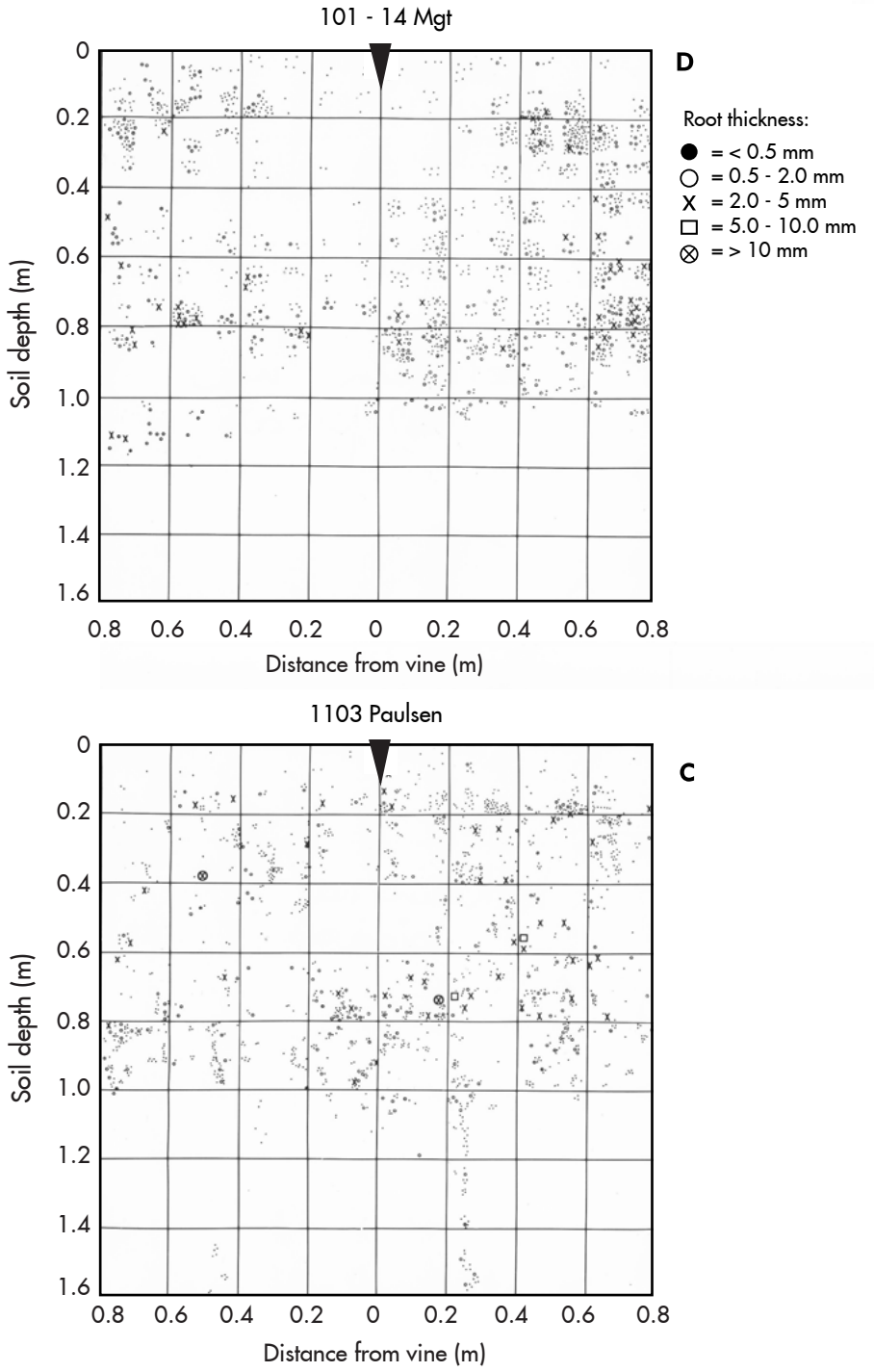


Fig. 4.3.5 B+C Root distribution of 101-14 Mgt (B) and 1103 Paulsen (C), grafted with Chenin blanc and grown in a Clovelly soil, Stellenbosch. Grid size: 20 cm x 20 cm.

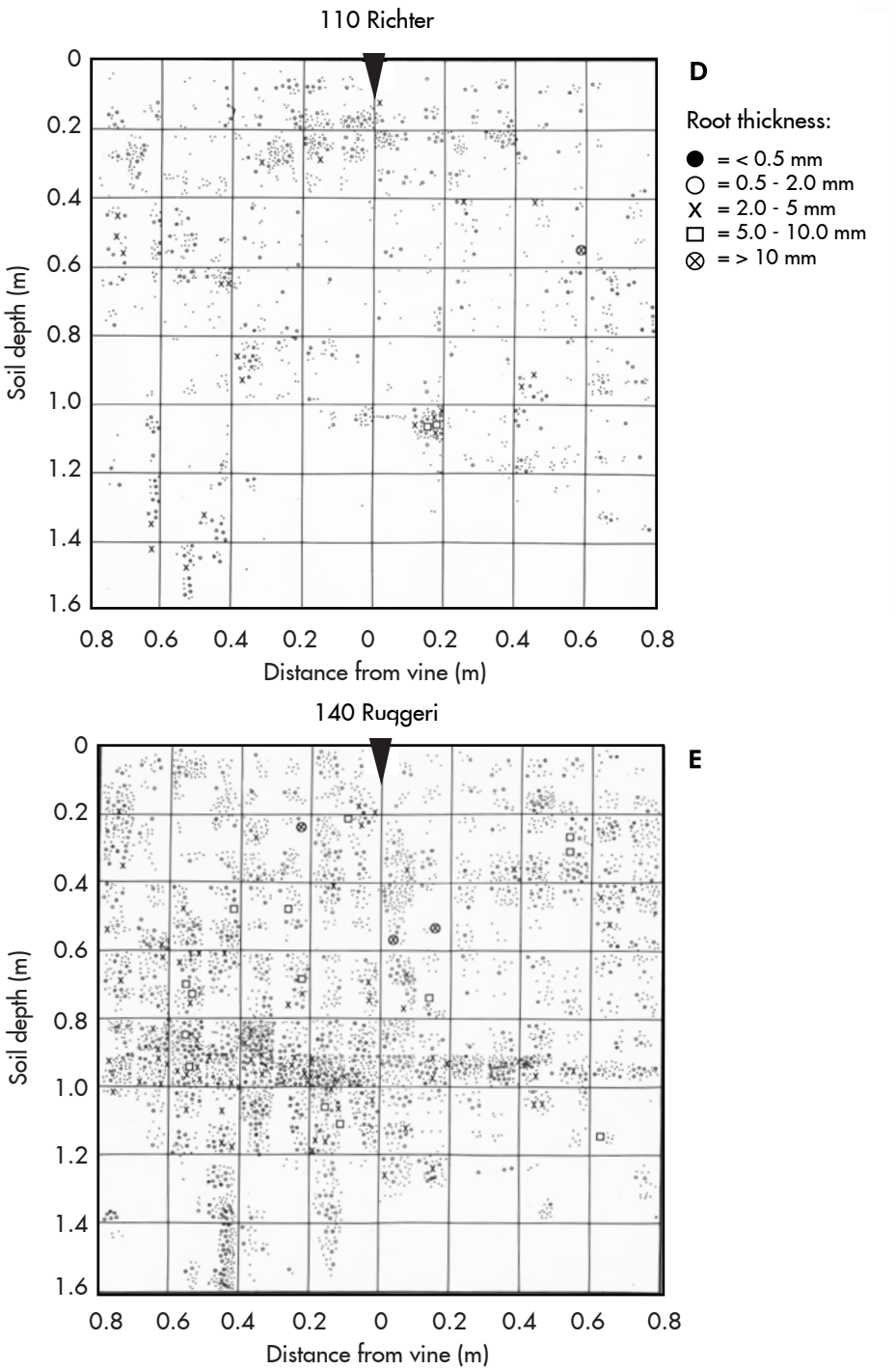


Fig. 4.3.5 D+E Root distribution of 110 Richter (D) and 140 Ruggeri (E), grafted with Chenin blanc and grown in a Clovelly soil, Stellenbosch. Grid size: 20 cm x 20 cm.

In contrast to the above, Penkov and Spirov (11964) found with four rootstocks and 10 graft combinations that the genetic nature of the rootstock was totally overshadowed by soil properties as far as depth penetration was concerned. Unfortunately, differences in root densities were not reported. Southey (1992) also found that the size and position of the zone of maximum root density were more dependent on soil properties, in this case salinity in the subsoil, than on rootstock cultivar. Shallower root development was promoted when vertical growth was physically or chemically restricted. Root density differed largely between rootstocks, with 216/3 Castel, 1103 Paulsen and 99 Richter having the most dense root systems. A good correlation was found between root density and above-ground growth.

Rootstock cultivars, with their different root growth properties, have a large effect on vine performance, depending on the soil type on which it was planted. The adaptibility of Ramsey on irrigated sandy soil is clearly illustrated in Table 4.3.2, whereas other rootstocks, such as De Waal, Rupestris du Lot, 3306 Couderc, 143-B Mgt and Jacquez, did not perform as well. On more fertile silt soil, all rootstocks, except Jacquez, yielded better (Table 4.3.3). There were significant differences for both growth and yield between different clones of 99 Richter (Table 4.3.4). These data illustrate that rootstock cultivar, as well as clone, exerts significant effects on the performance of the scion. This is most probably driven by differences in root distribution patterns.

Table 4.3.2 Growth and yield performance of Chenin blanc, grafted on nine rootstock cultivars, over a 10-year period, on red sandy soil, Lutzville. (Zeeman, 1985. Unpublished final report)

Rootstock	Cane mass (t/ha)	Crop mass (t/ha)
Ramsey	4.22	27.21
99 Richter	3.11	25.93
110 Richter	2.72	25.77
101-14 Mgt	2.61	24.51
De Waal	3.03	23.71
Rupestris du Lot	3.22	21.84
3306 Couderc	1.83	18.29
143-B Mgt	2.30	17.53
Jacquez	1.92	16.44
LSD ($p \leq 0.05$)	0.97	3.71

Table 4.3.3 Growth and yield performance of Chenin blanc grafted on ten rootstock cultivars over a 10-year period, on a silt soil, Vredendal (Zeeman, 1985. Unpublished final report)

Rootstock	Cane mass (t/ha)	Crop mass (t/ha)
99 Richter	3.87	42.36
Ramsey	3.46	40.81
Metallica	3.21	40.77
143-B Mgt	4.02	40.38
101-14 Mgt	3.16	39.26
110 Richter	2.80	36.50
Rupestris du Lot	3.39	36.49
3306 Couderc	3.01	34.47
333 E.M.	2.82	34.21
Jacquez	1.48	17.39
LSD ($p \leq 0.05$)	1.19	4.12

Table 4.3.4 Growth and yield performance of Chenin blanc grafted on ten rootstock cultivars over a 10-year period, on a Dundee soil, Montagu (Zeeman, 1985. Unpublished final report)

Rootstock	Cane mass (t/ha)	Crop mass (t/ha)
99 Richter (RY 13)	2,50	28,41
Metallica	2,68	27,71
Dog Ridge	2,72	26,28
Ramsey	2,66	25,21
101-14 Mgt (NIWW)	1,93	25,10
110 Richter	2,26	23,62
143-B Mgt	3,22	23,29
101-14 Mgt (KWV)	2,38	22,68
3306 Couderc	2,00	22,41
Rupestris du Lot	2,47	21,08
99 Richter (NIWW)	1,66	20,21
Jacquez	2,04	20,18
99 Richter (2/2/10)	1,49	17,99
99 Richter (RY 30)	1,55	17,20
De Waal	1,84	16,54
LSD ($p \leq 0,05$)	0,44	3,36

Harmon and Snyder (1934) worked with 25 scion/rootstock combinations (about 25 years old) on a San Joaquin sandy loam soil and found clear differences in root distribution between rootstocks. Regardless of scion, the roots of Australis, Ramsey and Riparia Grand Glabre rootstocks were relatively shallow, with most roots in the first 60 cm soil depth. The rootstocks 420-A Mgt, Constantia, 3309 Couderc and Rupestris St. George were generally deep rooted through the first 90 cm soil depth, with some roots penetrating into the 120 cm soil layer. As a whole it appeared that Dog Ridge had the deepest roots. Root mass varied for both the rootstock and vigour of the scion, while tendencies concerning depth of rooting were probably determined by the rootstock cultivar. For the same rootstock, root mass was generally highest for the more vigorous scions, whereas for the same scion, root population varied much between rootstock cultivars, both with regards to depth of distribution and total mass. In a 20-year-old vineyard with three rootstocks, Morano and Kliewer (1994) found that the roots of Rupestris St. George colonised a gravelly soil deeper and more densely than was the case with 110 Richter and Aramon Rupestris Ganzin 1. These differences were also reflected in the above-ground performance.

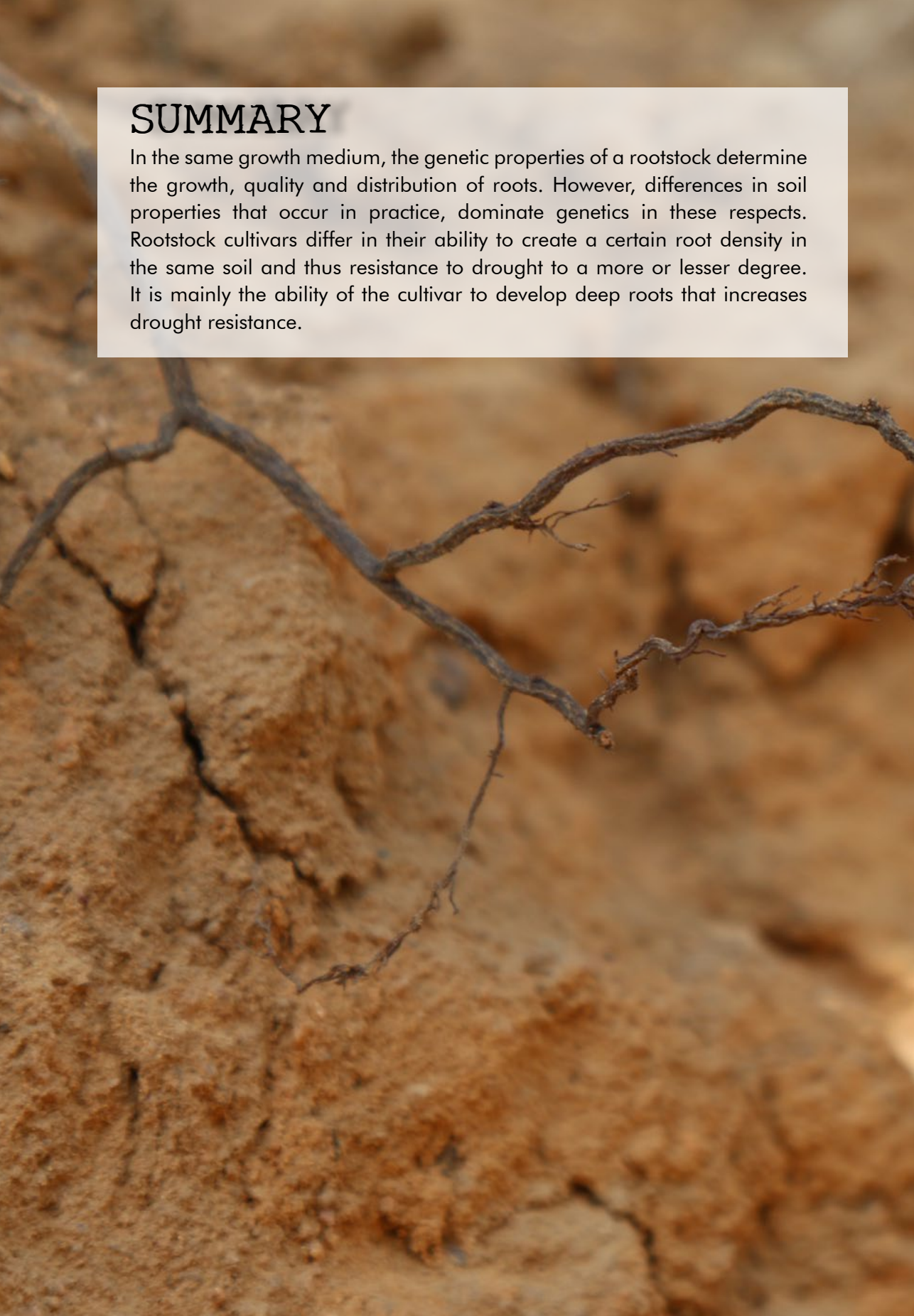
Drought resistance is linked to certain root properties (Branas & Vergnes, 1957). Rootstocks with little shallow and/or deeper penetrating roots have a better chance to resist dry conditions, but those with more small and thin roots are more exposed to drought. It must be accepted that there are also differences between rootstocks concerning the ability of roots to take up water at high tensions. Concerning wetness resistance, it may be that shallow rooted rootstocks are more resistant, but deep roots are probably more adapted to wet conditions in the subsoil, hence the possibility that it is deep rooted rootstocks that are better adapted and that the roots of less resistant rootstocks are shallow in order to escape wet subsoil conditions. The more wetness resistant 3306 Couderc and 1616 Couderc rootstocks for example have a larger portion deep roots than the wetness sensitive 3309 Couderc, 110 Richter and Rupestris du Lot.

The root systems of rootstocks differ in their ability to take up nutrients (Branas & Vergnes, 1957; Kidman *et al.*, 2014), which must be taken into account in attempts to determine a direct relationship between root system and above-ground growth. The classification of rootstocks by Branas and Vergnes (1957) according to the nature of their root systems, is shown in Table 4.3.5.

Table 4.3.5 Classification of rootstocks according to total, shallow and deep root masses, with Rupestris du Lot as reference cultivar (++), whereas for the other cultivars, (+) indicates less and (+++) more roots (Branas & Vergnes, 1957)

ROOTSTOCK	Root mass category		
	Total roots (0-125 cm)	Surface roots (0-25 cm)	Deep roots (45-125 cm)
Riparia Gloire de Montpellier	+	++	+++
Rupestris du Lot	++	++	++
3309 C	+	+	++
3306 C	+	+	+++
Riparia Rup. Massannes	+	+++	+
161 - 49 C	+	+	+
420 A Mgt	+++	+++	+
5 BB	+	++	+
SO 4	++	+++	+
99 R	+++	+	++
110 R	+++	+++	+
41 B Mgt	+++	+++	++
333 EM	+++	+++	++
1616 C	+	+	+++
216 - 3 C	+	+	+
G 1	+++	++	++
106 - 8 MG	+	+++	+
44 - 53 M	+	++	+++
196 - 17 C	+	++	++

Bauerle *et al.* (2008) found that the roots of vigorous vines are more flexible in the utilisation of water during summer without irrigation, with thinner roots in the surface 0 - 20 cm soil layers, but thicker roots in the deeper (> 60 cm) soil layers, whereas root thickness of low vigour rootstocks did not differ between soil layers. Low vigour vines produced a larger portion of roots during winter months, with increasing root density over the 3-year study period, whereas high vigour vines produced roots mainly during summer. High vigour vines have more flexibility regarding lateral soil water content, but have similar drought resistance than low vigour vines, as indicated by root survival.



SUMMARY

In the same growth medium, the genetic properties of a rootstock determine the growth, quality and distribution of roots. However, differences in soil properties that occur in practice, dominate genetics in these respects. Rootstock cultivars differ in their ability to create a certain root density in the same soil and thus resistance to drought to a more or lesser degree. It is mainly the ability of the cultivar to develop deep roots that increases drought resistance.

4.4 Planting width

Plant density affects the size, density and distribution of vine roots througout the soil profile (Hidalgo, 1968; Kubečka, 1968; Archer & Strauss, 1985; Archer, 1991; 1991/2; Hunter, 1998a; 1998b; Archer, 2000). With increasing plant density, root mass per vine decreased, but root density in kg and/or number of roots per m^2 profile wall increased. Branas and Vergnes (1957) found that with increasing plant density, root mass per m^2 increased, together with vigour, yield and shoot mass. However, shallow roots (25 - 45 cm) decreased, whereas deeper roots (65+ cm) increased, due to increased competition in the most densely populated 25 - 45 cm soil layer. This pointed to better utilisation of the soil volume, coupled to increased above-ground vigour per soil surface unit.

Hidalgo (1968) also found for Tempranillo/99 Richter, that root mass per vine was inversely correlated to plant density (1.85 - 4.2 kg/vine), but that root density was directly correlated (0.82 - 0.47 kg/m^2). He found a curvilinear relationship of: Root mass = 5.98 - 2.06(Plant density) + 0.25(Plant density)^2, and a direct relationship of Root density (kg/m^2) = 0.34 + 0.11(Plant density), with r = 0.70 (Fig. 4.4.1).

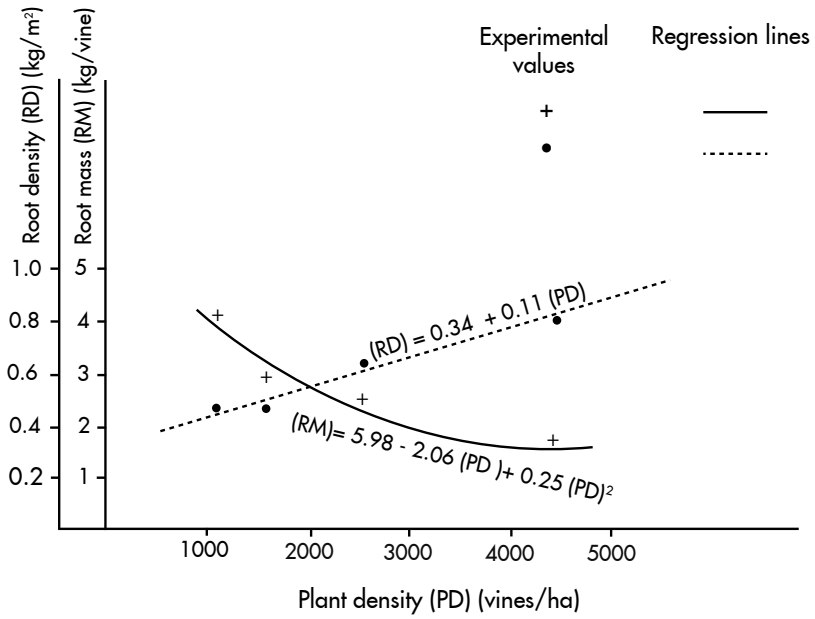


Fig. 4.4.1 Relationship between root system and plant density. (Redrawn from Hidalgo, 1968)

In order to identify poor utilisation of soil, the relationship between root density and vegetative vigour potential (VP) per square meter surface must be taken into account. For this, there was a relationship of: Vigour per m^2 (VP)= -25.47 + 82.31(Root density), with r = 0.76 (Hidalgo, 1968; Fig 4.4.2).

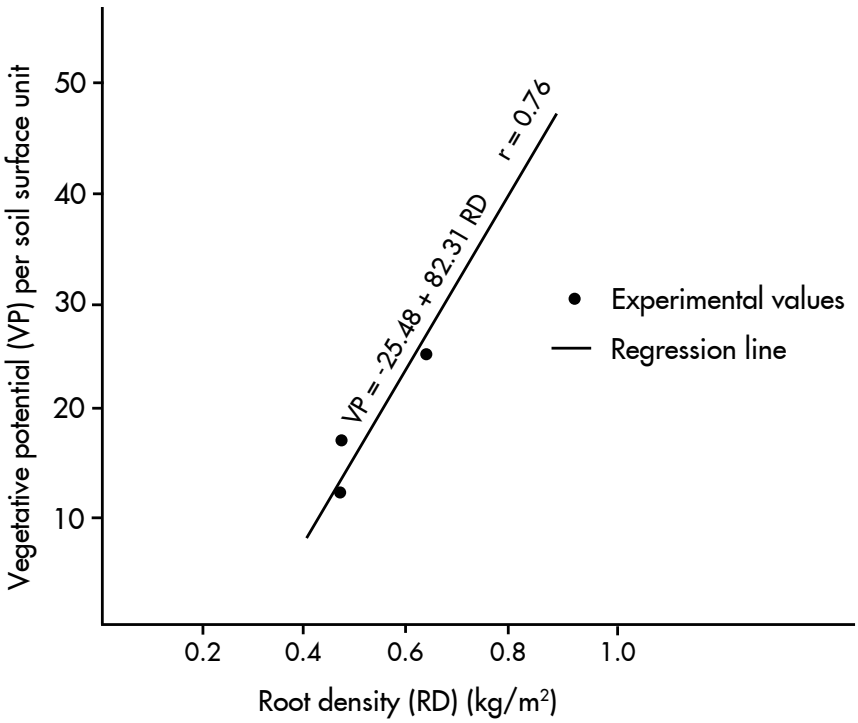


Fig. 4.4.2 Relationship between root density (RD) and vegetative potential (vigour or shoot mass, VP) per surface unit. (Redrawn from Hidalgo, 1968)

The effect of plant density on the development and yield of the vine is determined by the fertility of the environment. With increasing plant density, the root system of the vine diminished, but this is largely compensated for by the larger number of vines per surface unit and thus greater total root density. The utilisation of soil in vineyards is related to vigour, which increases with increased root density. Narrow spacing is seemingly advantageous, but if too narrow, leads to reduced vigour, which is not always desirable. This also makes cultivation impractical, with increased total production costs, which are directly linked to number of vines per hectare (Hidalgo, 1968; Hunter, 1998b).

Kubečka (1968) also found that planting width noticeably affected the root properties of grapevines (Table 4.4.1). An increase in row width (less vines per hectare) caused an increase in fine root length, as well as in fine roots dry mass per vine. Contrarily, root density, expressed as root length, as well as dry mass per m^2 soil surface and 80 cm soil depth, decreased from the 1.3 m to the 1.7 m row width, but increased again for the 2.8 m row width. He also found a negative correlation between above- and underground plant parts. This is partly in accordance with the results of Archer (1990; 1991/92; 2000).

Table 4.4.1 The effect of row width on the root properties of 10-year-old Italian Riesling (Kubečka, 1968)

Trellis/ pruning system	Planting width (m)	Mean < 0,4 mm diameter root length/ vine (cm)	Mean fine roots dry mass/vine (g)	Total root length/ m^2 - 80 cm depth (cm)	Total roots dry mass/ m^2 - 80 cm depth (g)
Guyot (low)	1.3 x 1.1	16 272	173.50	11 696	121.3
Hedge (medium)	1.7 x 1.1	19 374	203.07	10 360	108.6
Moser (high)	2.8 x 1.1	36 646	441.66	11 897	143.4

The large inter-row distance was more advantageous as the site for the development of active roots (< 0.4 mm diameter) and had 6.7 g/m^2 of this, against the 4.16 g/m^2 of the medium inter-row distance. The narrow inter-row distance only had 2.88 g/m^2 fine roots. The largest number of small and thin roots (up to 1 mm diameter) occurred at 20 - 40 cm depth for the narrow inter-row distance and the smallest number at 60 - 80 cm soil depth. A similar relationship was found for the large inter-row distance in terms of both root length and root mass. For the medium inter-row distance, the largest number of roots was found at 40 - 60 cm and the smallest number at 60 - 80 cm soil depths.

Very vigorous, widely planted grapevines also had vigorous root systems. Most roots, expressed as mass or length, were encountered in good soil at 20 - 60 cm soil depth. Between 20 - 40 cm and 40 - 60 cm there were practically no essential differences. Adsorption of nutrients from the soil water is dependent on the surface dimensions of active roots (i.e. the root hairs),

that are mostly formed on the thin roots. Roots up to 1 mm diameter were found especially at 20 - 40 cm soil depth and were fewer in the 40 - 60 cm layer. This demands that cultural practices for the application of organic or mineral fertilisers should be at least 20 - 25 cm deep and that irrigation water should penetrate to at least 40 - 60 cm deep (Kubečka, 1968).

Archer (1990, 1991/2), under dry land and Hunter (1998a) under irrigation conditions, in the same vineyard, found an increase in fine root density throughout the soil profile up to 1.2 m soil depth for six different planting widths. Under dry land, there was no significant differences between plant densities for total number of roots per vine (Archer, 1991/2), but with irrigation, Hunter (1998a) found that the number of roots for the narrowest spacing (1.0 x 0.5 m) was more than 50% less than that of the widest spacing (3.0 x 3.0 m). This was in accordance with the root mass per vine. Under dry land, the root density (number of roots per m^2 profile wall) of the narrowest spacing was more than 4.4 times that of of the widest spacing (Archer, 1990), whilst it was 2.3 times more with irrigation (Hunter, 1998a). For dry land, the root index (< 2 mm diameter ÷ > 02 mm diameter), as indication of root system quality, was 85 for the narrowest and 30 for the widest spacing (Archer, 1990), whereas this was 17 for both these spacings under irrigation (Hunter, 1998a). For dry land, the cane mass per vine was 7.2 times lower for the narrowest spacing, compared to the widest spacing, but the cane mass per ha was 2.4 times higher (Archer, 1991/2). The same tendency was found for irrigated vines (Hunter1998a).

According to Branas and Vergnes (1957), the susceptibility of the grapevine to water stress increases with increasing plant density because of increasing canopy mass per m^2 soil surface and root competition, but also because there is a larger proportion of roots in the upper soil layers, which dry out first and which cannot be compensated for by the larger portion of roots in the deeper soil layers. Horizontal root distribution diminished towards the mid-row at narrow (1 m) planting distance, but not the vertical distribution. Homogeneity of horizontal root distribution increased with increasing inter-row distance and the ratio of root mass in the mid-row to root mass next to the vine row, will probably approach a value of 1 as inter-row distances increase.

Hidalgo (1968) found that, even in deep alluvial soil, where plant density was increased from 1 111 vines per ha to 4 444 vines per ha, root mass decreased correspondingly from 4.2 kg/vine to 1.8 kg/vine, but that root density, expressed as total root mass per unit soil surface, increased from 0.42 kg/m^2 to 0.82 kg/m^2 (Fig. 4.4.3).

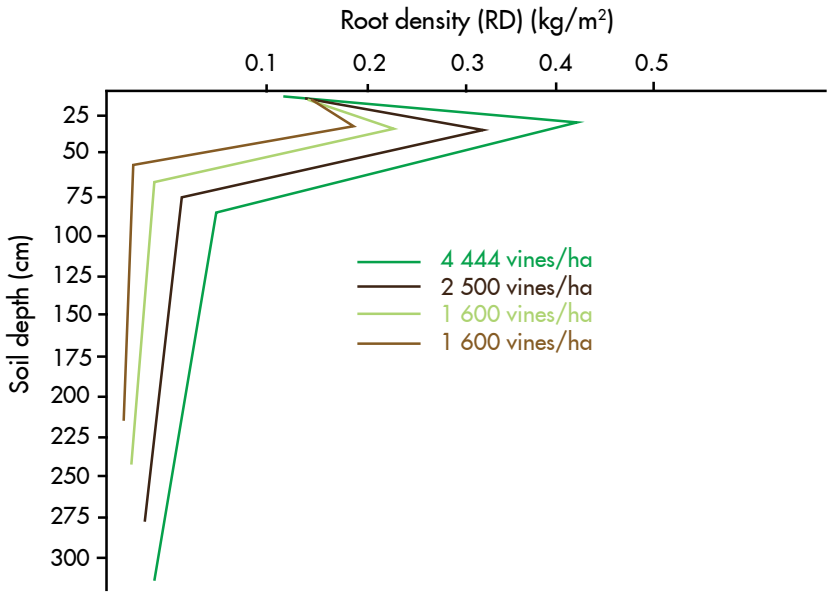


Fig. 4.4.3 The effect of planting distance on the root density of vineyards. (Redrawn from Hidalgo, 1968)

According to Parfenenko (1968), the horizontal and vertical distribution of grapevine roots is independent of planting distance between vines during the first year of development. In contrast, the results of Archer and Strauss (1985) showed that, three years after establishment, the roots of narrowly spaced vines penetated the soil at a sharper angle than that of wider spaced vines. Furthermore, Archer (1990, 1991, 1991/2) found that nine years after planting, root density, as well as depth penetration, decreased with wider vine spacing, while no thick roots (5 to > 10 mm diameter) were found for the two narrowest spacing treatments (Fig. 4.4.4, 4.4.5, 4.4.6; Table 4.4.2).

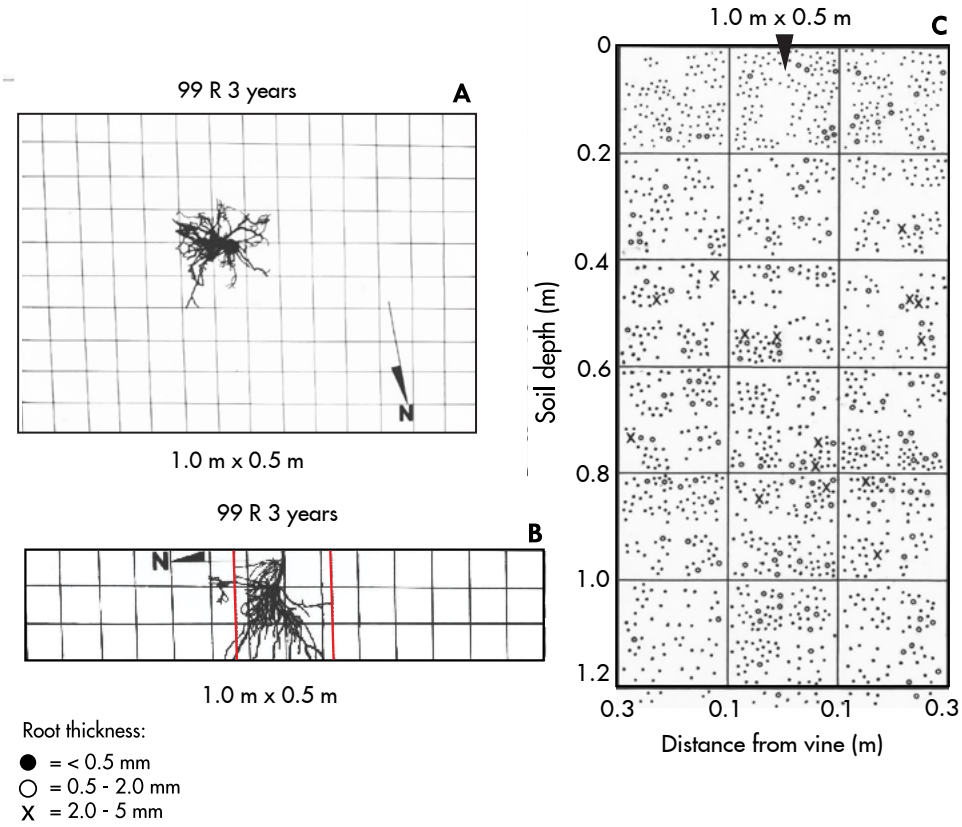


Fig. 4.4.4 The effect of 1.0 x 0.5 m planting width on the root distribution of grafted 99 Richter vines.
A: Horizontal root distribution down to 60 cm soil depth, three years after planting.
B: Vertical root distribution three years after planting. Red lines indicate theoretical space for one vine (note the sparce overlapping).
C: Profile wall study nine years after planting (note intensive colonisation of especially fine roots to more than 1.2 m depth).
Grid size for A, B & C: 20 cm x 20 cm.

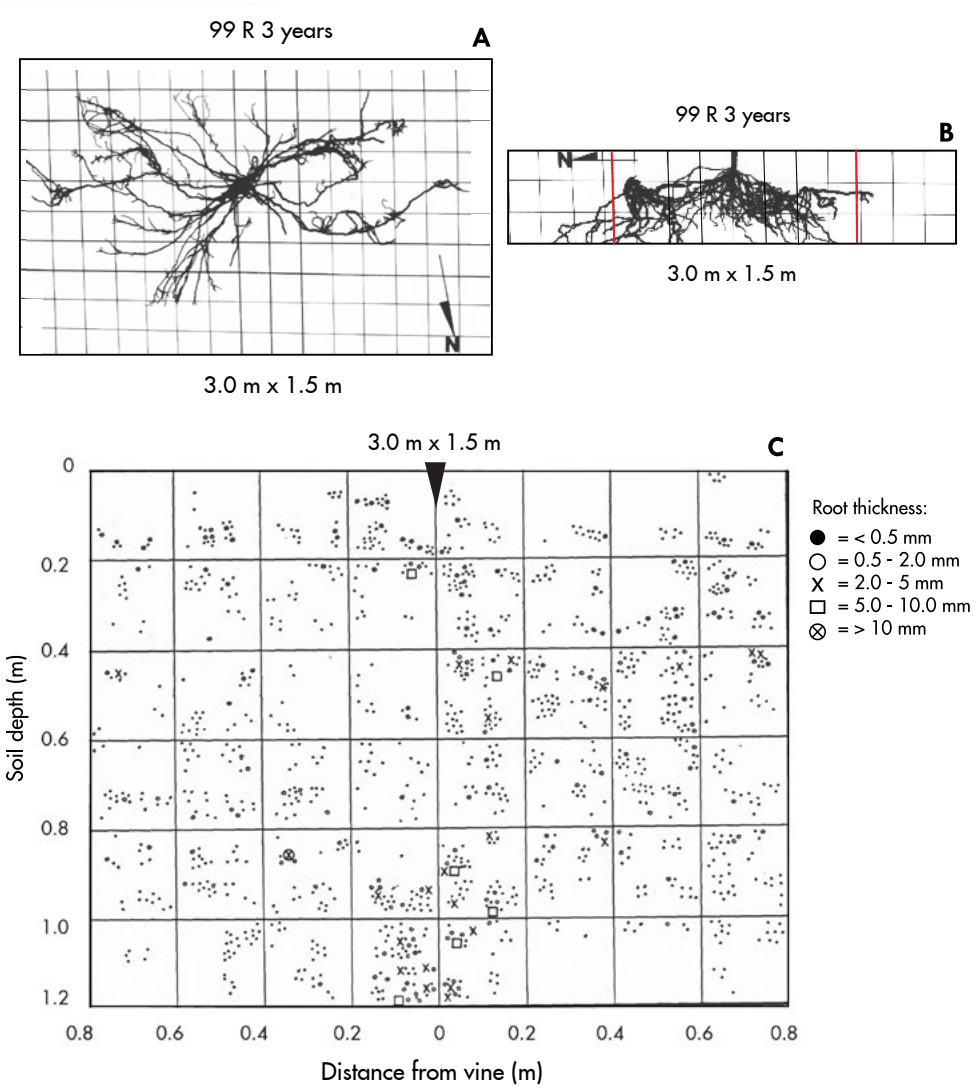


Fig. 4.4.5 The effect of 3.0 x 1.5 m planting width on the root distribution of grafted 99 Richter vines.
A: Horizontal root distribution down to 60 cm soil depth, three years after planting.
B: Vertical root distribution three years after planting. Red lines indicate theoretical space for one vine (note the relative sparce overlapping).
C: Profile wall study nine years after planting (note the less intensive colonisation of roots in the top 10 cm depth).
Grid size for A, B & C: 20 cm x 20 cm.

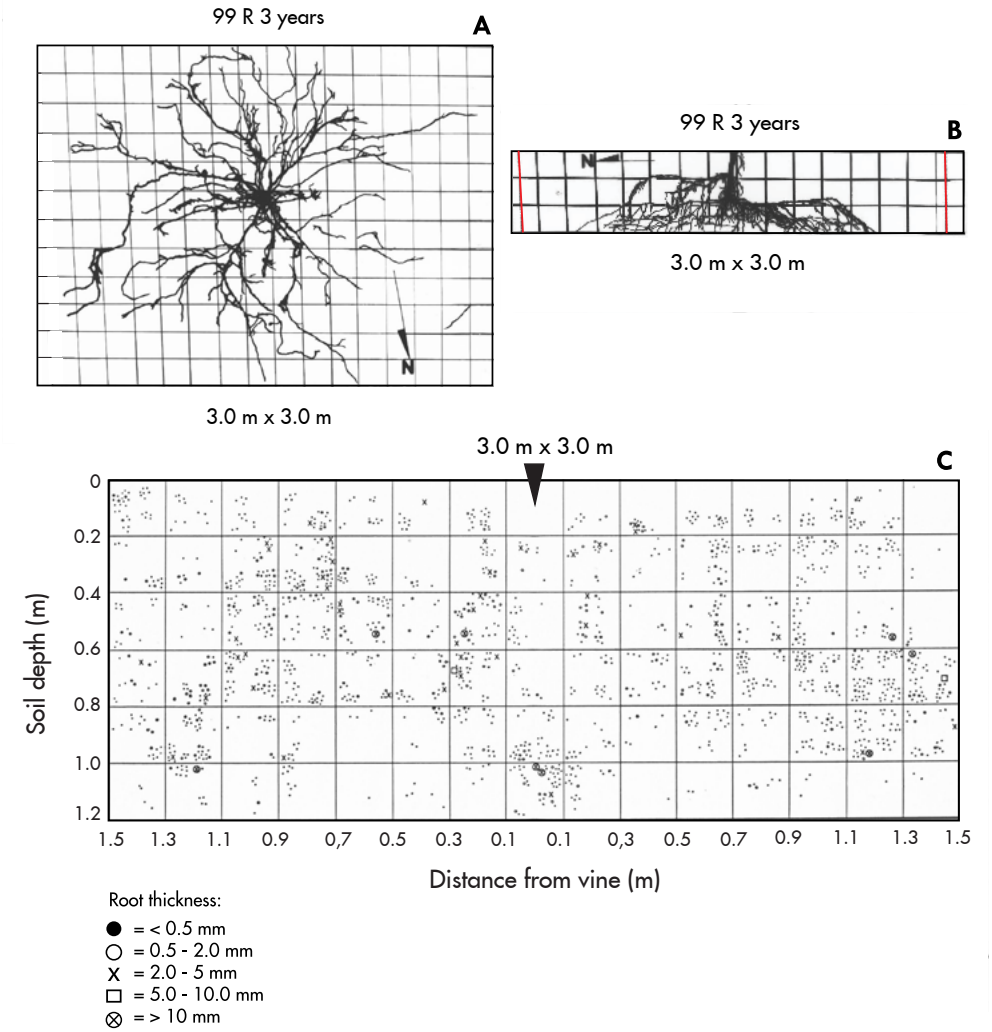


Fig. 4.4.6 The effect of 3.0 x 3.0 m planting width on the root distribution of grafted 99 Richter vines.
A: Horizontal root distribution down to 60 cm soil depth, three years after planting.
B: Vertical root distribution three years after planting. Red lines indicate theoretical space for one vine (note the no overlapping).
C: Profile wall study nine years after planting (note the less intensive colonisation of roots in the top 10 cm and the bottom 20 cm depth levels. Grid size for A, B & C: 20 cm x 20 cm.

Table 4.4.2 Effect of planting width on grapevine root distribution (%) in different soil layers (Archer, 1990)

Planting width (m)	Soil depth (cm)						
	0-20	20-40	40-60	60-80	80-100	100-120	120-140
1.0 x 0.5	21	13	14	18	18	14	2
1.0 x 1.0	22	15	19	21	13	9	1
2.0 x 1.0	26	23	17	12	15	7	0
2.0 x 2.0	16	24	26	21	10	3	0
3.0 x 1.5	12	17	19	18	20	14	0
3.0 x 3.0	12	17	18	28	18	7	0

About 23% of the roots of narrowly spaced vines occurred in the upper 20 cm soil layer, whereas it was only 12% in the case of wider spaced vines (Table 4.4.2). This was ascribed to the more complete ground shadow of the narrowly spaced vines that probably caused more even soil temperatures in the upper soil layer (Archer, 1990).

The more intensive root colonisation obtained with narrow vine spacing caused a more intensive soil water useage from beginning to end of the growing season (Fig. 4.4.7). This finding is in accordance with the observations of Branas (1974) and Champagnol (1979), who thought that this was possibly also true for nutrients. There can, therefore, be cases of too early depletion of the soil water content by narrowly spaced vines, resulting in disadvantageous effects on vineyard performance, as in the case of dry land vineyards.

Although the presence of thick roots (5 to > 10 mm diameter) is enhanced by wider planting widths, the percentage of thin roots is remarkably constant over planting widths (Table 4.4.3). However, it is evident that root density is enhanced by narrower planting widths.

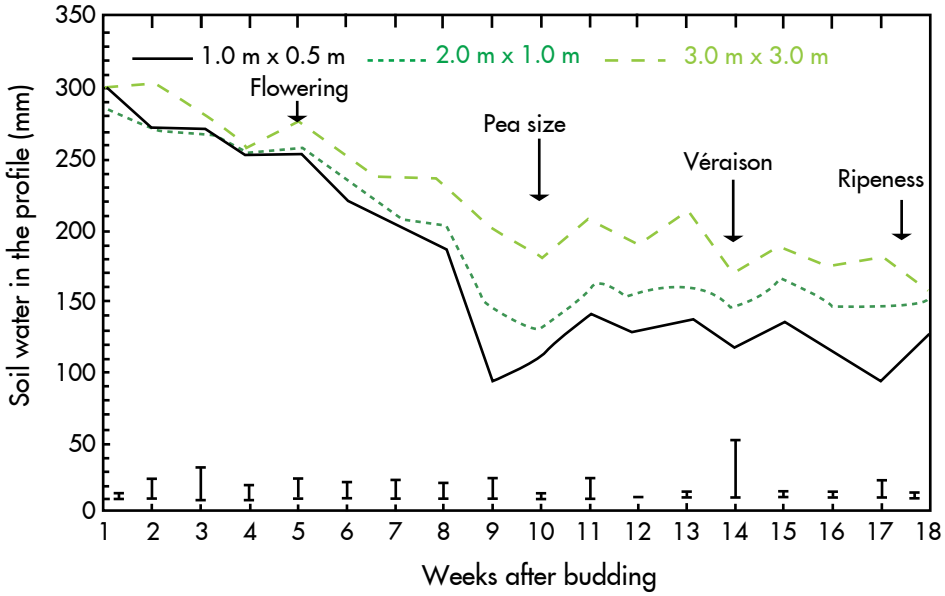
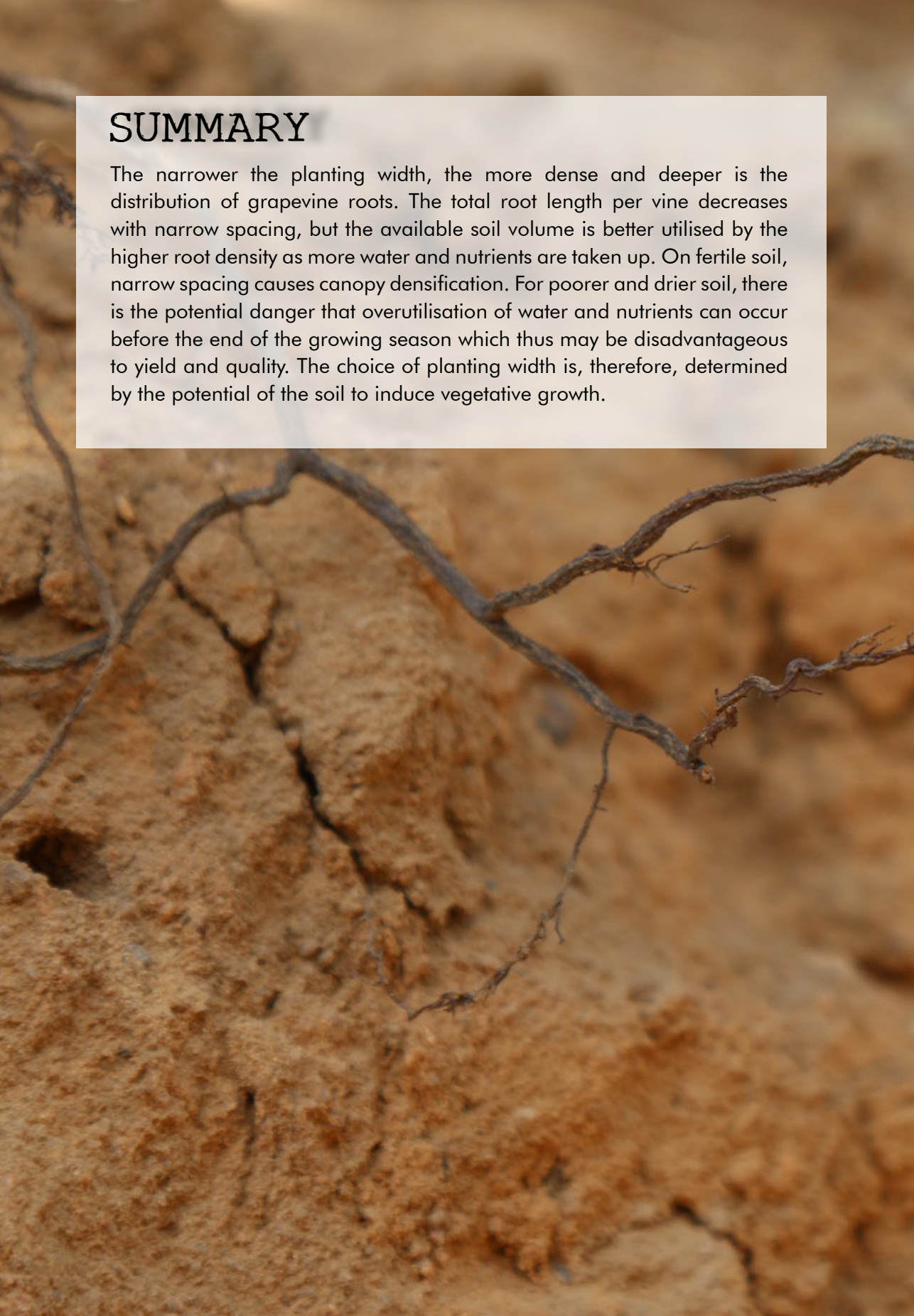


Fig. 4.4.7 The effect of the more intensive root colonisation of narrow planting widths on soil water usage during the growing season. Vertical bars = LSD ($p \leq 0.05$). (Archer, 1990)

Table 4.4.3 The effect of planting width on the distribution of fine and thick roots (number per m^2 profile wall). (Archer, 1990)

Root diameter (mm)	Plantng width (m)					
	1 x 0.5	1 x 1	2 x 1	2 x 2	3 x 1.5	3 x 3
< 2.0	2034 (98.8%)	1589 (99.4%)	893 (97.2%)	367 (97.4%)	613 (97.5%)	452 (96.8%)
> 2.0	24 (1.2%)	9 (0.6%)	26 (2.8%)	10 (2.5%)	16 (2.5%)	15 (3.2%)

In Romania, Matuzoc (1977) also found that roots of narrowly spaced vines utilised the soil volume concerned more completely than wider spaced vines and that they also penetrated deeper and consequently could utilise water reserves in the soil that could not be reached by the wider spaced vines. Less water evaporation was also observed at narrow spacing, from where higher yield was obtained, without loss in quality.



SUMMARY

The narrower the planting width, the more dense and deeper is the distribution of grapevine roots. The total root length per vine decreases with narrow spacing, but the available soil volume is better utilised by the higher root density as more water and nutrients are taken up. On fertile soil, narrow spacing causes canopy densification. For poorer and drier soil, there is the potential danger that overutilisation of water and nutrients can occur before the end of the growing season which thus may be disadvantageous to yield and quality. The choice of planting width is, therefore, determined by the potential of the soil to induce vegetative growth.

4.5 Trellising system

In a study on different trellising systems on a calcareous soil with an impenetrable hardpan at 70 cm depth, Van Zyl and Van Huyssteen (1980) found that larger trellises induced denser root systems than the smaller trellises (Fig. 4.5.1 A & B). This had a direct relationship with shoot growth.

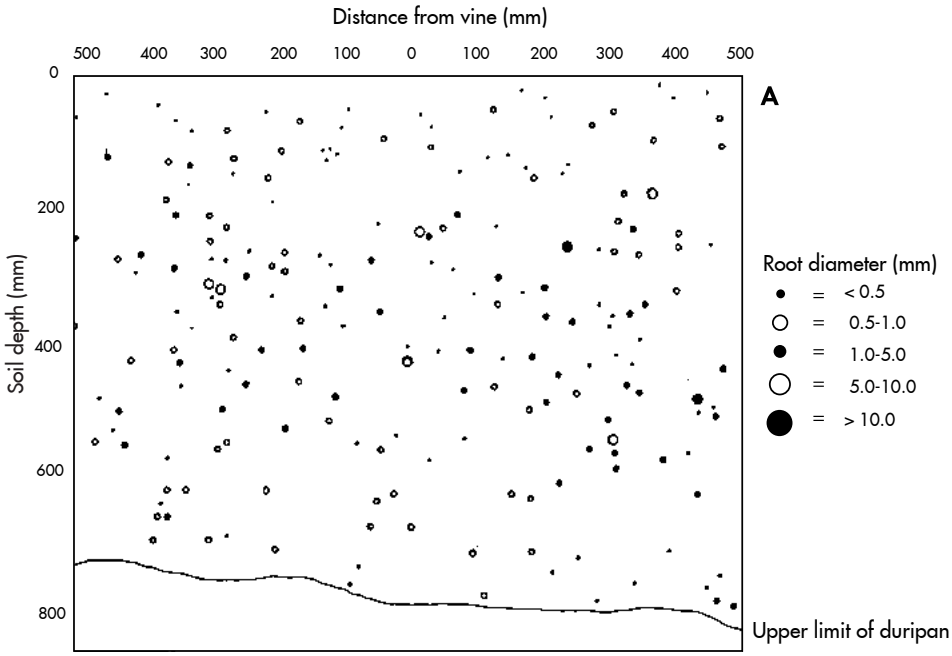


Fig. 4.5.1 A Root distribution of Chenin blanc/101-14 Mgt bush vines, on a calcareous soil, Robertson. (From: Van Zyl & Van Huyssteen, 1989)

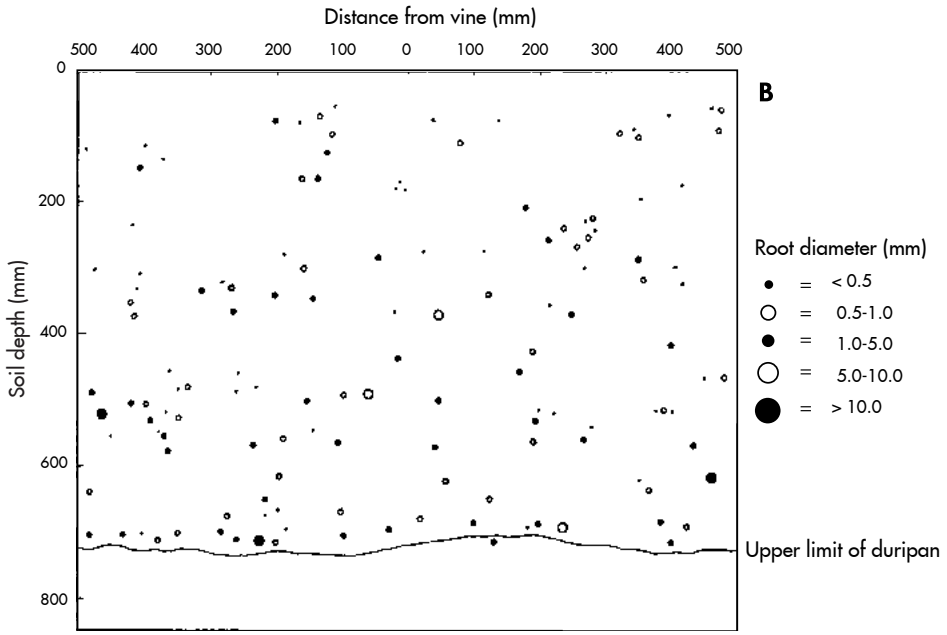


Fig. 4.5.1 B Root distribution of Chenin blanc/101-14 Mgt bush vines, trained on a slanting trellis, on a calcareous soil, Robertson (From: Van Zyl & Van Huyssteen, 1989)

Archer *et al.* (1988) also found that the intensity of root colonilisation is affected by the size of the trellising system (Fig. 4.5.2 A, B, C & D). This study was done in a 10-year-old Chenin blanc/99 Richter vineyard in the Stellenbosch area. Vine spacing was 3.0 m x. 1.5 m and experimental vines were selected accoding to trunk circumference and shoot mass, representative of the trellising treatments. Vines were pruned to the same bud load per shoot mass in order to obtain a yield:cane mass ratio of 4:1 to 5:1. Fig. 4.5.2 shows that root density, as well as depth penetration of vine roots, is enhanced by enlargement of the above-ground growth.

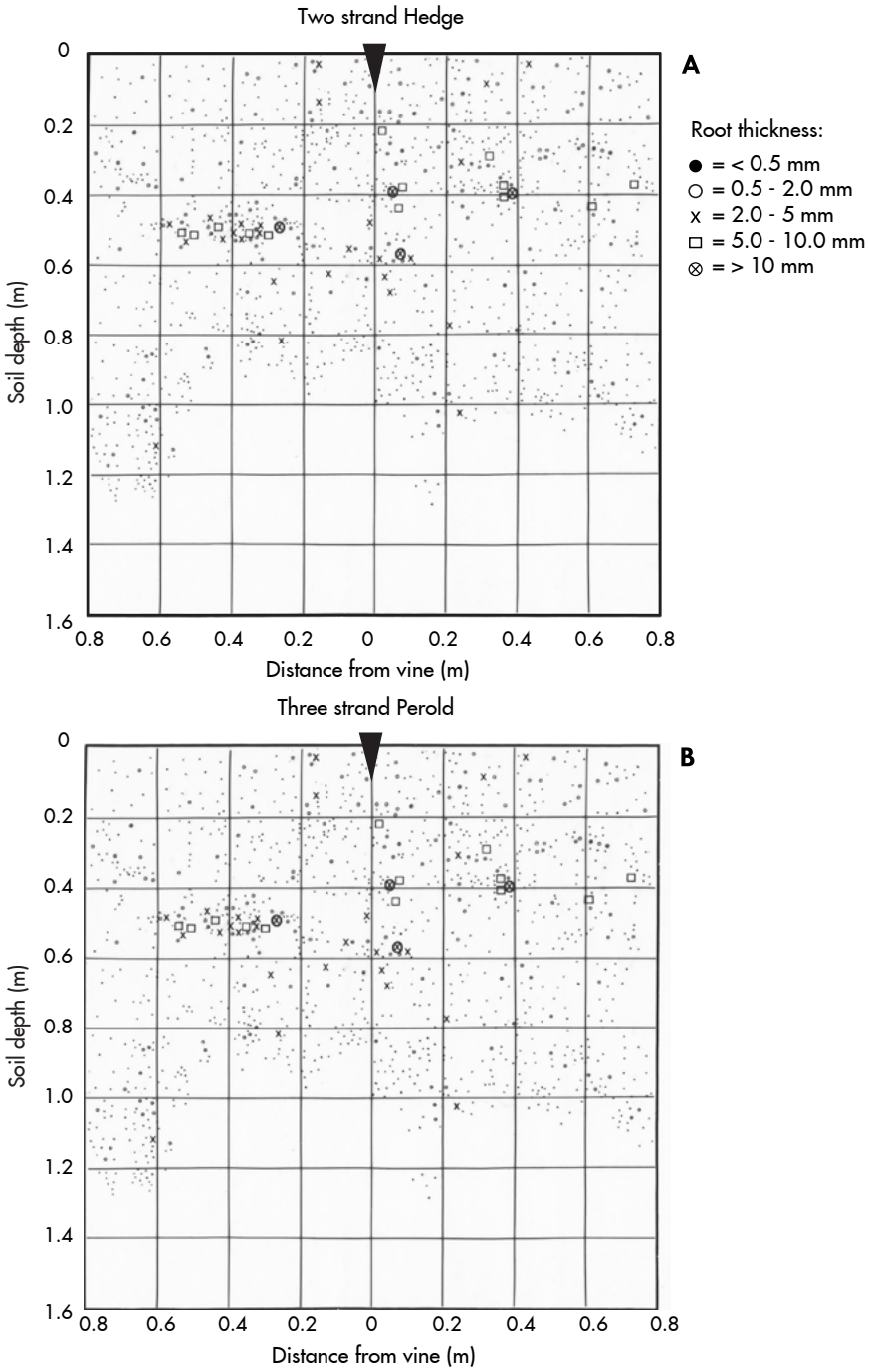


Fig. 4.5.2 A+B Effect of trellising system on the depth and intensity of root distribution of Chenin blanc/99 Richter vines on a Two Strand Hedge and Three strand Perold trellising systems at Nietvoorbij, Stellenbosch. Grid size: 20 cm x 20 cm. (Redrawn from Archer *et al.*, 1988)

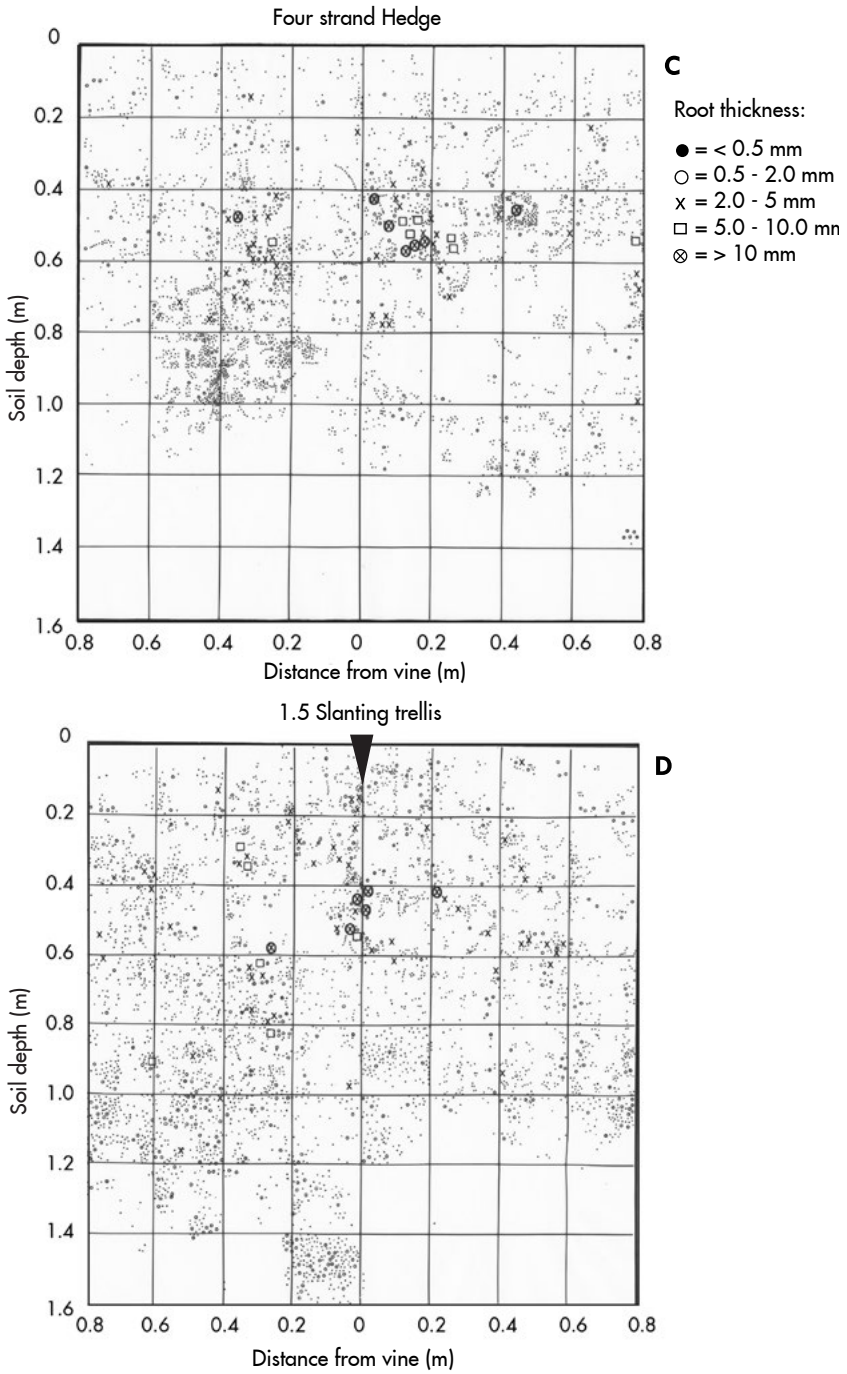


Fig. 4.5.2 C+D Effect of trellising system on the depth and intensity of root distribution of Chenin blanc/99 Richter vines on a Four strand Hedge and 1.5 Slanting trellising systems at Nietvoorbij, Stellenbosch. Grid size: 20 cm x 20 cm. (Redrawn from Archer et al., 1988)

With root studies on Chenin blanc/99 Richter vines that were converted to double the original planting distance by removing alternative vines (doubling of cordon length and soil volume per vine) and changed to a Lyre system (doubling of cordon length, but constant soil volume per vine), Hunter and Volsckenk (2001) found that, after five years, the roots of the lengthened cordon vines with double the soil volume had double the number of roots, but that root density (number of roots per m^2) was similar between treatments. Increases in shoot growth per vine due to doubling the cordon length, were constrained in the case of the Lyre system because of a static soil volume, which caused better foliage aeration.

4.6 Pruning

Under dry land conditions with two cultivars and bud loads that varied between 24, 48 and 60 buds per vine, Mirzalieva (1968) found that the best root development occurred at the medium bud load (48). Higher bud loads restricted total root length.

According to Comas *et al.* (2010), minimal pruning caused a more rapid development of foliage in spring, together with earlier initiation of root growth in the upper soil layers, probably because of more favourable temperatures therein.

Hunter *et al.* (2016) showed that increased foliage density, obtained with mechanical and minimum pruning, resulted in significant increases in number of < 0.5 mm diameter roots for Sauvignon blanc and Shiraz, grafted onto 99 Richter. Comas *et al.* (2005) found that yield and root growth of 25-year-old Concord were 26% more with minimal pruning than for the more severe hand pruning. The commencement of earlier root growth coincided with an earlier and larger above-ground growth.

4.7 Canopy management

According to Rogers (1939), A.J. Heinecke established with apple trees in 1936 that root growth was restricted by leaf removal and that R.G. Hatton and J. Amos found in 1927 that removal of lateral shoots of apple trees during summer brought root growth practically to a stop. Contrarily, random removal of 33% of leaves over the entire vine during berry set, pea size and véraison significantly increased the number of roots per m^2 profile wall over four seasons (Fig. 4.7.1, Hunter & Le Roux, 1992). It was

especially the fine roots (≤ 0.5 mm diameter) that benefited from this, which implicated better water and nutrient uptake. Together with improved foliage efficiency, it increased the quality and yield performance of the vineyard. However, there were indications that the density of thick roots (> 5 mm diameter) declined over time, especially where leaf thinning was done early (Hunter *et al.*, 1995).

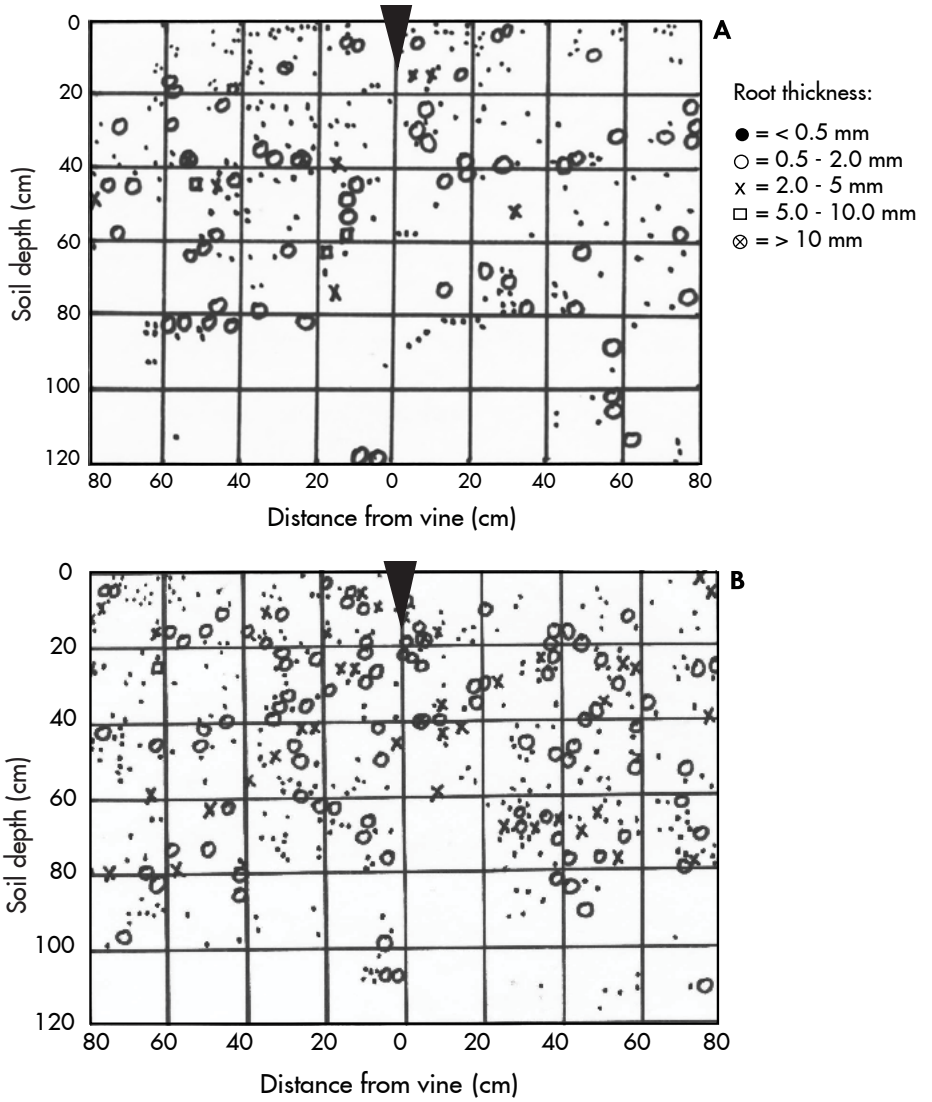
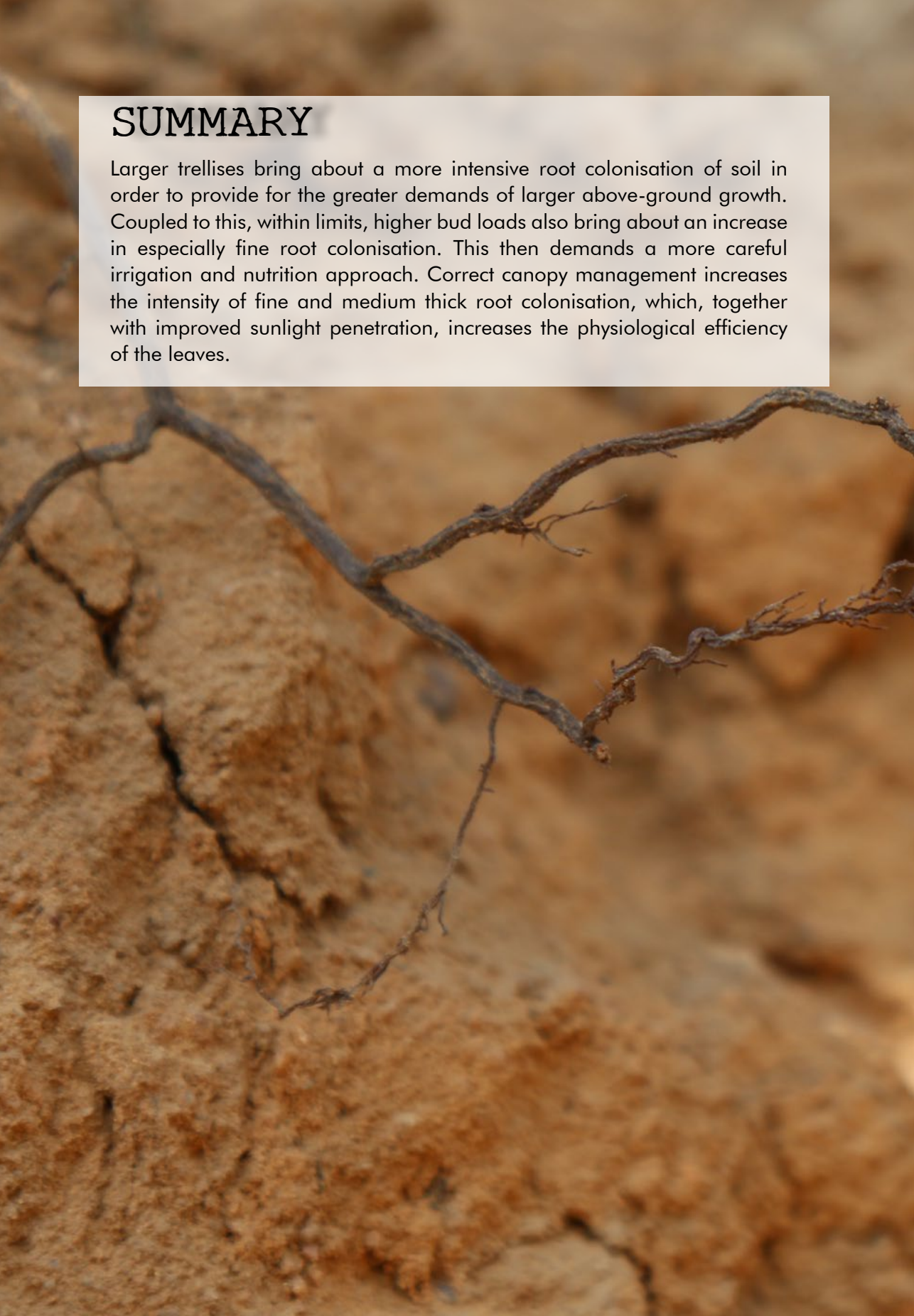


Fig. 4.7.1 Effect of leaf removal on root distribution and density of Cabernet Sauvignon/99 Richter at Nietvoorbij, Stellenbosch.
A: No leaf removal.
B: 33% random leaf removal. Grid size: 20 cm x 20 cm.
(Redrawn from Hunter & Le Roux, 1992)

Contrarily, Buttrose (1966) and Kliewer and Fuller (1973 found that leaf removal decreased total root dry mass of potted Muscat d'Alexandrie and Thompson Seedless vines. However, they did not do root distribution or root density studies and their drastic leaf removal treatments were not in agreement with practical recommendations. Therefore, their results cannot be directly compared to that of field grown grapevines.

In Chile, Corvalan *et al*. (2016) tested the effect of two types of photo selective nets, which both reduced photosynthetic radiation with 20%. Shoot length of 3-year-old potted Pinot noir vines was more under nets, but leaf surface was the same as for the control. However, dry root mass was 84% higher under pearl-coloured net and only 45% higher under red net. The mechanism involved is unknown and demands further study in that it can contribute to the potential use of photo selective nets to constrain excessive sunlight radiation in the context of climate change.



SUMMARY

Larger trellises bring about a more intensive root colonisation of soil in order to provide for the greater demands of larger above-ground growth. Coupled to this, within limits, higher bud loads also bring about an increase in especially fine root colonisation. This then demands a more careful irrigation and nutrition approach. Correct canopy management increases the intensity of fine and medium thick root colonisation, which, together with improved sunlight penetration, increases the physiological efficiency of the leaves.

4.8 Planting holes

Already in the first century A.D., Columella (±76 A.D.) recommended deep (90 cm) planting holes for grapevines, of which the bottoms must be loosened in order to ensure deep root growth, that buffers the vine and guarantees the quality of the harvest. He further recommended that about 2.3 kg stones be placed in the bottom of planting holes to aid in drainage during winter and to supply water during summer. A quantity of red grape skins must be placed in the the bottom of holes for white grape cultivars and white grape skins for red grape cultivars. Columella also recommended that the planting holes should be filled stepwise over a period of three years. According to him, this effort is worthwile in order to ensure that vine roots grow downward. Most researchers are in agreement that the depth of planting affects later root development (Deidda, 1964; Diofasi & Kirali, 1968). However, contrary to Columella, it was found that vines or trees that are planted deeper show a more horizontal root distribution in contrast to shallowly planted vines, which have a tendency towards a more vertical root distribution. This is within limits, because experience has shown that vines that are planted too shallowly, struggle to survive because of desiccation. The dimensions of planting holes in normal soils should be at least 50 x 50 x 50 cm in all directions (Columella, 76 A.D.)

In their study on planting holes, Archer and Hunter (2010) found that the method of planting affects the root growth and distribution of vines throughout the lifetime of the vineyard. They recommended that planting holes be made large enough to accommodate the roots of nursery vines (not trimmed shorter than twice the length of a pruning shear) and that the sides and bottom of each hole be perforated with forks in order for young roots to colonise the soil without being restricted from expansion by compacted or smeared sides and bottoms. Furthermore, the holes should be made in such a way so that they extend on both sides of the planting line, the vine being planted in the middle of the hole and the hole filled while gently pulling the vine upwards, or the roots evenly spread around a cone of soil made in the bottom of the hole, to ensure downward pointing roots. Poorly made planting holes restrict root growth and root colonisation (Fig. 4.8.1; 4.8.2), with the result that vines perform far beneath their ability. This often leads to a vineyard that never breaks even economically and must then be replaced prematurely. Above-ground growth is to a large extent dictated by the size and performance of the root system, therefore a small, weakly developed root system results in poor shoot growth (Fig. 4.8.3) (Archer & Hunter, 2004/5; Archer & Hunter, 2005/6).

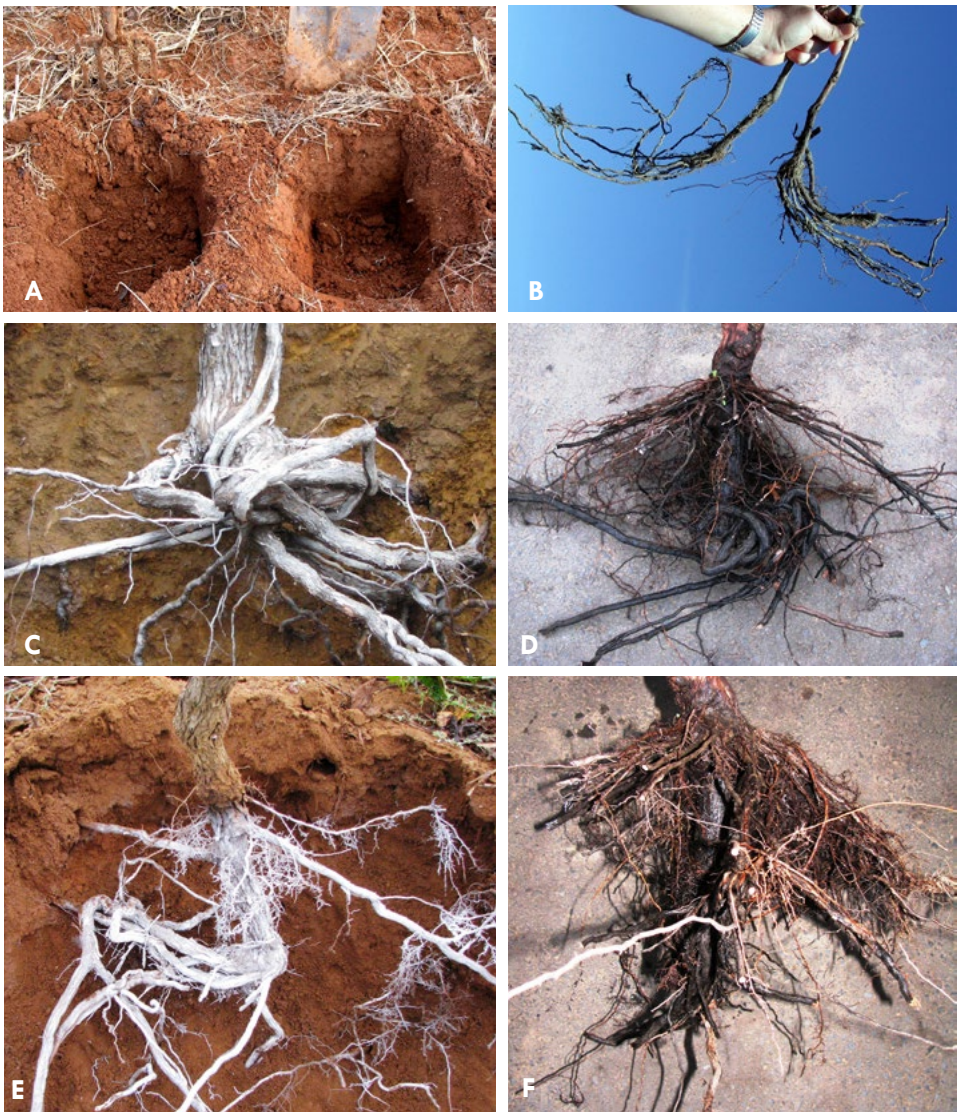


Fig. 4.8.1 Effect of planting holes on grapevine root distribution. A: Planting hole made by a fork (left) and a spade (right). Note the compacted sides caused by the spade. B: Vines one year after planting against the compacted side of a hole. Root growth was only towards one side, without deep penetration. C: Ten-year-old roots, still restricted to the bottom of the planting hole. D: Twelve-year-old roots that struggled several years to escape the compacted sides and bottom of the planting hole. Note that the original roots drowned. E: Nine-year-old roots that, even in sandy soil, struggled a long time to escape the planting hole. F: Fourteen-year-old roots in a spade-compacted planting hole in clay soil. Note the drowned original roots and the second set of roots that developed closer to the soil surface. (Picture B: VORI. Pictures A and C to F: E. Archer)

Fig. 4.8.2 Effect of planting holes on grapevine root distribution. A: Vine roots on a compacted bottom of a spade made hole. Note that roots initially grew upwards to escape. B: Eight-year-old root system in a compacted planting hole. C: Root growth five years after planting in a shallow hole with compacted sides. Note the compressed rootstock roots as well as the covered graft joint. Rootstock roots suffocated and scion roots formed. D: Root growth eight years after planting against compacted side of a hole. Note that roots still struggle to escape the hole and even grow in circles in order to stay in loose soil. E: Root growth 25 years after planting in a small, compacted hole. Note how roots first grew in circles to escape. F: Root distribution and depth growth one year after planting in a correctly made hole. Roots excavated to 60 cm depth. (Picture A: VORI. Pictures B to F: E. Archer)

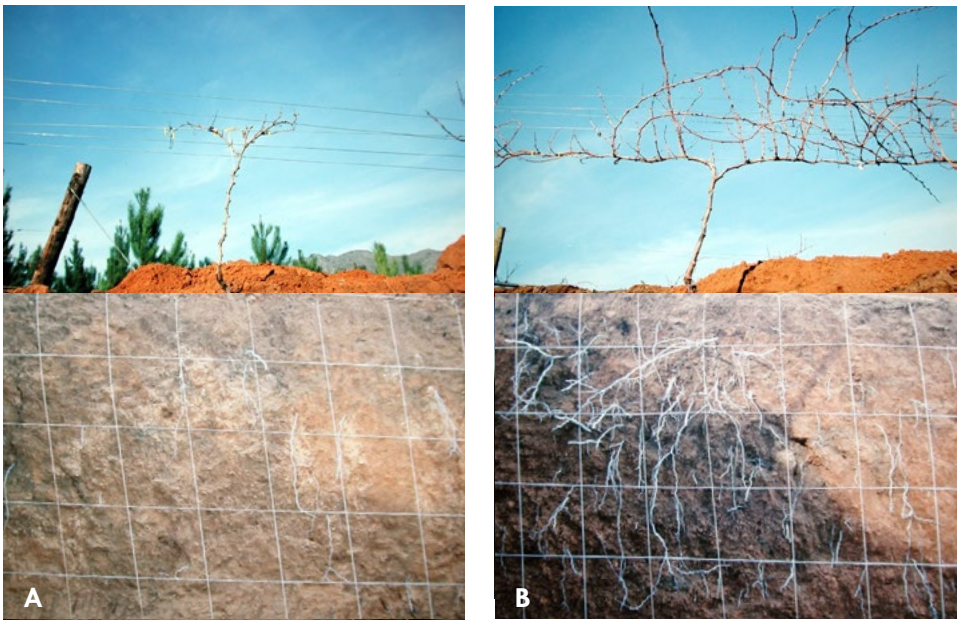


Fig. 4.8.3 Above-ground and underground growth of vines, two years after planting in the same row. A: Spade made planting hole of which the sides could not readily be penetrated by roots. Note weak above-ground growth reflecting poor root development. B: Fork made planting hole with unhindered root expansion. Note strong above-ground growth, in balance with rootgrowth. Grid size: 20 cm x 20 cm. (Pictures: E. Archer)

Great advantages were also obtained with correctly made planting holes with Sultanina table grapes in the Orange River region, where vines could almost be fully developed during the first growing season, with roots colonising the available soil volume almost completely within 10 months after planting (Fig. 4.8.4). Planting hole dimensions were 50 x 50 x 50 cm. In the second growing season, this vineyard already produced more than 1 000 cartons of grapes per hectare.

Fig. 4.8.4 Root distribution and above-ground growth of Sultanina/Ramsey, Orange River region, 10 months after planting. (Picture: E. Archer)

4.9 Pests and diseases

Vine roots are attacked by various pests, e.g. phylloxera, nematodes, magarodes, snout beetles, black maize beetle and white fringed beetle (De Klerk & Loubser, 1988). Of these pests, phylloxera, nematodes and magarodes are the most important.

Phylloxera (*Daktulosphaira vitifolii*) (Fig. 4.9.1) destroyed vineyards world-wide during the late 1800s by drastically impairing the functioning of both old and new roots. This root aphid appears seasonally in response to rising soil temperatures, as well as to active root growth (De Klerk & Loubser, 1988). It becomes active in September, goes through a peak in December and tapers off up till the end of May, to hibernate during winter. The wounds caused by the long sucking mouth parts of phylloxera serve as ideal intrusion sites for other rot-causing organisms, which can then destroy the whole root system (Omer *et al.*, 1995). At the same time, the saliva of phylloxera causes abnormal cell division, leading to the formation of nodosities on young roots, sometimes with the shape of a shepherd's crook, and turberosities on older roots (Fig 4.9.2). In this way, the normal anatomy (Britz, 1968) and physiology of the roots are impaired, which cause the vine to wither and to eventually die. The effective control of phylloxera is primarily based on the use of resistant or tolerant rootstocks (Wapshere & Helm, 1987), good soil preparation and the use of good root establishment practices, so that large, well distributed root systems can be obtained (Loubser & Ueckermann, 1997). Young vines must be encouraged to develop deep and effective root systems as quickly as possible by means of well made planting holes, irrigation and yield control, in order to successfully cope with any possible stress conditions.

Fig. 4.9.1 Phylloxera feeding on a vine root causing galls

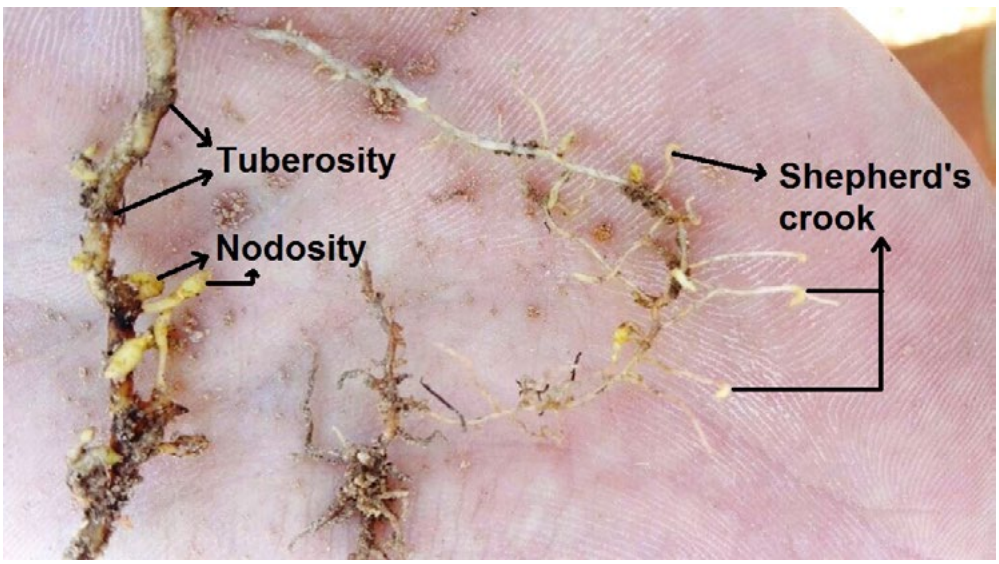


Fig. 4.9.2 Different galls caused by phylloxera on the roots of US 8-7 rootstock (Picture: D. Kritzinger, Agrimotion)

Nematodes are widely distributed in Western Cape vineyards and it is especially root knot, lesion, dagger and spiral nematodes that cause the most damage (De Klerk, 1981). Dagger nematodes (*Xiphenema index*) also transfer fanleaf virus and, furthermore, have a drastic disadvantageous effect on all root functions, especially those concerning water and nutrient uptake (Van Zyl *et al*., 2012). Naturally, this will also impair the production of hormones and thus cause stunted shoot growth and decline in yield. The best method of combating these pests is the use of resistant rootstocks (e.g. Harmony and Freedom) (Van Zyl *et al*., 2012). In a study with two *Vitis vinifera* cultivars and five rootstocks, Joubert (1971) found large differences concerning the resistance of grapevine roots against attacks of *Meloidogyna hapla* nematodes. Abnormal xylem tissue formed in susceptible cultivars that impaired the upward transport of water and nutrients, whereas other histologic changes also often appear. More resistant cultivars form wound periderm at the bite site that prevents the nematodes from reaching the xylem. Furthermore, it was found that these more resistant cultivars prevent the completion of the life cycle of the nematode. Sauer (1967) obtained similar results in his study and found large differences in resistance against root knot nematodes between different rootstocks. It was especially 101-14 Mgt and Rupestris du Lot that fared better. For effective chemical control of nematodes, the phenology of root growth must thoroughly be taken into account in order to optimise the timing of application (McKenry, 1984).

According to Nicol and Heeswijck (1997), the most common nematodes in Australian vineyards are root knot-, citrus- and root lesion nematodes. Dagger- and ring nematodes are also present, but in limited numbers. Four species of root knot nematodes attack grapevine roots, *viz. M incognita, M. javanica, M. arenarie* and *M. hapla*. The females reproduce phartenogenetically and can cause up to 60% losses in yield. One species of citrus nematode is known, *viz. Tylenchus semipenetrans*, that causes 20 - 30% losses in yield. There are a number of root lesion species, but they ause relaitively small losses in yield. Only one species of ring nematode is known that cause only minimal losses in yield, in spite of causing fairly large degrees of root girdling.

Nematodes are generally fond of sandy soils and chemical control is difficult. It is good practice to plant heat-treated vines and to make use of resistant or tolerant rootstocks. Preliminary determination of which nematodes occur

in soil shoud be made in order to be able to decide on the necessity of chemical treatment. Furthermore, nematode repressive cover crops such as wild mustard can be used.

According to McKenry (1984), root knot nematodes attack the area just behind the root-cap and penetrate there. Most other nematodes also attack the root ends or immediate areas. On a mass base, roots consist of about 0.05% of available soil mass, which makes the practice of nematode control by washing toxic products throughout the whole soil volume appear inefficient. It is clear that future approaches must be to apply nematode control products *via* translocation through the root system, rather than through the soil. If soil-carried products must nevertheless be used, it should be applied on the berms, where 56% of structural roots < 2 mm diameter are present and where 72% of new root growth can be reached. In 2008, the University of California released five new rootstocks with total to very strong resistance to nematodes. They are UCD GRN-1, -2, -3, -4 and -5.

Magarodes (M) are scale-insects of which the larvae occur in soil and, equipped with long sucking snout parts, suck out the sap from root cells, whilst injecting poisonous substances (De Klerk & Loubser, 1988; De Klerk, 2017) (Fig 4.9.3). Although there are about 70 species world-wide on a wide range of host plants, there are only 10 species known in South Africa (De Klerk, 2017). Of these, five species attack vineyards, *viz. M. greeni, M. trimeni, M. capensis, M. vredendalensis* and *M. prieskaensis* (Fig. 4.9.3). They impair general root functions, with accompanying decline in vigour (shorter and thinner shoots, with leaves curling downward), cordon arms that die and ultimately total vine losses. The decline and eventual death of the root system happens over time, during which the above-ground performance of vines is seriously reduced as regards both yield and quality. This ailment is especially evident on vines that suffer because of other causes. Presently, there is no rootstock resistant to magarodes and control thereof is designated to chemical products, whilst practices that keep the vines as far as possible free of stress play an important role.

Fig. 4.9.3 *Margarodes prieskaensis* on vine roots in the Orange River Region of South Africa. (Pictures: Johan van Zyl, Nexus, 2017)

Various fungus patogens attack grapevine roots and cause rot, with deadly effect on the vine (Marais, 1988). The most important fungi that attack vine roots are *Phytophthora* and *Pythium* species and both cause noticeable changes in especially the ultra structure of root cells, which then impair normal cell functions (Marais & De la Harpe, 1982; Marais, 1988). Large differences in resistance against *Phytophthora cinnamomi* occur between rootstocks and it is especially those with *Vitis vinifera* in their parentage that perform better. Rootstock cultivars with more glutamin acid, argenine and aspartic acid in their root exudates are more susceptable than others. The most susceptable rootstocks are 99 Richter, 1045 Paulsen, 1103 Paulsen and Rupestris du Lot. Warm water treatment of grafted vines is prescribed as an effective control measure (Marais, 1988). *Phytophthora cinnamomi* occurs down to a soil depth of 320 mm and spreads horizontally to about 1 m within the first year of infection (Marais, 1988). The spreading of this pathogen is mainly determined by water movement and the population peaks in November, December and January. The occurrence and spreading of *Pythium* species follow very much the same pattern as that of *Phytophthora*.

Other fungi that attack grapevine roots are *Phaeomoniella chlamydospora* (Petri disease) and *Cilindrocarpon* species (Black foot disease) (Halleen *et al.*, 2004; Mostert *et al.*, 2006; Halleen *et al.*, 2006a; Halleen *et al.*, 2006b; Halleen, 2010). Altogether 11 species of Petri disease (Fig. 4.9.4 A) have already been identified. They mainly occur in young vineyard plantings where they can cause significant losses in vines. Black foot infection (Fig. 4.9.4 B, C & D) mainly occurs in nusery vines and can become acutely expressed in young vineyard plantings where vines are stressed because of environmental conditions (especially unfavourable soil conditions). Both these two fungus diseases curtail new root formation, as well as effective translocation of water and minerals. In this way, general growth as well as normal plant performance are impaired.

Fig. 4.9.4 A: Petri disease symptoms in a bisected grapevine root. B: Black foot symptoms in the rootstock, immediately below the graft joint. The typical browning of bark und underlying tissue is prohibitive for normal vine functioning. C: Bisection of a severely Black foot infected grapevine root, in which no transportation is possible. D: Black foot infection at the base of a young grapevine that hampers new root formation (Pictures: Francois Halleen, ARC Institute, Nietvoorbij)

These diseases can be controlled with warm water treatment (50°C for 30 minutes) of young nursery vines, together with supportive *Trichoderma* treatments during the first three years after planting.

Armillaria root rot fungi have not yet been reported in South Africa, but they exist in the USA (Winkler *et al.*, 1974). There it is also known as the acorn root fungus and girdles the trunk and thicker roots of grapevines. It also destroys the phloem, cortex and cambium of roots and can kill only single roots or the whole root system. Affected roots have a pleasant mushroom odour and do not smell acidic or stink. No rootstock or scion roots are resistant to *Armillaria*.

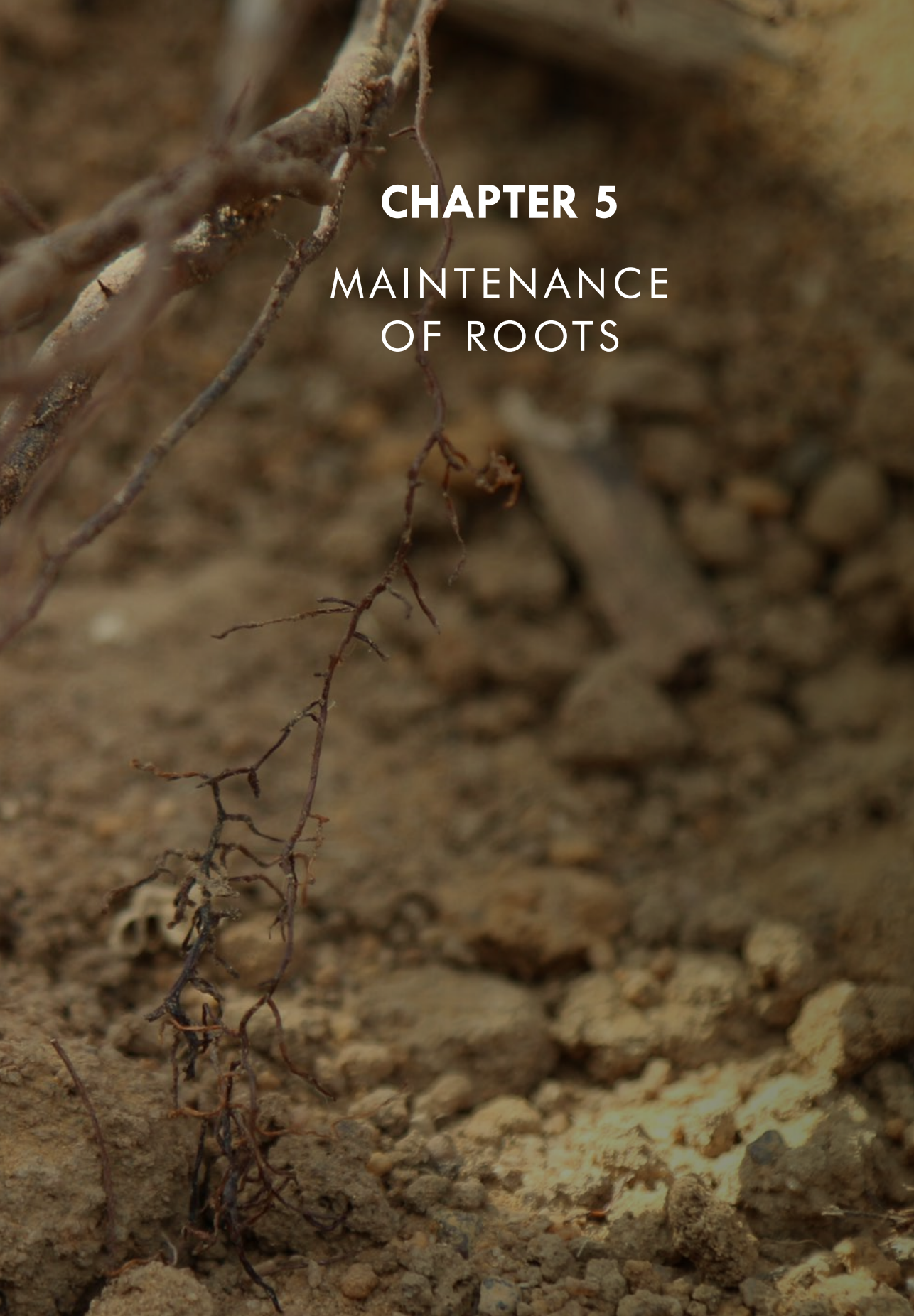
Infection with leaf roll virus has a negative effect on root growth and distribution (Fig. 4.9.5). This study was done in the same vineyard and in the same soil, with soil preparation and planting methods being similar. The roots of a heavily and a lightly infected vine were compared.

Fig 4.9.5 The effect of leaf roll virus on grapevine root growth and distribution. Left: Heavy infection. Right: Light infection. Grid size: 20 x 20 cm. (Pictures: E. Archer)

SUMMARY

The size and and porosity of the bottom and sides of planting holes have a decisive impact on root colonisation throughout the lifetime of the grapevine. Compacted sides and bottoms are highly inhibitory to root growth.Thus, the making of planting holes according to to the right procedures is critically important, and even if it takes longer, there is only one chance to do it right. Planting holes should be made to extend beyond both sides of the planting line and the vines then positioned in the middle of the hole and slightly pulled up whilst filling the hole, or the roots spread around a cone of soil in the bottom of the hole, so that the roots point downward. Roots should not be shortened more than two pruning scissor lengths.

Phylloxera, nematodes, margarodes, various fungus pathogenes and leaf roll virus have seriously inhibitive influences on the growth and distribution of grapevine roots and, therefore, affect the economic performance of the vineyard negatively. These pathogens must be efficiently controlled in order to enhance root growth and performance and, to ensure that grapevine cultivation remains viable.



CHAPTER 5

MAINTENANCE OF ROOTS

CHAPTER 5

MAINTENANCE OF ROOTS

5.1 Soil Preparation

Water and oxygen are essential for good root growth and therefore, especially in the face of climate change, it is necessary to create well buffered root systems. In this regard, effective physical and chemical soil preparation plays a cardinal role (Saayman & Van Huyssteen, 1981; Cass *et al.*, 1998; Archer & Hunter, 2010). Saayman and Van Huyssteen (1980) proved that deep trench ploughing resulted in a deeper and more homogeneous vine root distribution than shallow ploughing and rip cultivation. A highly significant direct correlation was found between effective soil depth and cane and crop mass. Without soil preparation, the preference zone for root growth is superficial, and there is no chance to establish a buffered root system (Fig. 5.1.1; Archer & Hunter, 2010). Fig 5.1.2 shows the impact of physical and chemical soil preparation on the growth and distribution of vine roots. Shallow soil preparation limits the depth penetration of roots. Subsoil zones which were ploughed upwards, as well as low pH and P contents, show that the soil preparation was insufficient to allow acceptable root colonisation. In accordance with this, Zerebkov (1966) and Cass *et al.* (1998) also found that deep physical and chemical soil preparation in suitable soil was advantageous for the development of well spread root systems. This correctly prepared soil volume must be maintained by practices such as mulching and inter-row rip cultivation (Cass *et al.*, 1998). A mulch benefits earthworms and soil microbes, while the ripper also does root pruning. Garcia de Lujan Gil de Bernabe and Gil Monreal (1982) found that, irrespective of rootstock, vine spacing, cultivation and other factors such as soil water content, soil properties exerted the most important effect on vine root development. Proper soil preparation before planting is of cardinal importance for the development of buffered root systems.

Fig. 5.1.1 Shallow root development with few fine roots, resulting from lack of soil preparation (Picture: VORI)

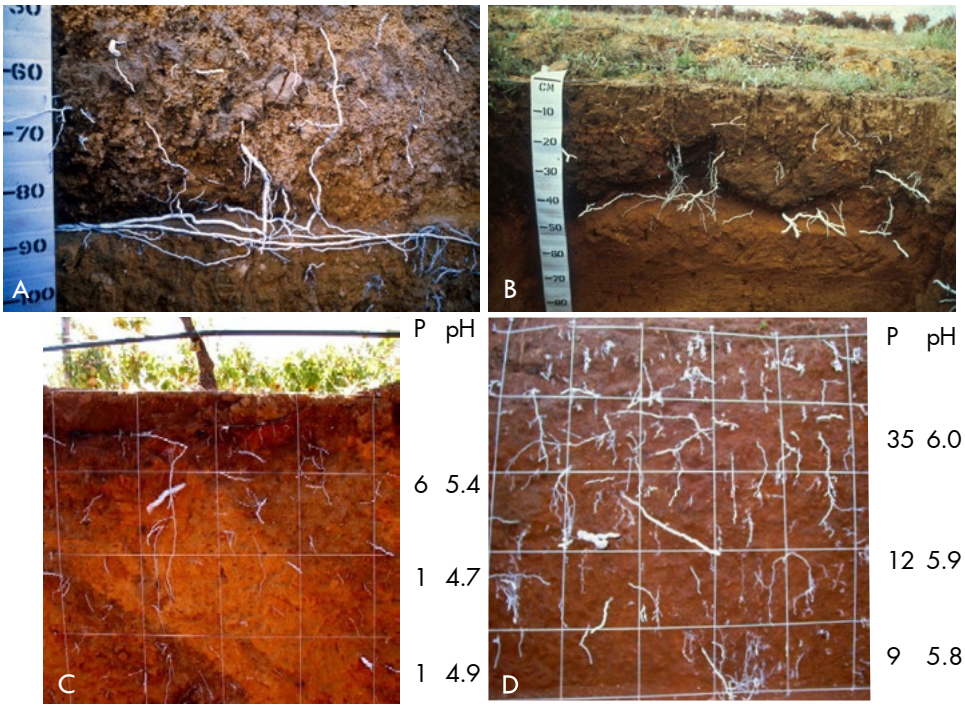
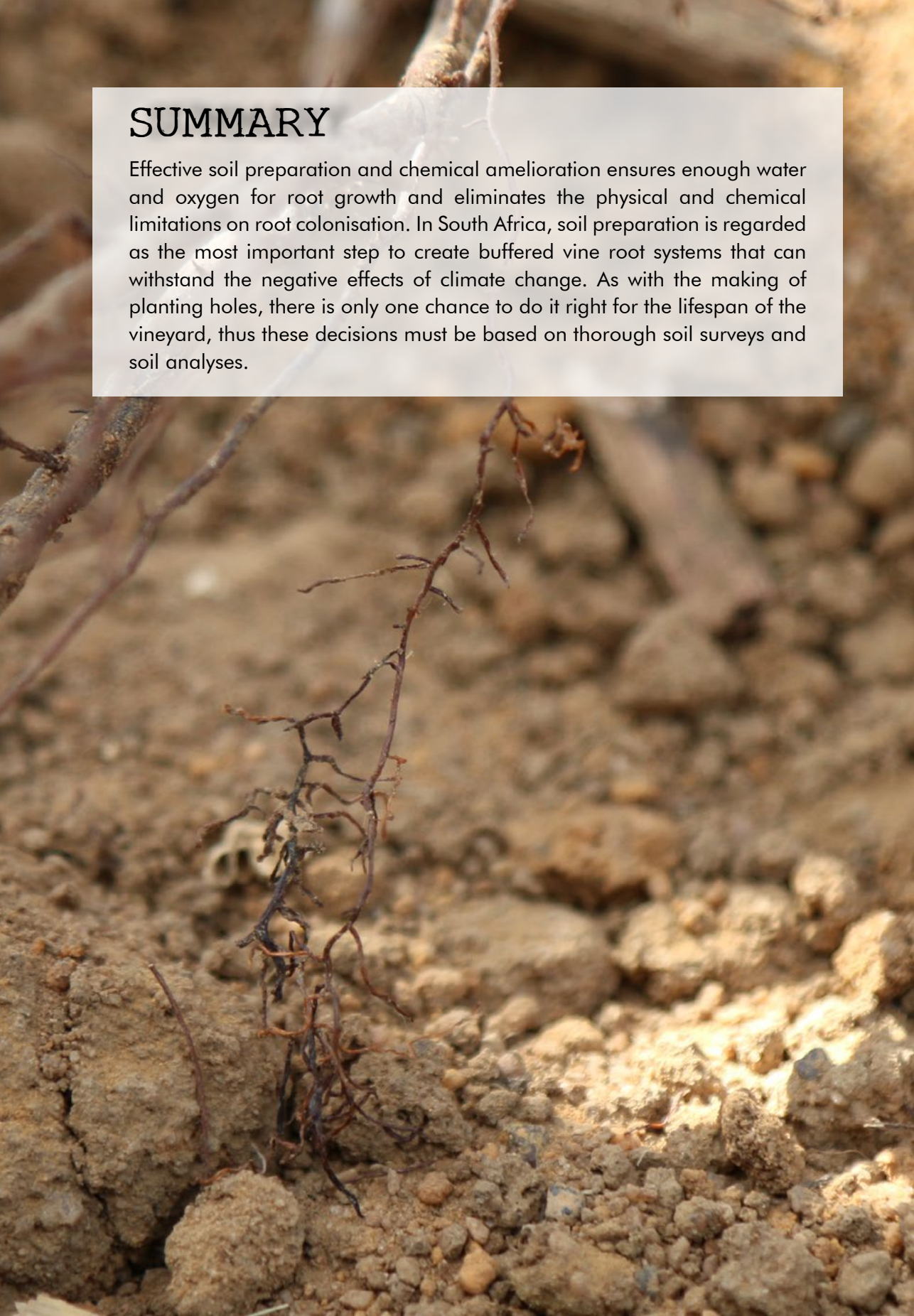


Fig. 5.1.2 The effect of physical and chemical soil amelioration on the growth and distribution of vine roots. A & B: Root penetration to deeper soil layers limited by depth of soil preparation (90 & 50 cm respectively) (Pictures: VORI).
C: Poor mixing showing zones of subsoil above and of topsoil below. Corrections of P as well as liming were clearly inadequate.
D: Root distribution as a result of good chemical and physical soil amelioration. P = Phosphate content in ppm (Bray II; norm 30 ppm). $pH_{(KCl)}$ = Soil acidity at 0 - 30, 30 - 60 and 60 - 90 cm soil depths. Grid size: 20 x 20 cm. (Archer & Hunter, 2010)



SUMMARY

Effective soil preparation and chemical amelioration ensures enough water and oxygen for root growth and eliminates the physical and chemical limitations on root colonisation. In South Africa, soil preparation is regarded as the most important step to create buffered vine root systems that can withstand the negative effects of climate change. As with the making of planting holes, there is only one chance to do it right for the lifespan of the vineyard, thus these decisions must be based on thorough soil surveys and soil analyses.

5.2 Periodic deep cultivation

Columella (c. 76 A.D.) recommended that vineyards be deeply cultivated periodically by hand-dug trenches to keep the soil loose and to promote new root growth from the wounds made on the roots. In doing so, root growth is kept relatively close to the vines. Furthermore he was of the opinion that it is advisable to shallowly delve the soil regularly with spades to allow water penetration during rain. He also advised to cut selected roots from time to time during the beginning of autumn close to the trunk to ensure new root growth. Regular root pruning has a dwarfing effect on top growth and is a technique used to make *bonsai* plants. Root pruning is also used to stimulate new root growth which is necessary to sustain shoot growth (Geisler & Ferree, 1984). Most root pruning practices are based on practical experience and more research is necessary to base these practices on scientific principles.

According to Barnard (1932), roots overlap notably, thus affecting growth negatively because of competition. To combat this, deep ploughing in winter is sometimes necessary in that main roots are frequently cut, leading to strong new growth in spring. According to him, deep ploughing between rows is without doubt an advantageous practice. Lateral roots growing upwards from the main roots are also cut strongly, but new expansive growth originates from the cut ends and it grows horizontally, thus forming masses of new roots at the base of the cultivated zone. Bunches of new feeder roots originate from these new roots, while cultivation to a depth of 12.5 cm prevents them from growing too close to the soil surface.

The extent of root regeneration after pruning through deep cultivation is dependent on soil type and probably also on rootstocks and scion cultivars (Van Huyssteen, 1988b). Litinov and Beskrovnyf (1979) found that between-row cultivation in a dry-land vineyard improved the soil water content during flowering up to 5.2%. In accordance, Melkojan *et al.* (1968) found that 45 - 50 cm deep between-row cultivation in stony soil in Armenia markedly improved the water content as well as the temperature of the soil. Especially the regrowth of pruned thick roots was notably improved and led to improved above-ground growth, while a decrease in berry shatter occurred, leading to increased berry and bunch mass. Deep cultivation in every second row improved the yield by 16.7%, while 34.9% improvement was found when cultivation was done in every row. Only 0.4% decrease in sugar content was measured.

A pruned root forms the following succession of zones from the pruning wound: an outer zone of dried cells; a zone infiltrated by wound substances, disorganised and necrotic; a zone of wound cork in the outer callus; a zone of meristematic callus and eventually a zone of transition into normal tissue (Geisler & Ferree, 1984). When root pruning is done before the completion of secondary growth (complete cambium ring around the xylem core), new roots originate from the pericycle. When root pruning is done after completion of secondary growth, new roots originate from the regenerated cambium of the callus zone (Fig. 5.2.1). Root pruning in cold soils (< 10°C) produces poorer results than in warm soils (20 - 25°C), thus root pruning during late autumn is less successful than during late spring. On the other hand, Kaiser (1969) found the optimum periods for root pruning to be beginning of May (autumn), September (spring) and January (mid-summer), but it was especially in May when most regrowth occurred.

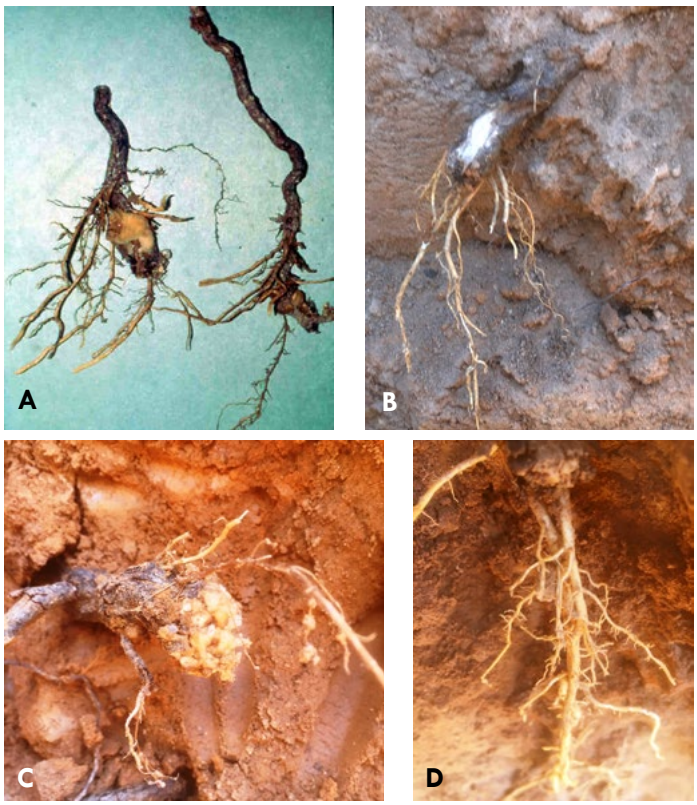


Fig. 5.2.1 A: Callus formation and emergence of new roots on pruned vine roots (Picture: VORI). B: New roots develop just behind the pruning wound. C: Granular form callus on pruned root. D: New roots are light yellow, thick and fleshy. B, C & D: In a dryland vineyard with 99 Richter in Darling, South Africa. (Pictures B, C & D: E. Archer)

Van Huyssteen and Weber (1980) found that roots cut by deep cultivation formed actively growing new roots of which the number and length increased with the diameter of the pruned root. They were of the opinion that the value of root pruning remains debatable. It has an immediate negative effect on shoot growth and yield, but can be positive in following seasons. It is possible that the main advantage of root pruning lies in the redistribution of roots, thereby utilising previously unused sources of water and nutrients. Cultivation to a depth of 50 cm in moist soil promoted the formation and growth of new roots from especially thicker roots (1.9 - 24.5 mm diameter) (Oprea *et al.*, 1967). For each root 7 - 12.7 mm in diameter, new roots (25 - 65 per vine) developed.

Root pruning at the right time can notably improve the root-soil contact surface (Fig. 5.2.2). The timing of cultivation is of cardinal importance and is determined by soil water content which should not be too high or too low (Cass *et al.*, 1998). Root pruning at the right time produced new framework roots in soil zones where no roots grew previously (Hansen, 2012). Re-compaction of soil in the work row causes roots to mostly colonise the berms and not the soil between rows.

Fig. 5.2.2 Root pruning after harvest causes branching and thus increased root/soil contact surface. (Picture: C. Snyman, Rust en Vrede)

Soil compaction readily occurs where most wheel traffic takes place and can reach 15 - 60 cm soil depth (McKenry, 1984). Periodic deep cultivation between rows to uplift compaction necessarily causes the cutting of roots (Van Zyl & Van Huyssteen, 1987; Van Huyssteen, 1988). Normally new roots form closely to the cut, but Van Zyl and Van Huyssteen found that this regrowth can take place as far back as 50 mm. The extent of regrowth is determined by the severity of pruning, root diameter and vine age: thicker roots give more regrowth than thinner roots and younger vines react stronger than older vines (Oniani, 1974). The more severe the pruning (closer to the vine), the bigger the negative effect on the growth of non-pruned roots (Geisler & Ferree, 1984).

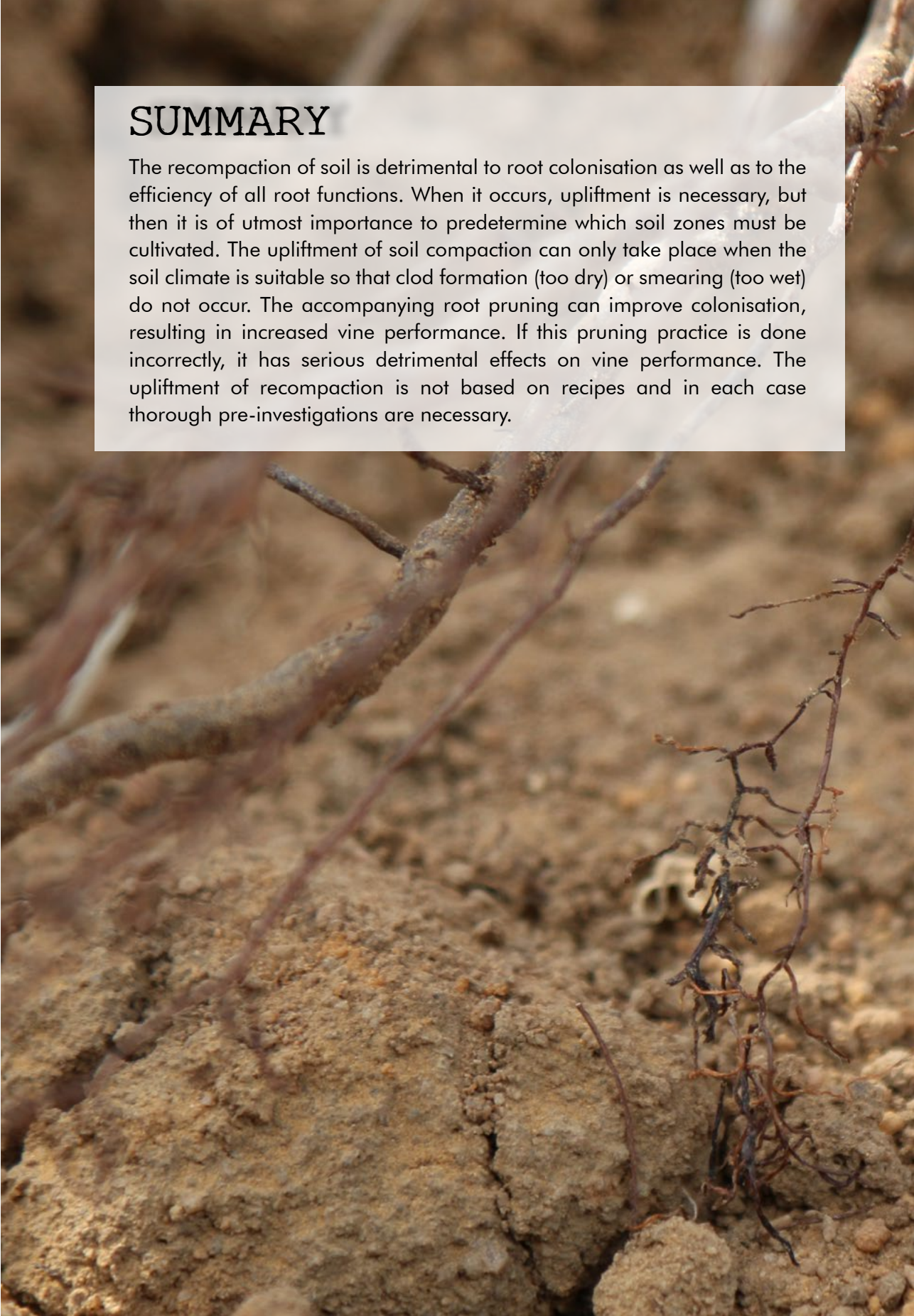
Local experience shows that merely uplifting compaction stimulates important regrowth of vine roots in the loosened rip furrow (Fig. 5.2.3).

Fig. 5.2.3 Regrowth of roots in the rip furrow after the loosening of compacted soil (Picture: E. Archer)

Pickering *et al.* (2009) found a strong relationship between strong vigour during the critical period after cap-fall and the appearance of bunch stem necrosis after véraison. They decreased bunch stem necrosis symptoms from 10 - 20% to 1 - 4% by pruning the roots of Cabernet Sauvignon 25 cm away from the vine row on both sides to a depth of 60 cm in autumn. This decrease lasted for three seasons. The control vines had to be topped regularly, but the reduced vigour of the root-pruned vines made topping unnecessary. Additional effects of root pruning were earlier ripening with smaller berries and better wine quality.

Root pruning in a wrong manner and at the wrong time affected shoot growth negatively and impaired yield. Repeated root pruning decreased the growth and yield performance of the vine and therefore it is not recommended more frequently than every five years (Van Huyssteen, 1981). For stimulating vigour, roots must be cut between the tractor tracks in every alternative work row during the post-harvest period in cases where soil compaction is harmful to root growth and functions (Van Zyl & Van Huyssteen, 1987). In so doing, it is ensured that root-stored carbohydrate reserves are not cut away unnecessarily.

Champagnol (1984) disapproved of deep cultivation with the aim to renew root growth because it weakens the vine in three ways: It decreases the number of root extremities; it causes the formation of new roots only in one part of the soil which is already strongly colonised, and it holds the risk of increasing the spreading of virus diseases.



SUMMARY

The recompaction of soil is detrimental to root colonisation as well as to the efficiency of all root functions. When it occurs, upliftment is necessary, but then it is of utmost importance to predetermine which soil zones must be cultivated. The upliftment of soil compaction can only take place when the soil climate is suitable so that clod formation (too dry) or smearing (too wet) do not occur. The accompanying root pruning can improve colonisation, resulting in increased vine performance. If this pruning practice is done incorrectly, it has serious detrimental effects on vine performance. The upliftment of recompaction is not based on recipes and in each case thorough pre-investigations are necessary.

5.3 Soil surface management

According to Degrully and Ravaz (1905), Columella advised in 76 A.D. that in young plantings the soil be loosened at the end of summer to a depth of 45 cm to destroy the shallow roots, thereby encouraging deeper root penetration. This was to improve the vine's resistance to cold and heat. Subsequent cultivations were shallow to eradicate weeds. This view was encouraged by various following publications, but late in the eighteen hundreds Guyot (1867) *inter alia* propagated that excessive cultivation, other than to control weeds, is detrimental to the development of shallow roots which have advantages for nutrition and aeration.

Most interception (fine) roots are found 7.5 - 25 cm deep below a mulch, but they are markedly deeper when the soil is covered with growing grasses. The latter increased the CO_2 concentration in the soil notably (Rogers, 1939). W.W. Yocum (according to Rogers, 1939) already found in 1935 that superficial fine root development is markedly increased by straw mulch because of soil water conservation in the top layers. In a nine-year-old vineyard with clean cultivation on a sand-loam soil, Goff (1897) found very few roots shallower than 45 cm and taproots to a depth of 240 cm. Similarly, Le Roux (1941) found that continuous clean cultivation created a plough-sole that is detrimental to deep penetration of vine roots. In accordance, Gabovic (1963) reported the largest concentration of root growth in the vine row between vines where the least soil compaction occurred, compared to the interrow where tractor wheel compaction limited root distribution.

Regular shallow cultivation created a root-free superficial layer, while weed competition had a similar effect (Van Huyssteen & Weber, 1980). The first was ascribed to continuous cultivation to approximately 20 cm, destroying roots, while the latter was due to competition for water caused by actively growing weeds. Morlat (1981) and Soyer *et al.* (1984) also found that a permanent cover crop strongly reduced vine root growth in the upper soil layers. Accordingly, Honda and Okazaki (1967) found notably more feeder roots under mulch than with clean cultivation, especially in the 40 - 60 cm deep soil layers.

Regular shallow cultivation can cause a plough-sole which prohibits root penetration (Fig. 5.3.1).

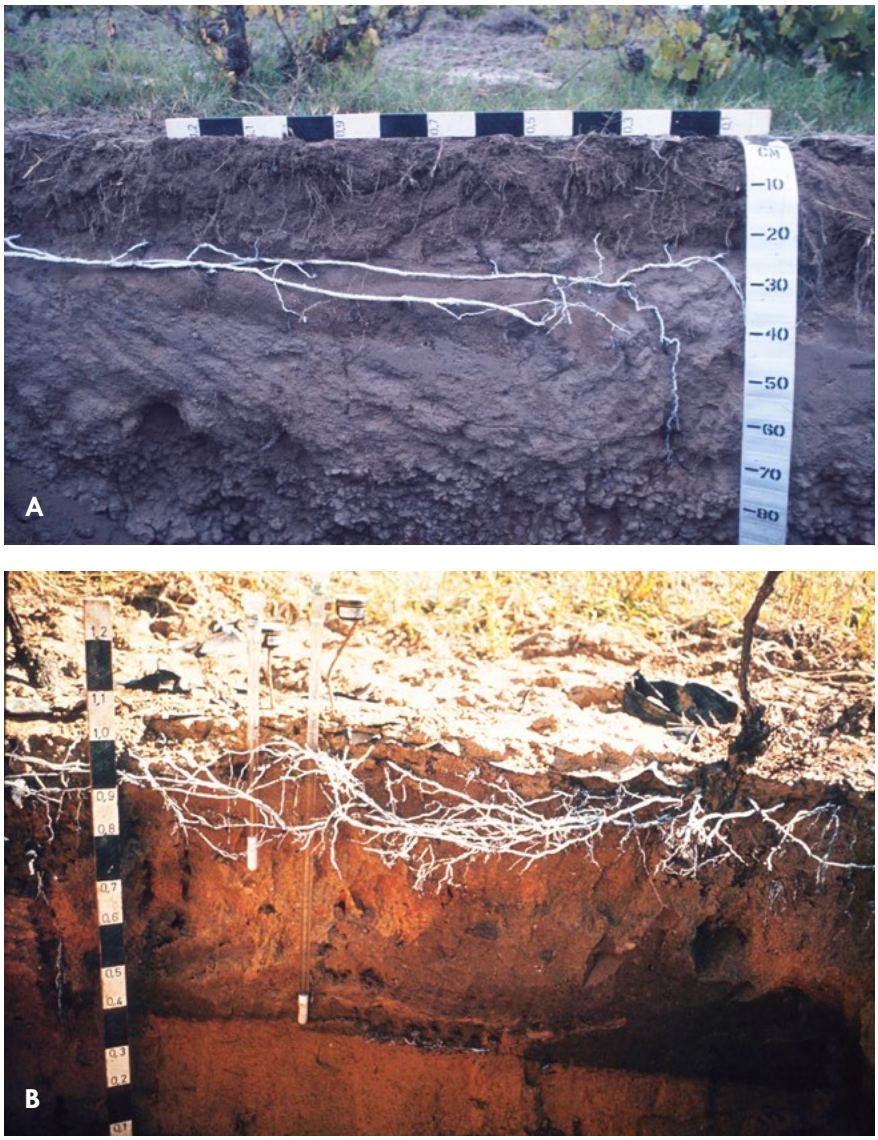


Fig. 5.3.1 Regular shallow cultivation causes a plough-sole through which vine root penetration is difficult. A: Shallow cultivation to 20 - 30 cm. B: Shallow cultivation to 10- 20 cm. Note that this caused that tensiometers were installed at wrong depths (Pictures: VORI)

Hansen (2012) also found that mulching on the berms improved root colonisation in the topsoil and that water use efficiency improved dramatically. This is in accordance with the results of local research where significantly more fine roots were found in the top 20 cm under mulch than with clean cultivation (Fig. 5.3.2).

Fig. 5.3.2 The positive effect of mulching on the distribution of especially superficial roots of vines. Left: Clean cultivation. Right: Mulching. Grid size: 20 x 20 cm. (Pictures: C. Snyman, Rust en Vrede)

Van Huyssteen and Weber (1980) found that clean cultivation as well as permanent cover crop suppressed root development in the top 20 cm soil depth, while straw mulch and weedicide advanced it (Fig. 5.3.3). In the case where weed competition was eradicated chemically, especially fine root development was promoted (Fig. 5.3.3 C). The competition of weed roots with vine roots reduced the number of the latter by 50% and it was especially the growth of fine roots that was detrimentally affected. The temperature fluctuation in the top soil layers under clean cultivation was probably the cause of little root growth in this zone. Van Huyssteen (1988) clearly showed that continuous mechanical cultivation reduced the number of fine roots (< 4 mm diameter) in the top 20 cm soil layer dramatically, compared to minimum cultivation. The negative impact of this was firstly reflected in shoot growth and later in yield.

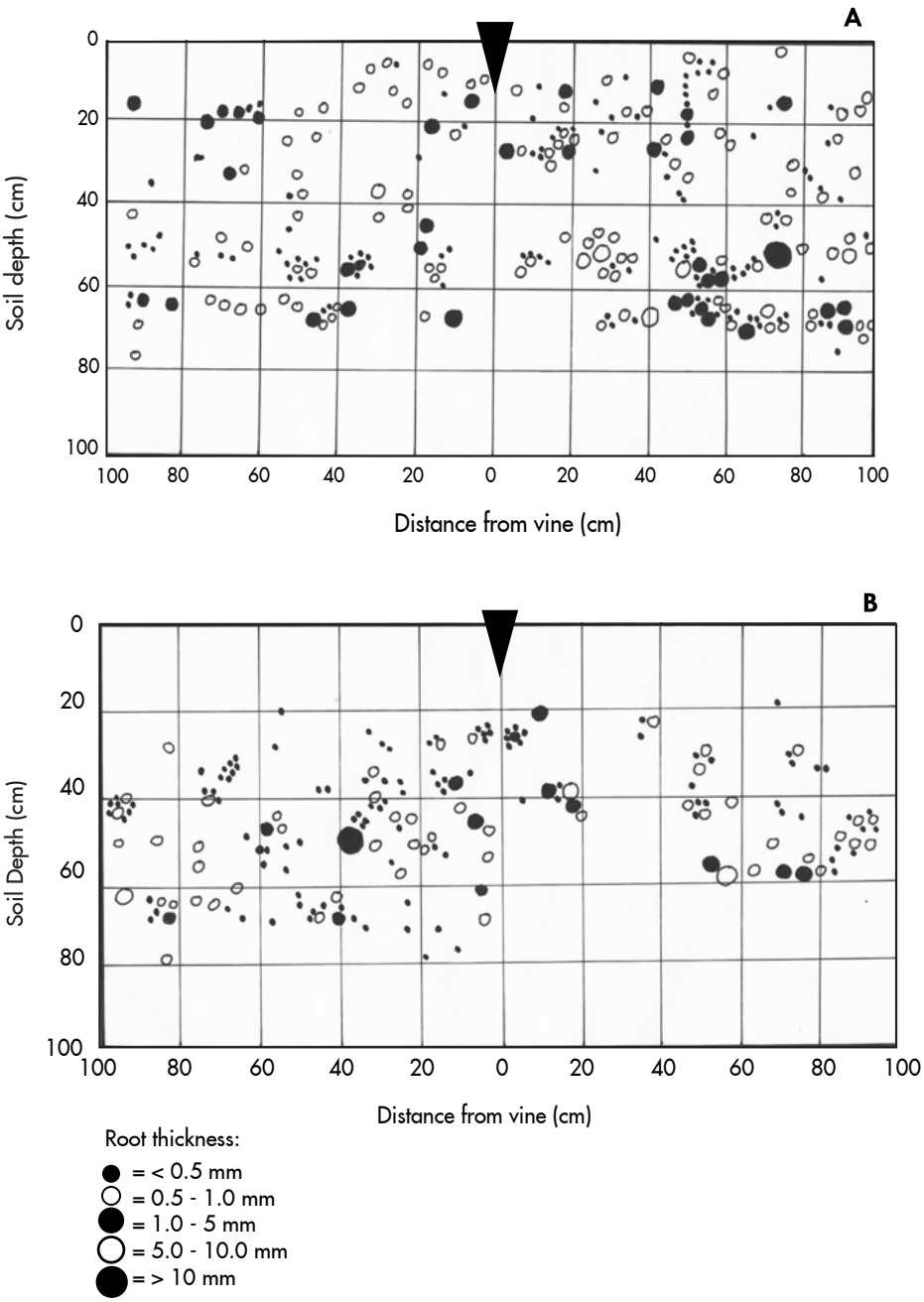


Fig. 5.3.3 A+B Root distribution under two different cultivation practices: A: Straw mulch. B: Clean cultivation. Note the inhibiting effect of clean cultivation on root development in the top soil layers. Grid size: 20 x 20 cm.
(Redrawn from Van Huyssteen & Weber, 1980)

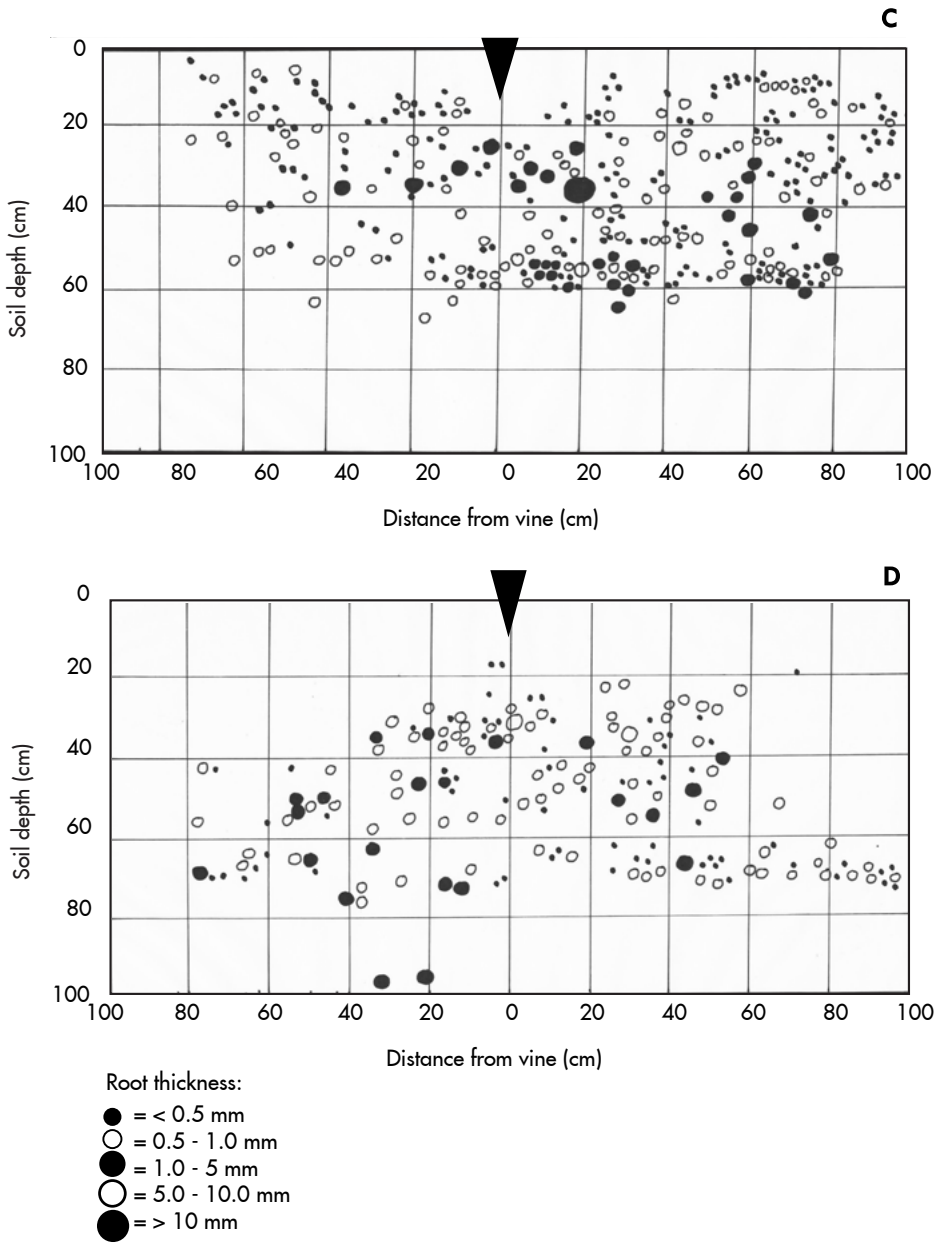


Fig. 5.3.3 C+D Root distribution under two different cultivation practices: C: Weedicide. D: Permanent cover crop. Note the inhibiting effect of permanent cover crop on root development in the top soil layers. Grid size: 20 x 20 cm. (Redrawn from Van Huyssteen & Weber, 1980)

The roots of a permanent sward in the work row showed strong competition to vine roots, especially in the top soil layers. This competition declined drastically closer to the vine row (Morlat & Jacquet, 2003). Although bulk density and mechanical resistance of the soil under permanent cover crop decreased, it had no direct advantages for vine roots.

Contrary to the results of Van Huyssteen and Weber (1980), Linares *et al*. (2009) found that grass and rye cover crop improved the fine root density of vines and reported 40% and 32% more roots/m^2 profile wall respectively than in bare soil (clean cultivation and weedicide), but that it did not affect total root mass. The yield (Merlot and Shiraz), however, was decreased with 15% by the cover crops. They ascribed the increased root density in the top soil layers to the elimination of the cover crop during the period of maximum root growth (flowering, véraison, post-harvest) and the use of irrigation. The cutting of vine roots by cultivation and the decline of physical soil properties through chemical weed control decreased the number of vine roots in the top soil layers.

In an experiment over 28 years with various types and quantities of organic material as a mulch, Morlat (2008) found that roots of < 2 mm diameter represented 73 - 79% of total roots. Only after 14 years since the start of the experiment, significant differences were measured for the first time. This implies that numerous experiments with mulching are terminated too early. Morlat (2008) found that applications of large amounts organic material (20 t/ha/yr cow dung) reduced the root system markedly, compared to the control treatment with no organic material. Moderate/low application of 2 t/ha/yr carved-up vine canes increased the root system notably, compared to the control treatment. The high applications of cow dung salinified the soil over the long term and also caused nitrate poisoning. Furthermore, the use of high quantities of organic material is not viable. The lower applications of carved-up vine canes contributed to sustainable viticulture as a result of better water use efficiency (more roots), improving growth and yield.

Gaiotti *et al*. (2016a, 2016b & 2017) found that the type of compost applied affected root distribution. Compost from cow dung did not have a significant positive effect on root distribution, but stimulated shoot growth and they ascribed this to a too high N supply that stimulated vigour but suppressed root growth. Morlat (2008) reported similar effects. Compost made from canes had a marked positive effect on vertical and horizontal root growth, especially when it was applied on the berms. This compost was

applied annually over a period of five years and was lightly incorporated. The control, work-row-applied cow dung compost, work-row-applied cane compost and berm-applied cane compost resulted in respectively 12, 15, 17 and 51 roots per m^2 profile wall 90 cm from the vine row over a period of five years. The latter probably resulted from a more efficient nutrient uptake due to the localised placing on the berms.

Morlat and Venin (1981) found in the Loire valley that fescue as permanent cover crop resulted in less than half the number of vine roots per m^2 compared to chemical weed control. Roots with < 1 mm, 1 - 2 mm and > 10 mm diameter were significantly less with the fescue, while the classes in between were not affected. Roots of less than one mm diameter were reduced, most probably because of a poorer resistance against the unfavourable water and mineral conditions caused by the fescue permanent cover, or because of direct competition (physiological inhibition, toxic root exudate, etc.). Irrespective of the horizon, roots < 2 mm in diameter were significantly reduced by the fescue, more so closer to the surface where the least physical/chemical limitations occurred. In the 25 - 50 cm horizon, the preference zone for the root framework, the number of 2 - 5 mm and > 10 mm diameter roots were significantly reduced by the fescue compared to chemical weed control. In the deeper horizons this tendency was reversed and the fescue treatment had a positive effect on the roots with 2 - 5 mm diameter. Deep plunging roots of 2 - 5 mm diameter were significantly more under the permanent fescue, which showed that the cover crop affected deep root penetration positively. This may have serious limitations if the deep soil layers are not utilisable. The improvement of the physical/chemical soil properties by the cover crop occurred in the top 0 - 10 cm and 10 - 25 cm layers only, where the biggest competition with vine roots took place, therefore the vine had only indirect advantages. In the superficial layer the competition with fescue blocked the establishment of vine roots and the further development thereof. The utilisation of this layer is very limited and was colonised by very small roots with a short lifespan.

In a 20-year-long experiment comparing bare soil (chemical weed control), permanent cover crop (natural weeds with a 0.5 m berm cleaned with weedicide) and conventional clean cultivation, Soyer (1984) found a significant increase in total root number with chemical control compared to clean cultivation and cover crop. With clean cultivation, no roots were found in the top 0 - 20 cm soil depth, while the preference zone shifted to the 20 - 50 cm depth layer (Fig. 5.3.4), so that the total root number of the

cover crop and clean cultivation treatments were comparable. A significant decrease in root density below 60 cm was found for the chemical weed control treatment. According to Soyer (1984), chemical control and clean cultivation gave satisfactory agronomical results, but the actively growing cover crop, because of water competition, was not advisable for the traditional narrow vine spacing (1.8 x 1.1 m) of Bordeaux.

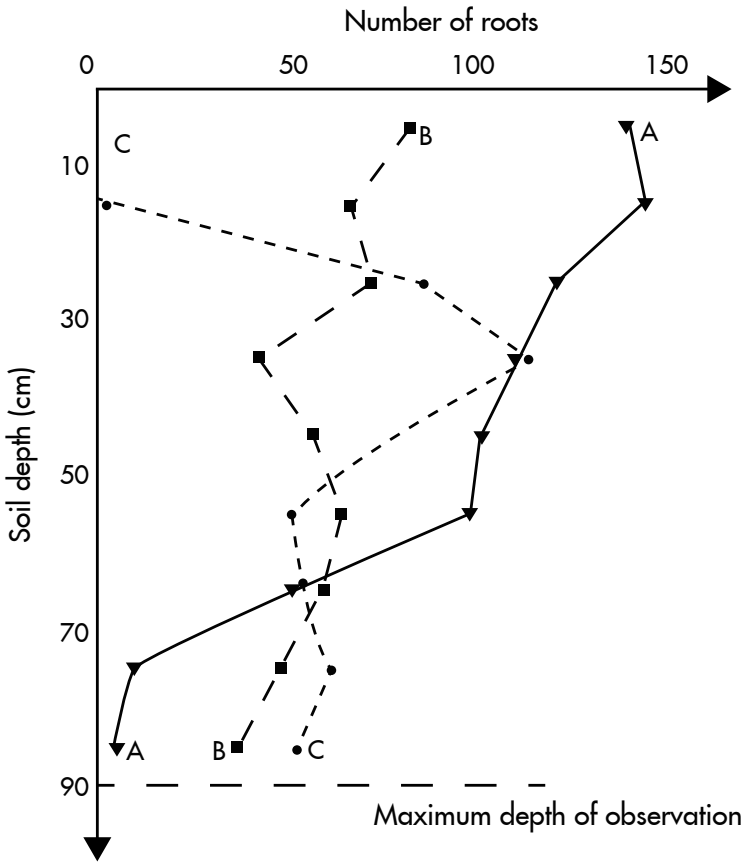


Fig. 5.3.4 Average number of root intersections/0.11 m² as a function of soil depth and cultivation practice; A: Chemical weed control. B: Permanent cover crop with clean berms. C: Clean cultivation. (Soyer, 1984)

Agulhon (1968) reported the first work with plastic covering during vine establishment that was done in France from 1963. In conjunction with better establishment and shoot growth, up to 152% more vine root mass was measured under plastic, compared to the control vines. These advantageous

effects manifested in earlier and bigger yields, therefore making this practice viable. The improved vigour was ascribed to more even day-night soil temperatures (the night soil temperatures were increased) and not so much to higher soil temperature. Additional advantages were the prevention of soil water evaporation and good weed control.

In South Africa, Van der Westhuizen (1980) used black plastic mulch during vine establishment and found, after one year, a threefold increase in roots over 80 cm depth compared to non-covered vines (Fig. 5.3.5). Even after 18 months, when the plastic started to erode, these vines maintained their advantage of improved root distribution of both shallow and deep roots. After the third and fourth seasons the covered roots were 66% and 93% more than the non-covered roots. This improved root growth reflected in cane mass and yield (full crop was reached one year earlier) with an advantage that continued to year five after planting. Van der Westhuizen (1980) ascribed this obvious better performance to more stable soil temperatures, improved water conservation, improved soil physical conditions and better weed control.

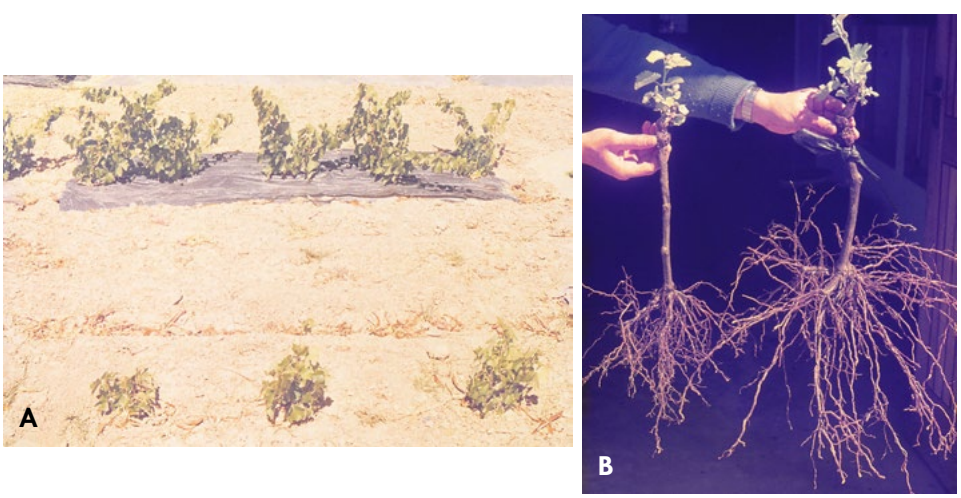
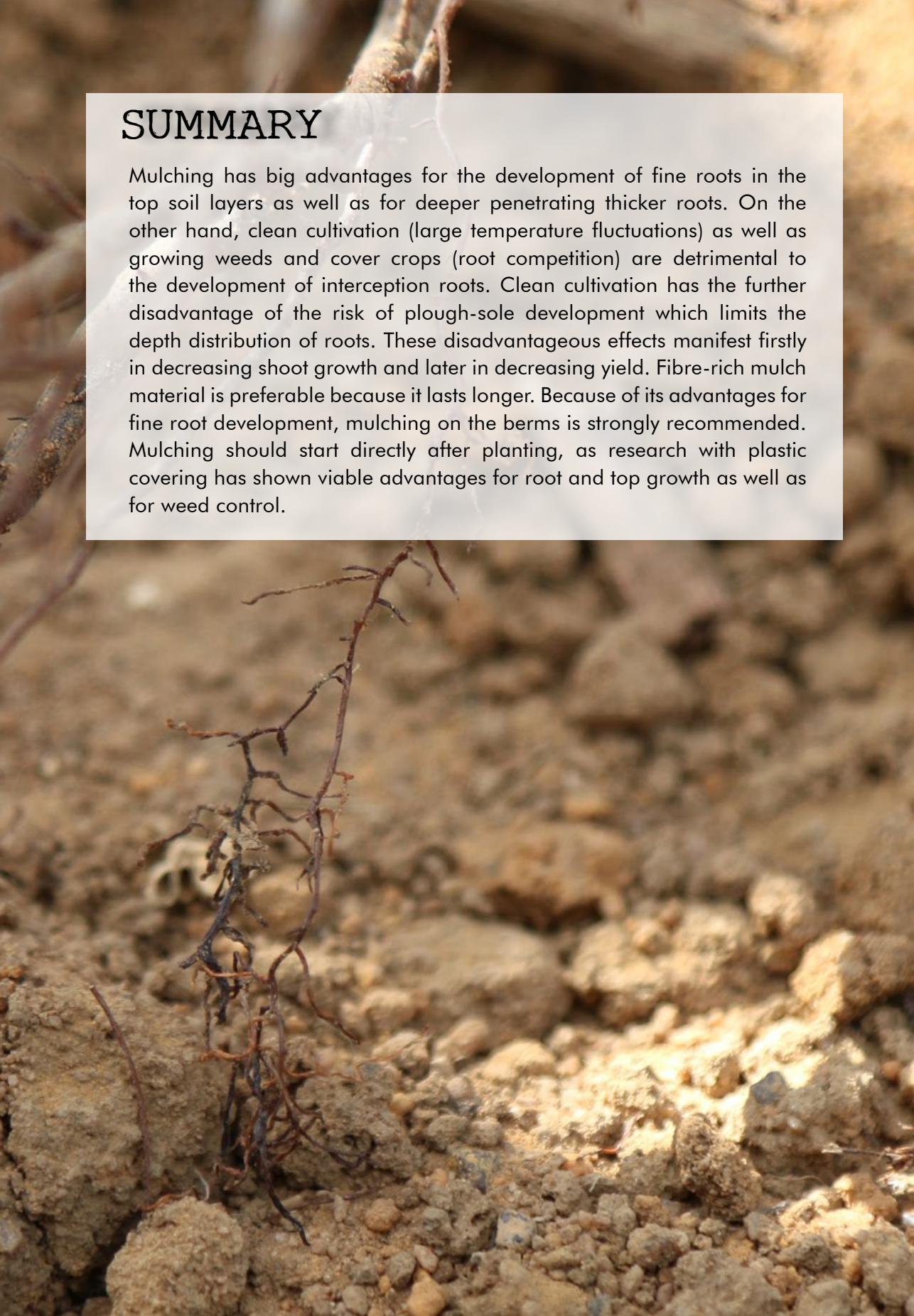


Fig. 5.3.5 Effect of plastic mulch during establishment of vines; A: Impact on above-ground growth. Back: With plastic. Front: Without plastic. B: Impact on root growth: Left: Without plastic. Right: With plastic. (Pictures: J.H. van der Westhuizen, VORI, 1980)



SUMMARY

Mulching has big advantages for the development of fine roots in the top soil layers as well as for deeper penetrating thicker roots. On the other hand, clean cultivation (large temperature fluctuations) as well as growing weeds and cover crops (root competition) are detrimental to the development of interception roots. Clean cultivation has the further disadvantage of the risk of plough-sole development which limits the depth distribution of roots. These disadvantageous effects manifest firstly in decreasing shoot growth and later in decreasing yield. Fibre-rich mulch material is preferable because it lasts longer. Because of its advantages for fine root development, mulching on the berms is strongly recommended. Mulching should start directly after planting, as research with plastic covering has shown viable advantages for root and top growth as well as for weed control.

5.4 Irrigation

Chemotropism and hydrotropism are the most important stimulants for root growth (Rogers, 1939). Perold (1926) reported that vine root growth is more affected by water than by geopatterns. In 1811, T.A. Knight determined that roots have the tendency to grow towards moist soil and he also found notably more root branching in fertile than in poor soil (Rogers, 1939). Le Roux (1941) found soil water to be the biggest driving force for root distribution under dryland conditions and that it dominated the genetic characteristics of the rootstock. He recommended that, especially for young vines, less frequent but more intensive irrigation be applied to attract the tap roots deeper into the soil. At the same time he warned against over irrigation causing the water table to rise too high, thereby seriously hampering root growth. Pomohaci (1967) showed that vine roots grew 7.2 m deep to reach the existing water table. A high water table resulted in shallow roots (Penkov & Dzilnajov, 1964). Roots utilise soil water tables by extracting water from the capillary zone above the table (Seguin, 1971). As the water table recedes while the vine is still in its vegetative growth phase before ripening, the roots follow closely behind, thus limiting its dependency on rain during this period. During ripening, shoot and root growth stop and the receding water table is no longer used. With the rising water table in autumn and winter, part of the root system is immersed. Big, permanent roots can endure the consequences of this immersion during winter when it is in a very slow life stage.

The effect of irrigation depends on the time of application (Barnard, 1932). Irrigation of Sultanina in Mildura, Australia, during end November caused white tips on spreading roots and some young feeder roots, while some new young feeder roots were formed, growing to an average length of five cm. This new growth browned quickly, while slow growth was maintained three weeks after irrigation. Irrigation at the beginning of January had the same effect, but new growth only reached an average length of 2.5 cm. The effects of later irrigations were less noticeable and more temporary.

Safran *et al.* (1975) did some of the first studies on the effects of drip irrigation on vines and found that the development of roots was restricted to the wetted soil volumes. Root development was less than for full surface irrigation and depended on soil properties, frequency of irrigation, delivery rate of the drippers and the quantity of water per application. In deep, well

aerated soil, deep and well distributed root systems developed which could also utilise deep penetrating winter rain. Under drip irrigation, 70% of the roots occurred in the top one meter of the soil and were concentrated in the vine row close to the dripper line, while with furrow irrigation the roots were more evenly spread throughout the whole profile (Mullins *et al.* 1992). Irrigation in furrows increased the number of fine and tap roots of Rupestris du Lot in Bulgaria and this improvement occurred in the top one meter of the soil (Magriso & Toncev, 1966).

In their investigation of the effects of spitter irrigation on Chenin blanc, Van Zyl and Weber (1981) found that 87% of roots occurred in the top 60 cm soil layer with the highest concentration (28.9%) at a depth of 30 -45 cm.

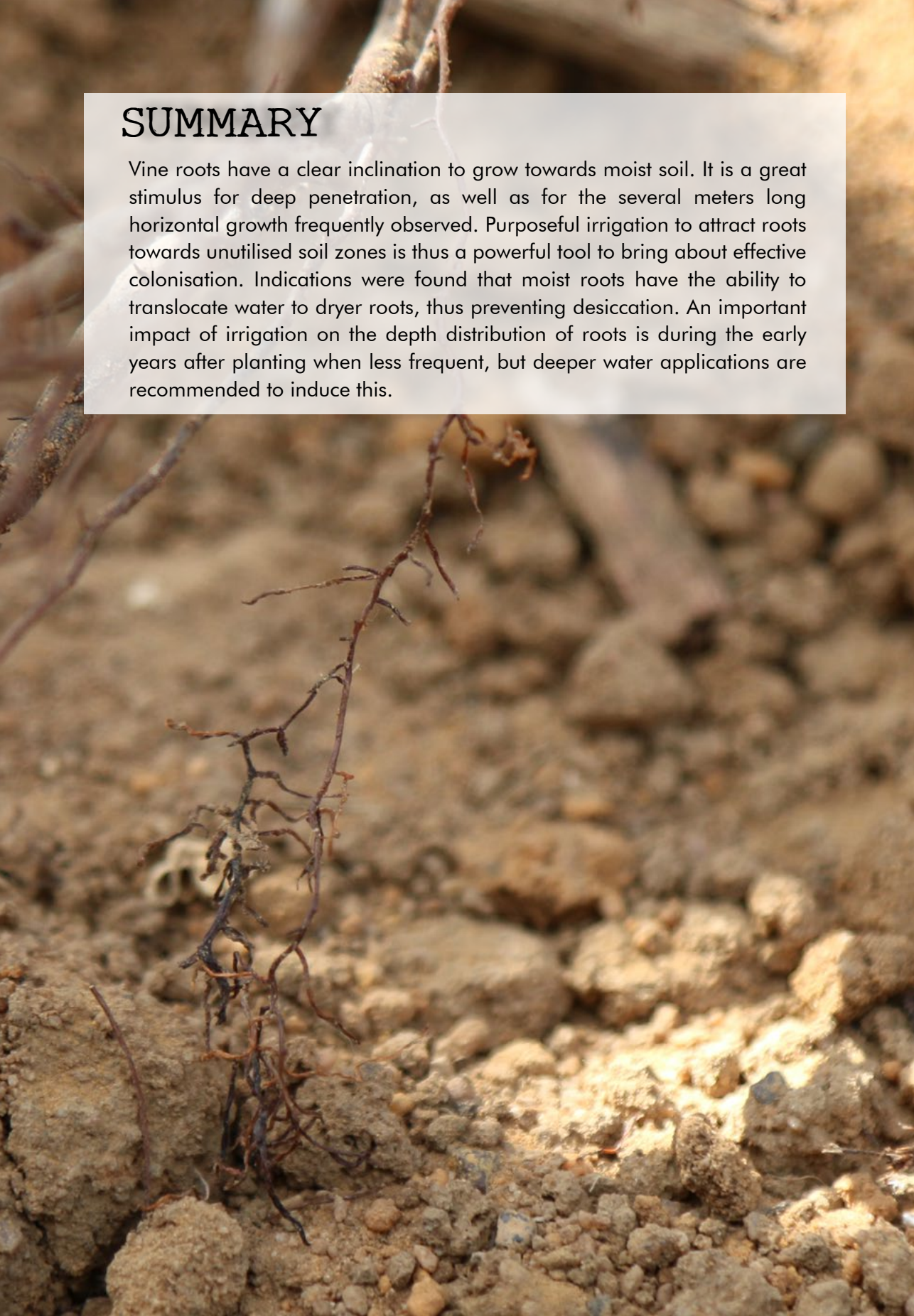
In Riverland, Australia, Soar and Loveys (2007) found that with changing from full surface to drip irrigation, roots became more concentrated under the dripper line within one year. Even after five years there was no decline in the root number of all root classes in the work row in spite of dry soil in this zone during the greatest part of summer. This can imply that these roots survived with water obtained from roots in the wetted zone and that roots which crossed the dry mid-row region served as pipe lines for water transport from neighbouring vines. A practical consequence of the bigger root system of vines established with full surface irrigation and then switched to drip, is an improvement of drought resistance compared to vines planted with drip irrigation from the beginning. These mid-row roots also have the potential of a source of stress hormones when they are wetted to ensure an increase in ABA in the xylem sap which can improve water use efficiency.

Van Zyl (1984b) did root studies with Colombar in Robertson, South Africa, at different soil water regimes and found that the number of actively growing root tips and root length followed the same pattern through the season and that both parameters are suitable to quantify new root growth. New root growth reached a maximum during flowering and after harvest, confirming the results of Conradie (1980) in pots and those of Van Rooyen *et al.* (1980) in lisimeters and Freeman & Smart (1976) in rhizotrons. Irrespective of water regimes, little root growth took place during mid-summer when water absorption was maximum. White root tips were thus not the only way of water uptake by the vine. During one season, root growth even started before harvest, which suggests that fruit removal is not the only

stimulus for the second growth peak of roots or that the grapes ceased to be the main sink for photosynthetic products at that stage. Significantly less actively growing root tips were found with a deficient irrigation treatment (Van Zyl, 1984b). On average, new root growth took place mainly in the top soil layers, namely 45 - 50% in the 0 - 30 cm layer, 34 - 35% in the 30 - 60 cm layer and 21 - 25% in the 60 - 90 cm layer. He concluded that, in contrast to shoot growth, root growth is not too much suppressed by limited irrigation because a large part took place after harvest and also because roots are much less sensitive to water stress than shoot growth.

Van Zyl and Van Huyssteen (1980) found that root density had no effect on the rate of water extraction. On the other hand Archer *et al.* (1988) and Archer (1990) found that higher root density induced by narrower vine spacing extracted soil water faster during the growth season than in the case of the lower root density of wider spaced vines (see Fig. 4.4.7).

Edwards *et al.* (2016) studied the effect of drastically reduced drip irrigation after berry set in the Riverland region of Australia on Chardonnay/Ramsey in a loamy sand soil. Contrary to Anderson *et al.* (2003), who found a 75% root survival with Concord for a less than 150 days period, they found that the majority of new roots survived three growth seasons of observation. Reduced irrigation of as much as 10% of normal, had only limited negative effects on roots. Mini rhizotron images showed no effect on root length, but a clearly reduced number of root deaths relative to root births. Soil cores showed a small decrease in root growth, only significant over four seasons. Their results illustrated the elasticity of the root system under water stress, given the reduction in top growth, to maintain the allocation of water from various sources to the roots.



SUMMARY

Vine roots have a clear inclination to grow towards moist soil. It is a great stimulus for deep penetration, as well as for the several meters long horizontal growth frequently observed. Purposeful irrigation to attract roots towards unutilised soil zones is thus a powerful tool to bring about effective colonisation. Indications were found that moist roots have the ability to translocate water to dryer roots, thus preventing desiccation. An important impact of irrigation on the depth distribution of roots is during the early years after planting when less frequent, but deeper water applications are recommended to induce this.

5.5 Fertilisation

Seguin (1971) found that the 'grand crus' vineyards of Bordeaux are mostly characterised by nutrient poor soil. Low element content indicated by soil analyses are more conspicuous than real because the vine, due to deep root penetration, can utilise large quantities of assimilable elements. On the other hand, low organic, and thus N content, is more real because it is localised in the superficial soil layers. Because poor soil limits vigour, reduced yield with higher quality is obtained. The lower mineral content of superficial soil layers enhances the development of roots in the deeper layers where elements not present in the upper layers are found, although when these upper layers are rich enough in minerals, the roots will colonise these layers. The vine has a long lifespan, 30 - 50 years, causing the roots to penetrate to great depths on account of normal geotropism processes. These deep root systems are frequently necessary for the vine to survive in poor and dry soils. Additional to geotropism, there are also chemotropism and hydrotropism which can promote or limit root expansion.

Serpuhovitina (1969) could show that there are definite cultivar differences in the utilisation of nutrients which was partly due to differences in vine root distribution. He also showed that, with or without N and K, super phosphate induced better root growth than de-fluorinated rock phosphate or K-metaphosphate. Lagutinska (1968) found that inorganic fertilisers alone caused a greater expansion of absorbing roots than organic fertilisers or farm manure. This points to the fact that these soils had no shortage of organic material but had a defect in inorganic nutrient elements. Le Roux (1941) found that where organic fertilisers were incorporated into the soil, the rotted and half-rotted material initiated good branching of especially fine roots.

In his research, Bozinova-Boneva (1969) found that vine roots reacted best on fertilisation with 200 kg N/ha plus 90 kg P/ha and that the two fertilisers on their own were not efficient. Some elements such as B and Ca must be present in adequate quantities in close proximity of the roots. Root branching of different crops seems highly dependent on available N and P. The provision thereof to only part of the root system can greatly satisfy the needs of the remaining roots (Woodham & Alexander, 1966).

With Chenin blanc in sand culture two periods of active root growth were identified, namely from approximately six weeks after budding until véraison and a second immediately after harvest (Conradie, 1988). In warmer areas the first period may start earlier. Vine roots are clearly a source of N from budding till the end of fast shoot growth and then again from véraison till harvest. Translocated N from the roots for the new growth contributed 40% of the total need. The N content of roots increased by 192% from harvest to bud-break, after which it decreased. This implied that roots are an important source of N during the pre-harvest period and a large sink during the post-harvest period (Fig. 5.5.1).

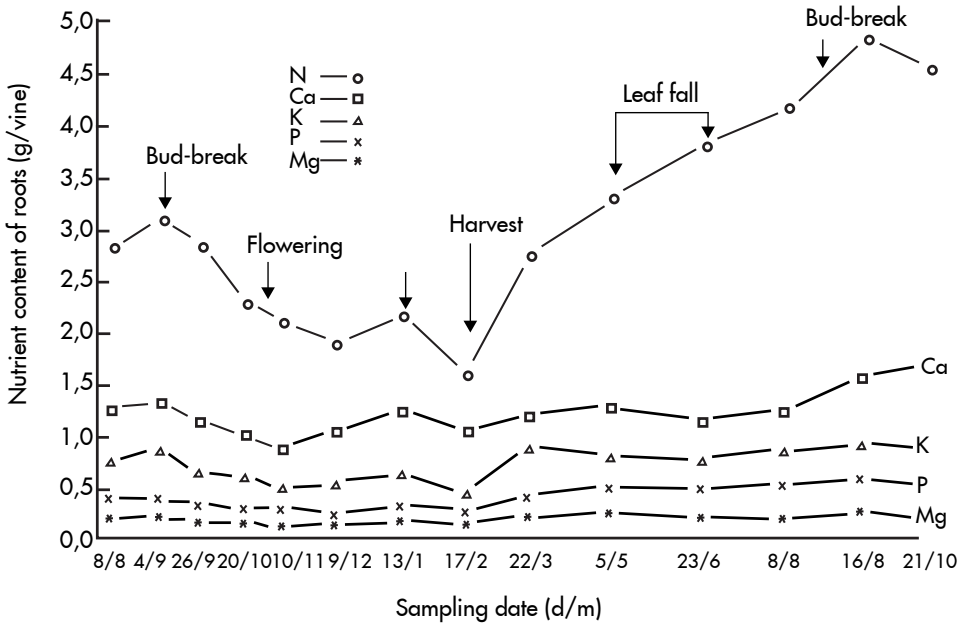


Fig. 5.5.1 Seasonal variation in the absolute quantities (g/vine) of N, P, K, Ca and Mg present in vine roots (Conradie, 1988).

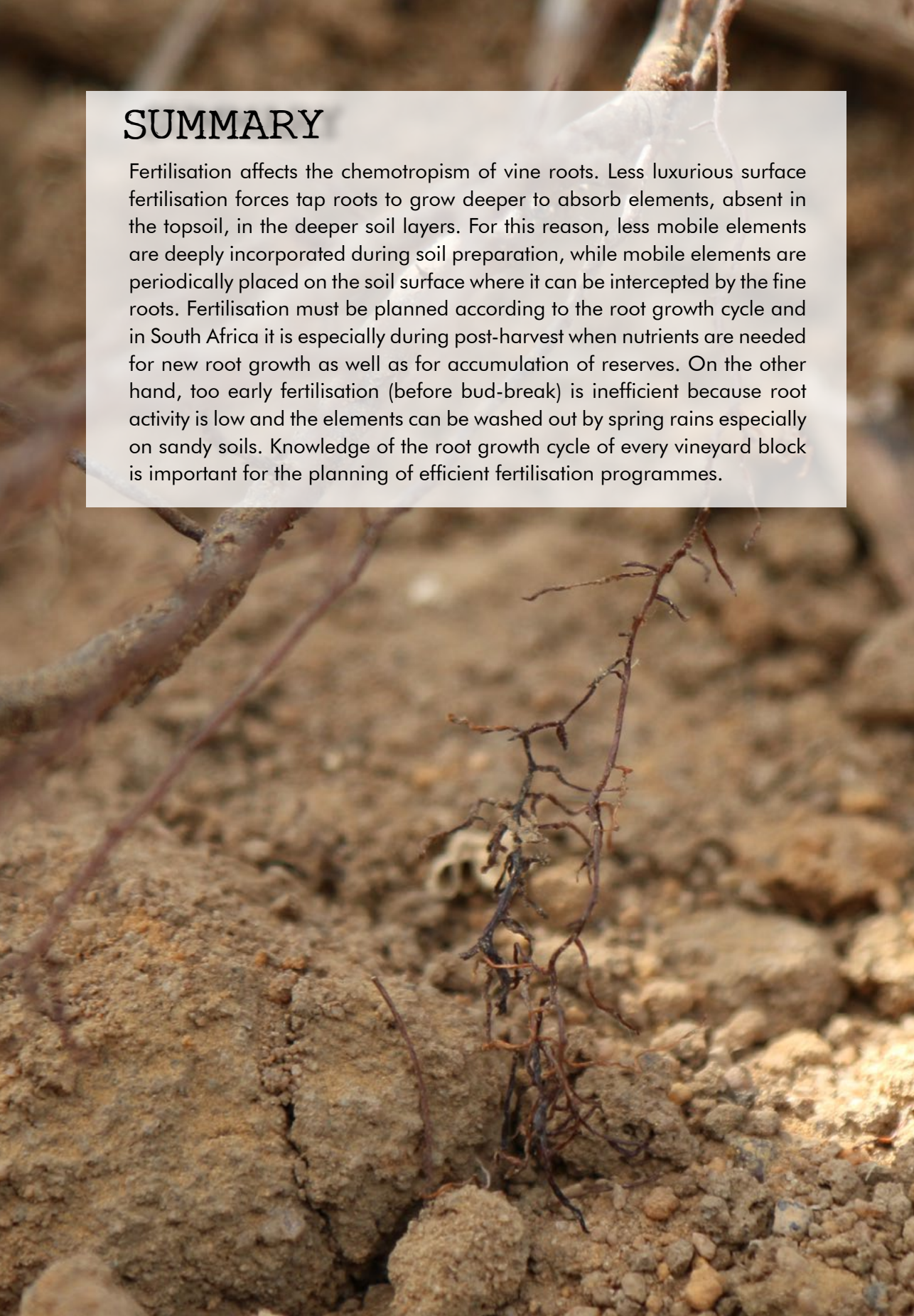
Roots clearly serve as an important source of N during early season and again one month before harvest. It is important that enough N must be present in the root zone during post-harvest when reserves are accumulated and this emphasises the importance of fertilisation during autumn under the climate conditions of the Western Cape, South Africa. After bud-break there is little root growth because of too wet and cold soils which means that too early fertilisation can be erroneous as it can be washed out by spring rain, especially in sandy soils. Eissenstat *et al*. (2006) is of the opinion that there

is little proof that fertilisation in autumn in the moderate climate regions in the northern hemisphere coincides with a period of high root activity. In these regions the efficiency of fertilisation can be improved by frequent applications of smaller quantities rather than big applications once or twice per year.

Seguin (1971) found more fine roots in Bordeaux in soil layers where Fe is present in reduced form (grey-blue colour) than when Fe is in oxidised form and present as concretions. In some cases the hardness of the concretions can be the cause, but he found that even in cases where the Fe-rich soil layer is brittle and well aerated, fine roots were absent. This could not be explained by physical and chemical analyses and further in-depth research is necessary to explain this phenomenon.

The presence of 'alios' (Fe-concretions) in Bordeaux soils were always regarded as a quality factor (Seguin, 1971). It is improbable that Fe-concretions on their own can be advantageous for wine quality in that in most cases it is not utilised by vine roots. It rather seems that the conditions in the Medoc determining the formation of Fe-concretions, namely the lowering of the water table in summer, are advantageous for proper ripening of grapes, thereby improving wine quality.

In Brazil, De Melo *et al.* (2016) found with pot experiments in which the Zn content of the soil was increased from 20 ppm to 160 ppm, that root dry mass decreased by 50% and shoot dry mass by 20%. They found roots to be a better indicator for Zn phytotoxicity than shoots.



SUMMARY

Fertilisation affects the chemotropism of vine roots. Less luxurious surface fertilisation forces tap roots to grow deeper to absorb elements, absent in the topsoil, in the deeper soil layers. For this reason, less mobile elements are deeply incorporated during soil preparation, while mobile elements are periodically placed on the soil surface where it can be intercepted by the fine roots. Fertilisation must be planned according to the root growth cycle and in South Africa it is especially during post-harvest when nutrients are needed for new root growth as well as for accumulation of reserves. On the other hand, too early fertilisation (before bud-break) is inefficient because root activity is low and the elements can be washed out by spring rains especially on sandy soils. Knowledge of the root growth cycle of every vineyard block is important for the planning of efficient fertilisation programmes.

CHAPTER 6
CONCLUSION

CHAPTER 6

CONCLUSION

World-wide, research on farming with sunlight in viticulture received much more attention than farming with vine roots. South Africa, with its often acidic and shallow soils on which viticulture is commonly practiced, took the lead during the 1980s and 1990s in creating optimal physical and chemical vine root environments through spearhead research done by a competent group of soil scientists at the ARC Institute Nietvoorbij at Stellenbosch. This improved vine root growth and reaction dramatically and is also the reason why South African vine root distribution patterns sometimes drastically differ from those observed in other countries. The South African approach created for each vine its own preference soil volume in which it can flourish and perform without competing with neighbouring vines.

No above-ground growth reaction takes place without a direct or indirect influence on the root system. Except for the absorption of water and nutrients, roots are also important production centres for hormones without which no growth can take place. All viticultural practices impact root development and growth and, therefore, the subterranean influence of these practices must be thoroughly understood and taken into account.

It seems clear that the colder the wine country, the more the root growth cycle is characterised by one peak close to véraison. Warmer (Mediterranean) climate countries clearly show two peaks of root growth, namely at full bloom and post-harvest. This has important implications for the timing of root farming practices in various regions and countries. In this regard, the period after harvest is critically important for capturing carbohydrate reserves in the roots because it has a huge impact on vine performance in the following growth season.

Vine roots are sensitive to any soil physical and chemical limitations, therefore it is important that all soil-related practices must be aimed at uplifting or preventing such constraints. The optimisation of all root functions have adirectly

positive impact on the growth and yield performance of the vineyard and in future, with climate change, this will become increasingly more important to ensure the sustainability of wine farming.

Buffered vine root systems are probably the most important weapon against climate change (warmer and drier) in the Western Cape of South Africa. It is, therefore, cardinally important to improve our knowledge concerning root growth, root reactions and root functions in order to make vine root farming successful. There is sufficient proof that a well-buffered root system improves the resistance against climate shocks, thus ensuring controlled vigour and constant wine quality. Also for this reason, the approach of limited soil utilisation by ridging and/or field hydroponics, as frequently found in the fruit industry, cannot be recommended for quality wine grape growing.

LITERATURE

LITERATURE

Agulhon, R., 1968. Paillage plastique à la plantation des vignes. Texte d'un exposé fait à Montpellier à l'occasion de la Journée Technique d'Information Viticole, 23 Avril, 1968.

Ambrosini, V.G., Voges, J.G., Canton, L., Couto, R. da R., Ferreira, P.A.A., Comin, J.J., De Melo, G.W.B., Brunetto, G. & Soares, C.R.F.S., 2015., Effect of arbuscular mycorrhizal fungi on young vines in copper-contaminated soil. *Braz. J. Microbiol.*, 46(4):1045-1052.

Anderson, L.J., Comas, L.H., Lakso, A.N. & Eissenstat, D.M., 2003. Multiple risk factors in root survivorship: A four-year study in Concord grape. *The New Phytologist,* 158:489-501.

Araujo, F.J., 1988. The response of three year-old Thompsson Seedless grapevines to drip and furrow irrigation in the San Joaquin Valley. Masters thesis, Univ. Calif., Davis.

Araujo, F.J. & Williams, L.E., 1988. Dry matter and nitrogen partitioning and root growth of young field-grown Thompson Seedless grapevines. *Vitis,* 27:21-32.

Archer, E., 1981. Klassifikasie, anatomie en morfologie. In: Burger J.D. & Deist, J. (reds.). *Wingerdbou in Suid-Afrika*. NIWW, Privaatsak X5026, 7600 Stellenbosch: Trio-Rand (SA), Litho: N'dabeni, 1-32.

Archer, E., 1990. Espacement studies on unirrigated, grafted Pinot noir (*Vitis vinifera L*). Ph.D. Thesis. Stellenbosch University, 7600 RSA.

Archer, E., 1991/2. Espacement studies with unirrigated, grafted Pinot noir (*Vitis vinifera L.*) grapevines. *Ann. Univ. Stellenbosch,* 1991/2:1-48.

Archer, E., 1996a. The importance of roots for successful viticulture. Part 1: The function of vine roots (In Afrikaans). *WineLand Technical* 84, T8-T10.

Archer, E., 1996b. The importance of roots for successful viticulture. Part 2: The distribution and management of vine roots (In Afrikaans). *WineLand Technical* 86, T7-T9.

Archer, E., 2000. How vine spacing impacts water use and root development. *Pract. Winery & Vineyard,* XX (6):23-29.

Archer, E. & Hunter, J.J., 2004/5. Vine balance: Its importance to successful cultivation. *WineLand Tech. Yearbook,* 2004/5:60-66.

Archer, E. & Hunter, J.J., 2005/6. Vine roots play an important role in determining wine quality. *WineLand Tech. Yearbook,* 2005/6:30-32.

Archer, E. & Hunter, J.J., 2010. Practices for sustainable viticulture. Part 1: Soil preparation for a proper root system. *WineLand Tech. Yearbook,* 2010:120-125.

Archer, E. & Hunter, J.J., 2010. Practices for sustainable viticulture. Part 3: Planting of vines. *WineLand Tech. Yearbook,* 2010:136-141.

Archer, E., Swanepoel, J.J. & Strauss, H.C., 1988. Effect of plant spacing and trellising systems on grapevine root distribution. In: The Grapevine Root and its Environment. Compiled by J.L. van Zyl. Dept. Agric. & Water Supply, Pretoria, RSA. *Tech. Comm.,* 215: 74-87.

Archer, E. & Strauss, H.C., 1985. Effect of plant density on root distribution of three-year-old grafted 99 Richter grapevines. *S. Afr. J. Enol. Vitic.,* 6(2):25-30.

Atkinson, D., 1980. The distribution and effectiveness of the roots of tree crops. *Hort. Rev.,* 2:424-490.

Barnard, C., 1932. The root system of Sultana. *Comm. Sci. Ind. Res. J.,* 5:89-93.

Bartchi, H. & Garrec, J.-P., 1981. A comparative study on the cytological localization of some mineral elements in the cortex of non-mycorrhizal *Vitis vinifera roots. Hort. Abs.,* 51(6):4457.

Bates, T.R., Dunst, R.M. & Joy, P., 2002. Seasonal dry matter, starch and nutrient distribution in Concord grapevine roots. *Hort Science,* 37:313-316.

Bauerle, T.L., Smart, D.R., Bauerle, W.L., Stockert, C. & Eissenstat, D.M., 2008. Root foraging in response to heterogeneous soil moisture in two grapevines that differ in potential growth rate. *The New Phytologist,* 179:857-866.

Beakbane, A.B. & Thompson, E.C., 1939. Anatomical studies of stems and roots of hardy fruit trees. *J. Pom. Hort. Sci.,* 17:141-149.

Bennett, J., Trought, M.C.T. & Jarvis, P., 2002. The importance of over-wintering carbohydrates on inflorescence development and yield potential. *Austr. & New Zeal. Gr. Grower & Winemaker,* Jan 2002:70-72.

Bidwell, R.G.S., 1974. Plant Physiology. Macmillan Publishing C., Inc. New York.

Böhm, W., 1979. Methods of studying root systems. Ecological studies, Vol. 33. Springer-Verlag: Berlin, New York.

Bollard, E.G., 1960. Transport in the xylem. *Ann. Rev. Plant Physiol.,*11:141-166.

Bonfante-Fasolo, P., 1978. Some ultrastructural features of the vesicular-arbuscular mycorrhiza in the grapevine. *Vitis,* 17:386-395.

Bonzon, B. & Picard, D., 1969. Matériel et methods pour l'etude de la croissance et du développement en pleine terre des systèmes racinaires. *Cah. ORSTOM, sér. Biol.,* 9:3-18.

Bouard, J. & Pouget, R.,1971. Physiologie de la croissance et du développement. In: J. Ribereaux-Gayon & E. Peynaud (eds.), Sciences et Techniques de la Vigne, Dunod, Paris, 329-413.

Boubals, D., 1977. L'évolution dangereuse des vignobles établis sur sol acide. L' example de Berlou dans la region de Saint-Chinian (Herault). *Prog. agric. vitic.,* 114(22). Spécial SITEVI: 491-493.

Bowen, G.D., 1985. Roots as a Component of Tree Productivity. In: *Attributes of Trees as* Crop Plants. Eds. M.G.R. Cannell & J.E. Jackson, pp. 303-315. Titus Wilson & Son: Kendal, Cumbria.

Bozinova-Boneva, I., 1969. The effect of different conditions of mineral nutrition on the absorptive and biosynthetic functions of the vine root system. *Hort. Abs.,* 40:3398.

Branas, J., 1974. Viticulture. Déhan: Montpellier.

Branas, J. & Vergnes, A., 1957. Morphologie du système radiculaire. *Prog. agric. vitic.*, Tome CLXV, 74me année, Nr. 3-4:29-32; Nr. 7-8:94-104; Nr. 9-10:122-129; Nr. 11-12:147-158; Nr. 13:173-183; Nr. 14-15:203-209.

Britz, C.J., 1968. 'n Anatomiese studie van *Vitis* wortels gesond en beskadig deur filloksera. M.Sc. Tesis. Univ. Stellenbosch, RSA.

Buckland, S.T. Campbell, C.D., Mackie-Dawson, L.A., Horgan, G.W. & Duff, E.I., 1993. A method for counting roots observed in minirhizotrons and their theoretical conversion to root length density. *Plant and Soil,* 153:1-9.

Burton, A.J., Pregitzer, K.S., Zogg, G.P. & Zak, D.R., 1988. Drought reduces root respiration in sugar maple forests. *Ecol. Appl.,* 8:771-78.

Buttrose, M.S., 1966. The effect of reducing leaf area on the growth of roots, stems and berries of Gordo grapevines. *Vitis,* 5:455-464.

Cailloux, M., 1972. Metabolism and the absorption of water by root hairs. *Can. J. Bot.,* 50:557-573.

Cass, A., Maschmedt, D. & Chapman, J., 1998. Managing physical impediments to root growth. *Austr. Gr. Grower & Winemaker*, June 1998, 13-17.

Champagnol, F., 1979. Le densité de plantation en viticulture. *Prog. agric. vitic.,* 96:185-195.

Champagnol, F., 1984. *Elements de physiologie de la vigne et de viticulture generale*. B.P. 13 Prades-le Lez, 34980 Saint-Gely-du-Fesc, France.

Clarke, S.J., Lamont, K.J., Pan, H.Y., Barry, L.A., Hall, A. & Rogiers, S.Y., 2015. Spring root-zone temperature regulates root growth, nutrient uptake and shoot growth dynamics in grapevines. *Austr. J. Gr. Wine & Res.,* 21:479-489.

Columella, L.J.M., ± 76 A.D. Columella on Agriculure, Books X – XII, Trees, (Transl. Foster, E.S. & Heffner, E.H. 1955). Loeb Classical Library, Harvard Univ. Press: London.

Comas, L.H., Anderson, L.J., Dunst, R.M., Lakso, A.N. & Eissenstat, D.M., 2005. Canopy and environmental control of root dynamics in a long-term study of Concord grape. *The New Phytologist,* 167:829-840.

Comas, L.H., Eissenstat, D.M. & Lakso, A.N., 2000. Assessing root death and rootsystem dynamics in a study of grape canopy pruning. *The New Phytologist,* 147:171-178.

Comas, L.H., Bauerle, T.L. & Eissenstat, D.M., 2010. Biological and environmental factors controlling root dynamics and function: Effects of root ageing and soil moisture. *Austr. J. Grape & Wine Res.,* 16:131-137.

Conradie, W.J., 1980. Seasonal uptake of nutrients by Chenin blanc in sand culture: I. Nitrogen. *S. Afr. J. Enol. Vitic.,* 1:59-65.

Conradie, W.J., 1981. Seasonal uptake of nutrients by Chenin blanc in sand culture: II. Phosphorus, potassium, calcium and magnesium. *S. Afr. J. Enol. Vitic.,* 2:7-13.

Conradie, W.J., 1983. Liming and choice of rootstocks as cultural techniques for vines in acid soils. *S. Afr. J. Enol. Vitic.*, 4(2):39-44.

Conradie, W.J., 1988. Effect of soil acidity on grapevine root growth and the role of roots as a source of nutrient reserves. In: The Grapevine Root and its Environment. Compiled by J.L. van Zyl. Dept. Agric. & Water Supply, *Tech. Comm.,* 215:16-29.

Conradie, W.J., 1992. Partitioning of nitrogen in grapevines during autumn and the utilisation of nitrogen reserves during the following growing season. *S. Afr. J. Enol. Vitic.,* 13:45-51.

Corvalán, N., Bastiás, R.M., Umanzor, C. & Serra, I., 2016. Grapevine root and shoot growth responses to photoselective nets: preliminary results. Proc. 1 Symp. on Grapevine Roots. *Acta Hortic.,* 1136.12:89-94.

Daulta, B.S. & Chauhan, K.S., 1980. Varietal variations in root growth of some grape cultivars (*V. vinifera L.*). *Prog. Hort.,* 12:37-39.

Davidson, J.M. & Hammond, L.C., 1977. Soil physical aspects of root development. *Soil and Crop Sci. Soc. of Florida, Proc.,* 36:1-4.

Degrully, L. & Ravaz, L., 1905. Sur la culture superficielle de la vigne. *Annales de l'ecole nationale d'agriculture de Montpellier* 5(1):64-87.

Deidda, P., 1964. Relationships existing between depth of planting, root development and shoot growth in rooted vine cuttings. *Hort. Abs.,* 36:728.

De Klerk, C.A., 1981. Wingerdplae. In: J.D. Burger & J. Deist (reds.), Wingerdbou in Suid-Afrika. NIWW, Privaatsak X5026, 7600 Stellenbosch. Trio-Rand (SA), Litho: N'dabeni, 433-462.

De Klerk, C.A., 2017. Identifikasie, beheer en bestuur van wingerdmargarodes. In: WineLand Tydskrif, Februarie 2017. *Winetech Tegnies,* 330:68-71.

De Klerk, C.A. & Loubser, J.T., 1988. Relationship between grapevine roots and soil-borne pests. In: *The Grapevine Root and its Environment*. Compiled by J.L. van Zyl. Dept. Agric. Water Supply, Pretoria, RSA. *Tech. Comm.,* 215:88-105.

De Melo, G.W.B., Da Silva, L.S., Brunetto, G., Zalamena, J. & Albarello, J.B., 2016. Sensitivity of grapevine rootstocks to changes in zinc concentration in the soil. Proc. 1 Int. Symp. on Grapevine Roots. *Acta Hortic.,* 1136.27:201-208.

Devlin, R.M., 1966. Plant Physiology. Reinhold Publishing Corporation: New York, Amsterdam, London.

Diofasi, L. & Kiraly, F., 1968. Comparative studies on grafts with rootstocks of different lengths in the vineyard. *Hort. Abs.,* 40:5816.

Doll, C.C., 1954. Studies of Concord grape roots in loess soil. *Amer. Soc. Hort. Sci.,* 65:175-182.

Dry, P., Loveys, B. Johnstone, A. & Sadler, L., 1998. Grapevine response to root pruning. *Austr. Gr. Grower & Winemaker Ann. Techn. Issue,* 414a:73-78.

Edwards, E.J., Pearce, A.F., Pech, J., McCarthy, M.G. & Tyerman, S.D., 2016. The effects of sustained deficit irrigation and re-watering on root production and turnover in warm climate viticulture. Proc. 1 Int. Symp. on Grapevine Roots. *Acta Hortic.,* 1136.13:95-102.

Erlenwein, H., 1965. The influence of nutrition and of the graft partner on the root growth of *Vitis* species and varieties. *Vitis,* 5:161-186.

Esau, K., 1967. Anatomy of Seed Plants (1st ed.). Int. Ed. John Wiley & Sons, Inc: New York.

Esau, K., 1976. *Anatomy of Seed Plants* (2nd ed.). Int. Ed. John Wiley & Sons, Inc: New York, London.

Eissenstat, D.M., Bauerle, T.L., Comas, L.H., Lakso, A.N., Neilsen, D., Neilsen, G.H. & Smart, D.R., 2006. Seasonal patterns of root growth in relation to shoot phenology in grape and apple. Proc. Vth Int. Symp. on Mineral Nutrition of Fruit Plants. *Acta Hortic.* 721, 21-26.

Field, S.K., Smith, J.P., Holzapfel, B.P., Hardie, W.J. & Neil Emery, R.J., 2009. Grapevine response to soil temperature: Xylem cytokinins and carbohydrate reserve mobilization from budbreak to anthesis. *Am. J. Enol. Vitic.,* 60:164-172.

Fitter, A.K., 1982. Morphometric analyses of root systems: Application of the technique and influence of soil fertility on root system development in two herbaceous species. *Plant Cell & Environment,* 5:313-322.

Freeman, B.M., 1983. At the root of the vine. *Austr. Gr. Grower Winemaker,* 232:58-64.

Freeman, B.M. & Smart, R.E., 1976. A root observation laboratory for studies with grapevines. *Amer. J. Enol. Vitic.,* 27:36-39.

Gabovic, V.I., 1963. The development of the vine root system in relation to soil density. *Hort. Abs.,* 33:4786.

Gaiotti, F., Marcuzzo, P., Battista, F., Belfiore, N., Petoumenou, D. & Tomasil, D., 2016a. Compost amendment effects on grapevine root density and distribution. Proc. 1 Int. Symp. on Grapevine Roots. *Acta Hortic,* 1136.16:115-119.

Gaiotti, F., Marcuzzo, P., Belfiore, N., Lovat, L. & Tomassi, D., 2016b. Vine response to compost addition on a sandy-loam soil in the North-East of Italy: Effects on root system, vegetative growth, yield and grape quality of Cabernet Sauvignon cv. XI Int. Terroir Congr. *Oregon,* July 10-14, 2016.

Gaiotti, F., Marcuzzo, P., Belfiore, N., Lovat, L., Fornasier, F. & Tomasi, D., 2017. Influence of compost addition on soil properties, root growth and vine performances of *Vitis vinifera* cv. Cabernet Sauvignon. *Scientia Horticulturae,* 225:88-95.

Gale, M.R. & Grigal, D.F., 1987. Vertical root distributions of northern tree species in relation to successional status. *Can. J. For. Res.,* 17:829-834.

Garcia de Lujan Gil de Bernabe, A. & Gil Monreal, L., 1982. Sobre la distribucion del sistema radicular de la vid. *Ann. Del Inst. Nac. De Invest. Agr.,* Serie: Agric 20(2). General Sunjurjo, 56, Madrid-3 (Spain).

Gebbing, H., Schwab, A. & Alleweldt, G., 1977. Mykorrhiza der rebe. *Vitis,* 16:279-285.

Geisler, D. & Ferree, D.C., 1984. Response of plants to root pruning. *Hort. Rev.,* 6:155-188.

Giese, W.G., Wolf, T.K., Velasco-Cruz, C. & Roberts, L., 2016. Cover crop and root pruning effects on the rooting pattern of SO4 rootstock grafted to Cabernet Sauvignon. *Am. J. Enol. Vitic.,* 67(1):105-115.

Gill, W.R. & Miller, R.D., 1956. A method for study of the influence of mechanical impedance and aeration on the growth of seedling roots. *Soil Sci. Soc. Amer. Proc.*, 20:154-157.

Goff, E.S., 1897. Study of roots of certain perennial plants. *Wisc. Agric. Exp. Sta. Rpt.,* 14:286-298.

Goff, E.S., 1898. The resumption of root growth in spring. *Wisc. Agric. Exp. Sta. Rpt.,* 15:220-228.

Goffinet, M.C., 1999. The water and food conducting system of the grapevine. In: Black Goo: Symptoms and occurrence of grape declines. *IAS/ICGTD Proceedings 1998,* ed. L. Morton. International Ampelography Society: Fort Valley, Virginia, USA.

Graham, J.H., Montague, D.T., Durham, R.E. & Herring, A.D., 2002. Root-zone refrigeration delays budbreak and reduces growth of two containerized, greenhouse grown grape cultivars. *Texas J. Agric. Nat. Resources,* 15:71-80.

Grobbelaar, N., Robbertse, P.J., Van Greuning, J.V. & Visser, J.H., 1979. Plantkunde: Anatomie en Fisiologie. Butterworth (SA).

Guyot, J., 1867. Etudes des vignobles de France. Tomes I, II & III. Impr. National, Paris.

Hacket, S., 1999. Vine root function. *Austr. Gr. Grower & Winemaker,* June: 23-24.

Halleen, F., Schroers, H-J., Groenewald, J.Z. & Crous, P.W., 2004. Novel species of *Cylindrocarpon (Neonectria) and Campyloncarpon* gen. Nov. associated with black foot disease of grapevines (*Vitis* spp.). *Studies in Mycology,* 50:431-455.

Halleen, F., Fourie, P.H. & Crous, P.W., 2006a. A review of black foot disease of grapevine. *Phytopathol. Mediterr.,* 45:S55-S67.

Halleen, F,. Schroers, H-J., Groenewald, J.Z., Rego, C., Oliviera, H. & Crous, P.W., 2006b. *Neonectria liriodendri* sp. nov., the main casual agent of black foot disease of grapevines. *Studies in Mycology,* 55:227-234.

Halleen, F., 2010. Pro-active control of Petri Disease and Black Foot Disease in newly established vineyards. *http://www.sawislibrary.co.za* Final Report.

Hansen, D., 2012. Mulching, soil amendments and management in a commercial vineyard. *Austr. Gr. Grower & Winemaker,* 581:38-41.

Harmon, F.N. & Snyder, E.,1934. Grape root distribution studies. *Proc. Am. Soc. Hort. Sci.,* 32:370-373.

Hatton, R.G. & Amos, J., 1927. Experiments upon the removal of lateral growth on young apple trees in summer. The effect on stem and root development. *J. Pom. & Hort. Sci.,* 6:61-71.

Hidalgo, L., 1968. Contribuţii la studiul densităţii radiculare la vița de vie. *Revista de Horticultură şi Viticultură*, 7-8:116-121.

Hildalgo, L., 1968. Contribution a l'étude de la densité radiculaire de la vigne. *Rev. Hortic. Vitic.,* 17:185-191.

Hildalgo, L. & Candela, M.R., 1969. Morfologia radicular de la vid. Ins. Nac. Invest. Agronom. Madrid, Spain.

Hilton, R.J. & Khatamian, H., 1973. Diurnal variation in elongation of roots of woody plants. *Can. J. Plant Sci.,* 53:699-700.

Holzapfel, B., 2004. Identifying manageable factors determining carbohydrate accumulation in reserves and rootgrowth of grapevines after harvest. *Final Report to: Grape and Wine Research Corporation. National Wine & Grape Research Centre.* Project CSU, 99/2:1-84.

Honda, N. & Okazaki, M., 1967. The effect of soil management on the root development. *Hort. Abs.,* 37:573.

Hooker, J.E., Jaizme-Vega, M. & Atkinson, D., 1994. Biocontrol of plant pathogens using arbuscular mycorrhizal fungi. In: *Impact of arbuscular mycorrhizal fungi on sustainable agriculture and natural ecosystems*. S. Gianinazzi & H Schüepp (eds).,191-200. Birkhauser: Berlin.

Huck, M.G., 1970. Variation in taproot elongation rate as influenced by composition of the soil air. *Agron. J.,* 62:815-818.

Huglin, P., 1986. *Biologie et Écology de la Vigne*. Editions Payot Lausanne: Paris.

Hunter, J.J., 1998a. Plant spacing implications for grafted grapevine I. Soil characteristics, root growth, dry matter partitioning, dry matter composition and soil utilisation. *S. Afr. J. Enol. Vitic.,* 19:25-34.

Hunter, J.J., 1998b. Plant spacing implications for grafted grapevine II. Soil water, plant water relations, canopy physiology, vegetative and reproductive characteristics, grape composition, wine quality and labour requirements. *S. Afr. J. Enol. Vitic.,* 19:35-51.

Hunter, J.J., Archer, E., Van Schalkwyk, D., Strever, A.E. & Volschenk, C.G., 2016. Grapevine roots: interaction with natural factors and agronomic practices. Proc. 1 Int. Symp. on Grapevine Roots. *Acta. Hortic.*,1136.10:63-80.

Hunter, J.J. & Le Roux, D.J., 1992. The effect of partial defoliation on development and distribution of roots of *Vitis vinifera* L. cv. Cabernet Sauvignon grafted onto rootstock 99 Richter. *Am. J. Eno. Vitic.,* 43(1):71-78.

Hunter, J.J., Ruffner, H.P., Volschenk, C.G. & Le Roux, D.J., 1995. Partial defoliation of *Vitis vinifera* L. cv. Cabernet Sauvignon/99 Richter: Effect on root growth, canopy efficiency, grape composition and wine quality. *Am. J. Enol. Vitic.,* 46:306-314.

Hunter, J.J. & Volschenk, C.G., 2001. Effect of altered canopy: root volume ratio on grapevine growth compensation. *S. Afr. J. Enol. Vitic.,* 22(1):27-30.

Israelsen, O. & Hansen, V.E., 1967. Irrigation Principles and Practices. John Wiley & Sons: New York, London & Sydney (447).

Jacoby, B., 1964. Function of the root and stems in sodium retention. *Plant Physiol.,* 39:445-449.

Jones, H.G., 1983. *Plants and Microclimate*. Cambridge Univ. Press.

Jooste, L.J., 1983. Invloed van grondtemperatuur op groei en sitokinienmetabolisme by wingerd *(Vitis)*. M.Sc. Tesis. Univ. van Stellenbosch, 7600, RSA.

Joubert, D.J., 1971. An anatomical and experimental study on changes induced by *Meloidogyne hapla* (Chitwood, 1949) in *Vitis* roots. PhD Thesis. Stellenbosch University, 7600, RSA.

Joubert, S. & Archer, E., 2000. The influence of mycorrhiza on vines (In Afrikaans). WineLand, May 2000, 86-88.

Juncu, V., Pituc, L. & Pituc, P., 1969. Studies of the root systems of the main varieties of vine rootstocks in the Jassy vineyard. *Hort. Abs.,* 40:3371.

Kaiser, G., 1969. The optimum period for deep soil cultivation in vineyards in relation to the recovery of damaged roots. *Hort. Abs.,* 39:507.

Kidman, C.M., Dry, P.R., McCarthy, M.G. & Collins, C., 2014. Effect of rootstock on nutrition, pollination and fertilization in Shiraz (*Vitis vinifers L*). *Vitis,* 55(3):139-145.

Kliewer, W.M. & Fuller, R.D., 1973. Effect of time and severity of defoliation on growth of roots, trunk and shoots of Thompson Seedless grapevines. *Am. J. Enol. Vitic.,* 24:59-64.

Kliewer, W.M., 1975. Effect of root temperature on budbreak, shoot growth and fruit-set of Cabernet Sauvignon grapevines. *Am. J. Enol. Vitic.*, 26:82-89.

Kocsis, L., Tarcsal, E. & Molnàr Kocsisné, G., 2016. Grape rootstock-scion interaction on root system development. Proc. 1 Int Symp on Grapevine Roots. *Acta Hortic.* 1136.4:27-31.

Kotze, W.A.G., 1973. The influence of aluminium on plant growth. *Decid. Fruit Grow.*, 23:20-22.

Kramer, P.J. & Bullock, H.C., 1966. Seasonal variations in the proportions of suberized and unsuberized roots of trees in relation to absorption of water. *Amer. J. Bot.,* 53:200-204.

Krauss, U. & Deacon, J.W., 1994. Root turnover of groundnut (*Arachis hypogaea L.*) in soil tubes. *Plant & Soil,* 166:259-270.

Kroemer, R., 1909. Organographie, Anatomie und Physiologie der Rebe. In: F. von Babo & E. Mach (eds.) *Handbuch des Weinbaues*, Paul Parey, Berlin. 6-177.

Kubečka, D., 1968. L'influence exercée par l'espacement sur la système radiculaire de la vigne. *Rev. Hortic. Vitic.,* 17:193-199.

Lagutinska, N.O., 1968. The effect of fertilizers on the development of the root system in vines. *Hort. Abs.,* 40:3397.

Lehnart, R., Michel, H., Lohnertz, O. & Linsenmeier, A., 2008. Root dynamics and pattern of Riesling on 5C rootstock using minirhizotrons. *Vitis,* 47(4):197-200.

Le Roux, M.S., 1941. Studies in verband met die worteldistribusie van die volwasse wynstok. M.Sc. (Agric.) Tesis. Universiteit van Stellenbosch, 7600 Stellenbosch, RSA.

Linares, R., Junquera, P., Lissarrgue, J.R. & Baeza, P., 2009. Influence of the soil management on the root system and its consequences in the agronomic behavior of the vine under Mediterranean climate. 16th Int. GESCO Symp. July 12-15, 2009, Univ. of Calif., Davis.

Linderman, R.G. & Davis, E.A., 2001. Comparative response of selected grapevine rootstocks and cultivars to inoculation with different mycorrhizal fungi. *Am. J Enol. Vitic.*, 52(1):8-11.

Litinov, P.I. & Beskrovnyf, A.S.,1979. The effect of deep cultivation of the soil on grapevine productivity. *Hort. Abstr.,* 49:5736.

Loescher, W.H., McCamant, T. & Keller, J.D., 1990. Carbohydrate reserves, translocation and storage in woody plant roots. *Hort. Science,* 25:274-281.

Loubser, J. & Ueckermann, P., 1997. Integrated approach towards nematodes and phylloxera in vineyards. *Dec. Fr. Grower.,* March, 1997:100-101.

MacVicar, C.N. *et al.,* 1977. Soil classification. A binomial system for South Africa. S.I.R.I., Dept. Agr. Tech. Serv., Pretoria.

Magriso, Y., 1979. Effect of some physical properties of the soil on root system development in the grapevine. *Hort. Abs.*, 51(6):4457 (393).

Magriso, Y. & Toncev, G., 1966. The effect of irrigation on the root system of the vine. *Hort. Abs.*, 36:6284 (730).

Mandel, R., Holzapfel, B., DeGaris, K. & Keller, M., 2001. Identifying manageable factors determining carbohydrate accumulation in reserves and root growth of grapevines after harvest. *Austr. Gr. Grower & Winemaker,* Feb. 2001:10-13.

Marais, P.G., 1988. Grapevine roots and soil-borne fungi. In: *The Grapevine Root and its Environment.* Compiled by J.L. van Zyl. Dept. Agric. Water Supply, Pretoria, RSA. *Tech. Comm.* 215:106-137.

Marais, P.G. & De la Harpe, A.C., 1982. Penetration of 99 Richter grapevine roots by *Phytophthora cinnamomi. S. Afr. J. Enol. Vitic.,* 3:82-86.

Marcelin, H., 1974. La vigne dans le sols du Roussillon. *Progrés agric. vitic.*, 91:548-555

Matuzoc, N.V., 1977. The effect of in-row spacing on the grapevine root system] (Ru). *Hort. Abstracts*, 1978(48):6404.

McKenry, M.V., 1984. Grape root phenology relative to control of parasitic nematodes. *Am. J. Enol. Vitic.* 34(4):206-211.

McLean, M., Howell, G.S. & Smucker, A.J.M., 1992. A minirhizotron system for in situ root observation studies of Seyval grapevines. *Am. J. Enol. Vitic.* 43(1):87-89.

McNairn, R.B. & Currier, H.B., 1967. Sieve plate callose formation in heated pypocotyl a factor in blocking axial phloem translocation. *Pl. Physiol.,* 42:19.

Melkonjan, A.S., Mkrtčjan, R.S. & Davtjan, M.O., 1968. The effectiveness of deep cultivation of interrows in vineyards on stony soils in Armenia. *Hort. Abstr.,* 39:4397, 1969.

Meyer, A.H., Valentine, A.J., Botha, A., Archer, E. & Louw, P.J.E., 2004. Young grapevine response and root colonisation following inoculation with arbuscular micorrhizal fungi. *S. Afr. J. Enol. Vitic.,* 25:26-31.

Meyer, A. & Wooldridge, J., 2008a. Arbuscular mycorrhizal fungi in Western Cape grapevine nurseries (Part I): Varieties and distribution. *WineLand Tech. Yearbook,* 2008/9:73-75.

Meyer, A. & Wooldridge, J., 2008b. Arbuscular mycorrhizal fungi in Western Cape grapevine nurseries (Part II): Spore counts, root colonisation and soil factors. *WineLand Tech. Yearbook,* 2008/9:76-78.

Meyer, A. & Wooldridge, J., 2009a. Arbuscular mycorrhizae (AM) in vineyards (Part I): Effect of AM inoculation, fungicide and rootstock on soil AM populations. *WineLand Tech. Yearbook,* 2009/10:31-33.

Meyer, A. & Wooldridge, J., 2009b. Arbuscular mycorrhizae (AM) in vineyards (Part II): Effects of AM on young grapevine performance. *WineLand Tech. Yearbook,* 2009/10:34-36.

Mirzalieva, N.N., 1968. The effect of the number of buds left after pruning on the development of the root system in vines. *Hort. Abs.,* 40:3383.

Möhr, H.D., 1996. Periodicity of root tip growth of vines in the Moselle valley. *Vitic. Enol. Sci.,* 51(2):83-90.

Morano, L. & Kliewer, W.M., 1994. Root distribution of three grapevine rootstocks grafted to Cabernet Sauvignon grown on a very gravelly clay loam soil in Oakville, California. *Am. J. Enol. Vitic.,* 45(3):345-348.

Morlat, R., 1989. Le terroir viticole: Contribution a l'etude de sa characterisation et de son influence sur les vins. Application aux vignobles rouges de moyenne vallee de la Loire. These docteur des science. Univ. de Bordeaux II, U.E.R Institut d'Oenologie.

Morlat, R., 2008. Long-term additions of organic amendmants in a Loire Valley vineyard on a calcareous sandy soil: II. Effects on root system, growth, grape yield and foliar nutrient status of a Cabernet franc vine. *Am. J. Enol. Vitic.,* 59:364-374.

Morlat, R. & Jacquet, A., 1993. The soil effects on the grapevine root system in several vineyards of the Loire valley (France). *Vitis,* 32:35-42.

Morlat, R. & Jacquet, A., 2003. Grapevine root system and soil characteristics in a vineyard maintained long-term with or without interrow sward. *Am. J. Enol. Vitic.,* 54:1-7.

Morlat, R., Puissant, A., Asselin, C., Leon, H. & Remoue, M., 2010. Quelques aspects de l'ínfluence du milieu édaphique sur l'enracinement de la vigne, consequences sur la qualité du vin. *Association Française pour l'Etude du Sol*-www.afes.fr: 125-145.

Morlat, R. & Venin, G., 1981. Effets compares de deux techniques d'entretien du sol sur l'énracinement de la vigne et sur le milieu édaphique. *Agronomie*, 1(10):887-896.

Mostert, L., Halleen, F., Fourie, P. & Crous, P.W., 2006. A review of *Phaeoacremonium* species involved in Petri disease and esca of grapevines. *Phytopathol. Mediterr.,* 45:S12-S29.

Mullins, M.G., Bouquet, A. & Williams, L.E., 1992. Biology of the grapevine. The Root System: 55-58. Cambridge Univ. Press.

Nagarajah, S., 1987. Effects of soil texture on the rooting patterns of Thompson Seedless vines on own roots and on Ramsey rootstock in irrigated vineyards. *Am. J. Enol. Vitic.,* 38:54-59.

Nassar, A.R. & Kliewer, W.M., 1966. Free amino acids in various parts of *Vitis vinifera* at different stages of development. *Proc. Amer. Soc. Hort. Sci.,* 89:281-294.

Nicol, J.M. & Van Heeswijck, R., 1997. Grapevine nematodes: types, symptoms, sampling and control. *Tech. Issue Austr. Gr. Grower & Winemaker* 1997:139-151.

Omer, A.D., Granett, J., De Benedictis, J.A. & Walker, M.A., 1995. Effects of fungal root infections on the vigor of grapevines infested by root-feeding grape phylloxera. *Vitis* 34 (3), 165-170.

Oniani, D.Y., 1974. The effect of severing grapevine roots on their regeneration. *Hort. Abs.,* 45:1459.

Oprea, D.D., Severin, E. & Taloi, N., 1967. Observations on root regeneration in vines. *Hort. Abs.*, 39:2337 (291).

Oslobeanu, M., 1968. Some aspects of the influence of the scion on the rootstock of bearing vines. *Hort. Abs.,* 39:777.

Parfenenko, L.G., 1968. The root systems of vines planted at different densities. *Hort. Abs.,* 40, 39.

Pellegrino, A., Lebon, E., Voltz, M. & Wery, J., 2004. Relationships between plant and soil water status in vine (*Vitis vinifera L.*). *Plant and Soil,* 266:129-142.

Penkov, M., 1974. The effect of structure of the soil profile on the distribution of the root system of the grapevine. Trans. 10th Int. Congr. Soil Sci., 1:246-253.

Penkov, M. & Dziljanov, B., 1964. The influence of soil conditions on the pattern and vigour of peach root systems. *Hort. Abs.,* 35:544.

Penkov, M, & Spirov, M., 1964. The influence of the soil on the distribution of the root system of certain varieties grafted on different rootstocks. *Hort. Abs.,* 35:5320.

Perold, A.I.,1926. *Handboek oor Wynbou*. Die Uitwendige en Inwendige Bou van die Wynstok: Die Wortel, 25-30. Pro Ecclesia: Stellenbosch.

Perry, R.L., Lyda, S.D. & Bowen, H.H., 1983. Root distribution of four *Vitis* cultivars. *Plant and Soil,* 71:63-74.

Pickering, A.H., Warrington, I.J. & Woollry, D.J., 2009. The impact of root-pruning on early and late bunch stem necrosis. *Austr.Vitic.,* 13:51-52.

Pituc, P., 1965. A study of the root system of terraced vines. *Hort. Abs.* 37:6536.

Pomohaci, M., 1967. New aspects of the structure of vine roots in reddish brown forest soils. *Hort. Abs.,* 39:294.

Pongrácz, D.P., 1968. The identification of dormant grape rootstock cultivars. *S. Afr. J. Agric. Sci.,* 11:655-672.

Pongrácz, D.P., 1969. Vergelykende anatomiese studies van een- en driejarige wingerdwortels (*Vitis* spp.). MSc (Agric.) Tesis. Universiteit van Stellenbosch.

Pongrácz, D.P., 1978. Practical Viticulture. David Philip: Cape Town.

Possingham, J.V. & Groot-Obbink, J., 1971. Endotrophic mycorrhiza and the nutrition of grapevines. *Vitis,* 10:120-130.

Pratt, C., 1974. Vegetative anatomy of cultivated grapes – a review. *Am. J. Enol. Vitic.,* 28:131-150.

Queen, W.H., 1967. Water and entrance through grape roots. *Pl. Physiol.,* 42:18-19.

Rahayu, Y.S., Walch-Lu, P., Neumann, G., Römheld, V., Von Wirén, N. & Bangerth, F., 2005. Root-derived cytokinins as long-distance signals for NO_3^--induced stimulation of leaf growth. *J. Exp. Bot.,* 56:1143-1152.

Randall, W.D. & Coombe, B.G., 1978. Grape roots – repository of many mysteries. *Austr. Gr. Grower & Winemaker,* 15:29-30.

Reeve, N.G. & Sumner, M.E., 1970. Effects of aluminium toxicity and phosphorus fixation on crop growth on Oxisols in Natal. *Soil Sci Soc. Am. Proc.* 34:263-267.

Reynolds, E.R.C., 1975. Tree rootlets and their distribution. In: J.G. Tottey & D.T. Clarkson (eds.). *The Development and function of Roots*. Acad. Press: New York. 163-177.

Ribéreau-Gayon, G. & Ribéreau-Gayon, P., 1971. Biochimie de la vigne et du raison. In: Ribéreau-Gayon & Peynaud (eds.) *Sciences et techniques de la vigne*. Dunod: Paris. 415-485.

Richards, D., 1983. The grape root system. *Hort. Rev.,* 5:127-168.

Richards, D. & Considine, J.A., 1981. Suberization and Browning of Grapevine Roots. In: *Structure and Function of Plant Roots*. R. Brouwer, O. Gasparikova, J. Kolek & B. Loughman (eds.). Junk Publ: The Hague, The Netherlands, 111-115.

Rogers, W.S., 1939. Root studies VII. A survey of the literature on root growth with special reference to hardy fruit plants. *J. Pom. Hort. Sci.,* 17:67-84.

Rogiers, S., 2007. The vascular system: The vine's super highway for transport and communication. *Austr. New Zealand Gr. Grower & Winemaker,* Sept. 2007.

Rogiers, S. & Clarke, S., 2014. Grapevine vegetative and reproductive development respond to soil temperature, *Wine & Viticulture J.,* Nov/Dec 2014:51-53.

Russell, R.S., 1977. Plant Root Systems: Their function and interaction with the soil. McGraw-Hill Book Company (UK): Maidenhead, Berkshire, England.

Saayman, D., 1982. Soil preparation studies: II. The effect of depth and method of soil preparation and of organic material on the performance of *Vitis vinifera* (var. Colombar on Clovelly/Hutton soil. *S. Afr. J. Enol. Vitic.,* 3(2):61-74.

Saayman, D., 1983. Investigations into the causes and control of Growth Arrestment Phenomenon of Sultana. II. Preliminary experimental investigations. *S. Afr. J. Enol. Vitic.,* 4(1):27-34.

Saayman, D. & Van Huyssteen, L., 1980. Soil preparation studies: I. The effect of depth and method of soil preparation and of organic material on the performance of *Vitis vinifera* (var. Chenin blanc) on Hutton/Sterkspruit soil. *S. Afr. J. Enol. Vitic.,* 1(2):107-121.

Saayman, D. & Van Huyssteen, L., 1981. Grondvoorbereiding. In: J. Burger & J. Deist (reds.), *Wingerdbou in Suid-Afrika*. NIWW, Privaatsak X5026, Stellenbosch. Trio-Rand (SA), Litho: N'dabeni, 120-140.

Safran, B., Bravdo, B. & Bernstein, Z., 1975. L'irrigation de la vigne par goutte à goute. *Bull. Off. Intern. Vigne,* 48:405-429.

Sauer, M.R., 1967. Root knot tolerance in some grape vine rootstocks. *Austr. J. Exp. Agric. Anim. Husb.,* 7:580-583.

Schreiner, R.P., 2005. Micorrhizas and mineral acquisition in grapevines. In: Christensen, L.P., Smart, D. (eds.), *Proceedings of the Soil Environment and Vine Mineral Nutrition Symposium*, 49-60.

Schubert, A., 1985. Les mycorhizes à vesicules et arbuscules chez la vigne. *Connais. Vigne Vin* 19:207-214.

Schubert, A. & Cravero, M.C., 1985. Occurrence and infectivity of vesicular-arbuscular mycorrhizal fungi in north-western Italian vineyards. *Vitis:* 24:129-138.

Schuurman, J.J. & Goedewagen, M.A.J., 1955. A new method for the simultaneous preservation of profiles and root systems. *Plant and Soil*, VI(4):373-381.

Seguin, G., 1968. Les discontinuités texturales dans les sols du vignoble bordelaise. *Connais. Vigne Vin,* 2:127-134.

Seguin, G., 1971. Sols de vignobles: Influence des facteurs naturels sur les caractères des vins. In: J. Ribereaux-Gayon & E. Peynaud (eds.), *Sciences et Techniques de la Vigne*, Dunod: Paris, 671-725.

Seguin, G., 1972. Repartition dans l'espace du systeme radiculaire de la vigne. *Compt. Rendus Acad. Sci.*, Paris, 274D:2178-2180.

Seguin, G. & Compagnon, J., 1970. Une cause du dévelopment de la pourriture grise sur les sols gravo-sableaux du vignoble bordelaise. *Connais. Vigne Vin,* 2:203-214.

Semina, N.P., 1965. The effect of scion/rootstock compatability on the condition of the root system. *Hort. Abs.,* 37:733.

Serpuhovitina, K.A., 1969. The root system and productivity of vine bushes in relation to nutrition. *Hort. Abs.,* 40:96.

Skene, K.G.M., 1967. Gibberellin-like substances in root exudate of *Vitis vinifera. Planta,* 74:250-262.

Skene, K.G.M., 1975. Cytokinin production by roots as a factor in the control of plant growth, 365-396. In: J.G. Torrey & D.T. Clarkson (eds.). *The Development and Function of Roots*. Acad. Press: New York.

Skene, K.G.M. & Kerridge, G.H., 1967. Effect of root temperature on cytokinin activity in root exudate of *Vitis vinifera L. Pl. Physiol.,* 42:1131-1139.

Smart, D.R., Carlisle, E., Goebel, M. & Nùñez, B.A., 2005. Transverse hydraulic redistribution by a grapevine (*Vitis rupestris x Vitis berlandieri* cv. 420A). *Plant, Cell & Environment,* 28:157-166.

Smart, D.R., Schwass, E., Lakso, A. & Morano, L., 2006. Grapevine rooting patterns: A comprehensive analysis and review. *Am. J. Enol. Vitic.,* 57:89-104.

Soar, C.J. & Loveys, B.R., 2007. The effect of changing patterns in soil-moisture availability on grapevine root distribution, and viticultural implications for converting full-cover irrigation into a point-source irrigation system. *Aust. J. of Grape & Wine Res.,* 13:2-13.

Southey. J.M., 1992. Root distribution of different grapevine rootstocks on a relatively saline soil. *S. Afr. J. Enol. Vitic.,* 13(1):1-9.

Southey, J.M. & Archer, E., 1988. The effect of rootstock cultivar on grapevine root distribution and density. In: The Grapevine Root and its Environment. Compiled by J.L. van Zyl. Dept. Agric. Water Supply, Pretoria, RSA. *Tech. Comm.,* 215:57-73.

Soyer, J.P., 1984. Techniques d'entretien du sol en vignoble bordelaise. Consequences sur la vigne (Production, vigeur, enracinement, nutrition) et sur le sol apres 20 ans d'experimentation. *Prog. agric. vitic.,* 101:315-320.

Stoev, K. & Rangelov, R., 1969. A contribution on the study of the morphology and physiology of the root system in vines. *Hort. Abs.,* 40:3870.

Swanepoel, J.J., 1983. 'n Vergelykende anatomiese studie met internodia van wingerdlote van onderskeie wingerdcultivars (*Vitis* spp.). M Sc Tesis. Universiteit van Stellenbosch.

Swanepoel, J.J. & Southey, J.M., 1989. The influence of rootstock on the rooting pattern of the grapevine, *S. Afr. J. Enol. Vitic.,* 10:23-28.

Taiz, L. & Zeiger, E., 1998. *Plant Physiology* (2nd ed). Sinauer Associates: Sunderland, Massachusetts.

Tardáguila, J., Bertamini, M., Guilivo, C. & Scienza, A., 1995. Rootstock effects on growth, dry weight partitioning and mineral nutrient concentration of grapevine. *Acta Hortic.,* 338:111-116.

Tomasi, D., Gaiotti, F., Mosetti, D. & Bragato, G., 2015. Influence of soil on root distribution: Implications for quality of Tocai Friulano berries and wine. *Am. J. Enol. Vitic.,* 55:363-372.

Torrey, J.G., 1976. Root hormones and plant growth. *Ann. Rev. Pl. Physiol.,* 27:435-459.

Tromp, J., 1983. Nutrient reserves in roots of fruit trees, in particular carbohydrates and nitrogen. *Plant and Soil,* 71:401-413.

Trouvelot, S., Bonneau, L., Redecker, D., Van Tuinen, D., Adrian, M. & Wipf, D., 2015. Arbuscular mycorrhiza symbiosis in viticulture: a review. *Agron. Sustain. Dev.,* 35:1449-1467.

Van Breda, N.G., 1937. An improved method in the study of root bisects. *S Afr. J. Sci.*, 34:260-264.

Van der Westhuizen, J.H., 1980. The effect of black plasic mulch on growth, production and root development of Chenin blanc vines under dryland conditions. *S. Afr. J. Enol. Vitic.,* 1:1-6.

Van Huyssteen, L. & Weber, H.W., 1980. The effect of selected minimum and conventional tillage practices in vineyard cultivation on vine performance. *S. Afr. J. Enol. Vitic.,* 1:77-83.

Van Huyssteen, L., 1981. Bewerking. In: J. Burger & J. Deist (reds.), *Wingerdbou in Suid-Afrika*. NIWW, Privaatsak X5026, Stellenbosch. Trio-Rand (SA) Litho: N'dabeni. 283-307.

Van Huyssteen, L., 1983. Interpretation and use of penetrometer data to describe soil compaction in vineyards. *S. Afr. J. Enol. Vitic.,* 4:59-56.

Van Huyssteen, L., 1988a. Soil preparation and grapevine root distribution – a qualitative and quantitative assessment. In: The Grapevine Root and its Environment, 1-15. Compiler, JL van Zyl. *Tech. Comm.* 215, Dept. Agric. & Water Suppl., RSA.

Van Huyssteen, L., 1988b. Grapevine root growth in response to soil tillage and root pruning practices, 44-55 In: The Grapevine Root and its Environment. Compiler JL van Zyl. *Tech. Comm.* 215. Dept. Agric. Water Suppl. Pretoria, RSA.

Van Leeuwen, C., Tregoat, O., Choné, X., Pernet, D. & Gaudillère, J.P., 2009. Vine waterstatus is a key factor in grape ripening and vintage quality for red Bordeaux wine. How can it be assessed for vineyard management purposes. *J. Int. Sci. Vigne Vin.,* 43:121-134.

Van Rooyen, F.C., 1980. The water requirements of table grapes. *Decid. Fr. Gr.,* 30:100-105.

Van Rooyen, F.C., Weber, H.W. & Levin, I., 1980. The response of grapes to a manipulation of the soil-plant-atmosphere continuum. I. Growth, yield and quality responses. *Agrochemophysica,* 12:59-68.

Van Rooyen, M., Valentine, A. & Archer, E., 2004. Arbuscular mycorrhizal colonization modifies the water relations of young transplanted grapevines (*Vitis*). *S. Afr. J. Enol. Vitic.,* 25(2):37-42.

Van Zyl, J.L., 1984a. Interrelationships among soil water regime, irrigation and water stress in the grapevine (*Vitis vinifera* L.). PhD dissertation. Stellenbosch University, 7600 Stellenbosch, Republic of South Africa.

Van Zyl, J.L., 1984b. Response of Colombar grapevines to irrigation as regards quality aspects and growth. *S. Afr. J. Enol. Vitic., 5*(1):19-28.

Van Zyl, J.L., 1988. Response of grapevine roots to soil water regimes and irrigation systems. In: *The Grapevine Root and its Environment*. Compiled by J.L. van Zyl. Dept. Agric. & Water Supply, Pretoria, RSA. *Tech Comm.*, 215:30-43.

Van Zyl, J.L. & Van Huyssteen, L., 1980. Comparative studies on wine grapes on different trellising systems: Consumptive water use. *S. Afr. J. Enol. Vitic.,* 1(1):7-14.

Van Zyl, J.L. & Van Huyssteen, L., 1987. Root pruning. *Dec. Fr. Grower,* 37:20-25.

Van Zyl, J.L. & Weber, H.W., 1981. Effect of various supplementary irrigation treatments on plant and soil moisture relationships in a vineyard (*Vitis vinifera* var. Chenin blanc). *S. Afr. J. Enol. Vitic.,* 2:83-89.

Van Zyl, S., Viviers, M.A. & Walker, M.A., 2012. *Xiphenema index* and its relationship to grapevines: A review. *S. Afr. J. Enol. Vitic.,* 33:21-32.

Vascenko, I.M., 1966. The influence of temperature on the formation of root systems. *Hort. Abs.,* 37:523.

Volder, A., Smart, D.R., Bloom, A.J. & Eissenstat, D.M., 2005. Rapid decline in nitrate uptake and respiration with age in fine lateral roots of grape: Implications for root efficiency and competitiveness. *The New Phytologist,* 165:493-501.

Volder, A., Anderson, L.J., Smart, D.R., Bloom, A.J., Lakso, A.N. & Eissenstat, D.M., 2009. Estimating nitrogen uptake of individual roots in a container- and field-grown plants using a N^{15} depletion approach. *Functional Pl. Biol.,* 36:621-628.

Wang, S., Okamoto, G., Hirano, K., Lu, J. & Zhang, C., 2001. Effects of restricted rooting volume on vine growth and berry development of Kyoho grapevines. *Am. J. Enol. Vitic.,* 52:248-253.

Wapshere, A.J. & Helm, K.F., 1987. Phylloxera and Vitis: An experimentally testable coevolutionary hypothesis. *Am. J. Enol. Vitic*. 38(3), 216-222.

Williams, L.E. & Smith, R.J., 1991. The effect of rootstock on the partitioning of dry weight, nitrogen and potassium, and root distribution of Cabernet Sauvignon grapevines. *Am. J. Enol. Vitic.,* 42(2):118-122.

Wilson, S.A. & Atkinson, D., 1979. Water and mineral uptake by fruit tree roots, 372-382. In: *Root physiology and symbiosis*. (eds.) A Riedacker & J. Gagnaire-Michard. *Proc. Int. Union for Res. Org. Symp.,* 1978. Centre Natl. Res. For., Nancy, France.

Winkler, A.J., 1962. General Viticulture. Univ. Calif. Press: Berkeley and Los Angeles.

Winkler, A.J. & Williams, W.D., 1945. Starch and sugars of *Vitis vinifera. Plant Physiol.,* 20:412-432.

Winkler, A.J., Cook, J.A., Kliewer, W.M. & Lider, L.A., 1974. *General Viticulture*. Univ. Calif. Press: Berkeley, Los Angeles, London.

Woodham, R.C. & Alexander, D. McE., 1966. The effect of root temperature on the development of small fruiting Sultana vines. *Vitis,* 5:345-350.

Zelleke, A. & Kliewer, W.M., 1980. Effect of root temperature, rootstock and fertilization on bud-break, shoot growth and composition of Cabernet Sauvignon grapevines. *Scientia Horticulturae,* 13(4):339-347.

Zerebkov, F.F., 1966. The formation of root systems on deep soils. *Hort. Abs.,* 37:523.

ACKNOWLEDGEMENTS

Lucinda Heyns for technical and organisational support in writing this book. Her effective liaison with the designers, linguists and printers lightened our workload tremendously.

Jan Booysen for valuable contributions to the technical contents and editing of the text as well as technical advice to the outlay of the book.

Dr. Jakob Deist for his leadership and contributions to our careers for many years as well as for his typically thorough contribution to the technical correctness of this work. His preface is a testimony of his insight and love for viticulture.

Dr. Albert Strever for valuable inputs to ensure the technical correctness of this work. His preface is clear proof of his unquestionable skills to teach and train future viticulturists.

Anne Kruger for the linguistic editing.

AFRICAN SUN MeDIA for the layout and design of this book.

Vine Roots is the result of identified industry priorities researched and written by two veteran technical role players. Special emphasis is placed on classic historical contributions made by highly regarded international specialists – This information is not readily accessible to all. Furthermore, it covers all aspects of grapevine roots, such as the growth, morphology, anatomy, physiology and functions thereof. It also gives a review of methods of root investigations, as well as factors that affect the growth and distribution of grapevine roots. This is followed by a discussion of techniques aimed at the maintenance of grapevine roots in order to make grapevine cultivation in South Africa viable and sustainable.

UNIVERSITEIT STELLENBOSCH UNIVERSITY

MONASH SOUTH AFRICA | villa

MONASH SOUTH AFRICA IN PARTNERSHIP WITH VILLA, YIELDING A BETTER TOMORROW

IGWS
INSTITUTE FOR GRAPE AND WINE SCIENCES