

Periodic drought effects on afrotemperate forests in the Southern Cape of South Africa

by

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Declaration

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Abstract

Understanding the effects of climate change is one of the cardinal issues within the natural resource management circles. Increased droughts are part of these changes. Afrotemperate forests, as well as their drier Afromontane counterparts suffer from periodic and seasonal droughts respectively. To better understand the effect of droughts on these forests, three key species namely *Olea capensis* (Iron wood), *Podocarpus latifolius* (Common Yellow wood) and *Pterocelastrus tricuspidatus* (Candle wood), were analysed using dendroecologic techniques. Two sites in the Southern Cape were selected according to a West-to-East moisture gradient, with the drier site being close to George and the medium moist site at the Diepwalle estate in the vicinity of Knysna. Growth ring measurements from each of the species were used to calculate basal area and basal area increment during the lifetime of the trees. Drought years for the sites were then selected based on the Standardised Precipitation and Evapotranspiration Index (SPEI), also indicated by the growth during the drought periods. Differences in growth patterns for all three species were observed. An event analysis was then used to quantify the difference in the resistance (R_t), recovery (R_c), resilience (R_s) and relative resilience (RRs). With values standardised around one (R_t , R_c and R_s) and zero (RRs), it was seen that the Candle wood had the highest (~0.92) resistance and the Yellow wood had the highest (~1.3) recovery after the drought. Iron wood stood apart from the other two species in the sense that it only reacted negatively towards the drought one year after the event in most cases. It was concluded that each of the species were significantly different in their reactions towards drought. This specific difference in drought reaction can give way to the possibility that the species together adapted to relieve the stress of a short drought by splitting the available resources over a longer period.

Opsomming

Dit is van uiterse belang vir bestuur doeleindes om die veranderende klimaat oor die wêreld te verstaan, insluitend die droogtes wat daarmee gepaard gaan. Die *Afrotemperate* woud-tipe, asook sy droeër teenstaander, die *Afromontane*, lei gereëld aan sporadiese en seisonale droogtes. Om hierdie woud-tipe se reaksie tot droogtes beter te verstaan, was drie boom spesies naamlik Ysterhout (*Olea capensis*), Kershout (*Pterocelastrus tricuspidatus*) en gewone Geelhout (*Podocarpus latifolius*), gekies vir die gebruik in 'n dendro-ekologiese studie. Twee areas was gekies van 'n westot-oos droogte gradient, met die droeër blok in die George omgewing en die meer vogtige een naby aan Knysna. Die jaarring metings van elke boom was gebruik om beide die basale oppervlakte en die basale oppervlak groei per jaar aan te teken. 'n Gestandaardiseerde reenvol en evapotranspirasie indeks (SPEI) was gebruik om vas te stel jare waarin matige tot sterk droogtes gebeur het. Hierdie gekose jare het aanduiding gegee dat daar wel 'n verskil waargeneem was in die groei patrone van elke spesie gedurende die droogtes. 'n Gebeurtenis analise is gebruik om 'n kwantitatiewe verskil te kon sien in die weerstand (R_t), herstel (R_c), weerstandbiedendheid (R_s) en relatiewe weerstandbiedendheid (RRs). Die was waargeneem dat Kerhout die hoogste weerstand (0.92) toon, terwyl die Geelhout 'n hoër herstel waarde (1.3) gehad het. Ysterhout het apart van die ander twee spesies gestaan in die dat dit eers een jaar na die droogte 'n reaksie getoon het teenoor die droogte. Dit was dus gevind dat daar spesifieke verskil is tussen al drie van die spesies teen opsigte van stres reaksies was. Hierdie verskil kan dan wel ook moontlik aandui dat hierdie spesies en woud-tipe op so 'n anier aangepas is dat dit die stress gedurende 'n kort droogte versprei oor 'n langer tydperk.

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List of abbreviations

ARC – Agricultural research council

DBH – Diameter at breast height

dpIR – Dendrochronological program library in R

DWAF – Department of water affairs and forestry

GLK – Gleichlaeufigkeit

GLMM – Generalized linear mixed models

PDSI – Palmer drought sensitivity index

SPEI – Standardized precipitation and evapotranspiration index

SPI – Standardized precipitation index

Rc - Recovery

RRs – Relative resilience

Rs - Resilience

Rt - Resistance

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1. Introduction

The field of tree ring based sciences is rapidly developing. Dendrochronology in broad sense is often used collectively for all tree ring based science fields (Schweingruber 1996, Planchon *et al.*, 2008). It involves for example dendroecology, which tries to contribute to the understanding of how environmental variables affect physiological processes and tree ring formation (Schweingruber 1996). Other fields are for example dendroclimatology, where the focus lies on establishing correlations between tree ring growth and climate based on recent measurements and then use this information to reconstruct the climate of past times where no climate records are available. The analysis of tree rings leading historical chronologies are known as dendrochronology in the specific sense. Dendrochronology thus deals with dating of tree rings and contributes for example to dating of old buildings or archaeological artefacts (Schweingruber 1996). In this thesis dendrochronology is further on used in its broader sense.

All of those tree ring based branches of science are based on the principle of tree ring formation, which is dictated by intrinsic responses to climate, external factors such as fire and competition with neighbouring trees (Fritts, 1976). Establishing chronologies over time gives one a better understanding of how past events affected trees in a certain area, which can improve the understanding of how environmental processes today, will affect trees in the future. Understanding how each of the factors contributing to ring formation affects the stand, will also help one to do better planning for management and resource utilization.

Amongst many others Dang (2006) recognised dendrochronology as a tool to be used for tree dating linked to climatic factors and radial growth. Though according to Worbes (2004) dendrochronology should be seen not only as a tool within science, but rather as an independent section in the natural sciences. In the sixteenth century, Leonardo da Vinci first recognised that there is a link between the width of year rings and climate. Because of this, he is seen as the “*father of dendrochronology*” (Worbes, 2004). Fritts (1976) claims that Andrew E. Douglass is the acknowledged “*father of [modern] dendrochronology*”. Douglass was a researcher at the Harvard college observatory, where he researched the effects of sunspots on climate, specifically precipitation. In 1904, he recognised ring patterns in stumps around the Flagstaff area in Arizona. But it was not until 1911 that he fully realised that he could use crossdating to determine sequential and relative dates for climatic events in areas where tree growth was regularly limited by climate. Through this, he was the first to realise

the full potential of crossdating based on tree rings, and therefore could be rightfully seen as the founder of dendrochronology as a science.

Douglass' discovery led to two major breakthroughs for dendrochronology; firstly that the tree rings could be used as a calendar to date every growth ring, but only if the date of the outer-most ring is known; and secondly that these tree ring calendars would be a representation growing conditions and would thus reflect past climatic developments and events. The use of tree rings for forest sciences thus follows two main aspects: (1) to reveal the reaction of trees to past environmental conditions and thus explain their growth (a branch of dendroecology) and (2) to use tree rings as proxy variables (surrogates) to reconstruct past environmental conditions (dendroclimatology). It is important to note that the second aspect fully relies on results of the first.

1.1 Application of dendrochronology

Tree rings are an exceptionally good source of sample data. The reason for this is because single year rings are easily measured and can easily be distinguished from others to form a sequential database to be linked with climate data. These rings can then be specifically dated to find the exact times for biotic occurrences or abiotic incidents. Gates and Mintz (1975) stated that little or no other source can so easily provide both accurate datability and good continuity. There are also very few other sources which can be as easily replicated and measured as that of tree rings.

To better understand variations in climate and identify specific events, climatic reconstructions from tree ring data could be used to date back events before climate records were constructed. Dating climate variations in this manner can help to extend climate knowledge to such an extent that it can increase today's statistics on climate variability (Fritts, 1976). Improvements such as this will help to better understand past climate events, as well as to predict future patterns and climate effects (Gates and Mintz, 1975). Results of Lamb *et al.* (1966) and Ladurie (1971) have helped to understand climate variability for the past thousand years, through the use of dendroclimatology. This data is however restricted to North-America and Europe. It can be expected then, that as dendrochronology and dendroclimatology are applied in further regions, better knowledge on climate variability will become available at a global scale. Sheppard (1966) speculated that the use of tree rings to piece together past climate events would help atmospheric scientists to better predict future climate variations. The implication of this is that one would be able to better distinguish

between natural climate situations and changes relative to unnatural and man-caused shifts in climate.

The problem with using trees to date back climate events is that trees can form rings irregularly. The usual ring formation in temperate climates starts in spring and continues through to summer where it then stops summer end, or at the start of autumn. Sharp boundaries are formed between individual years (Fig. 1), since the latewood has thicker cell walls than its earlywood counterpart.

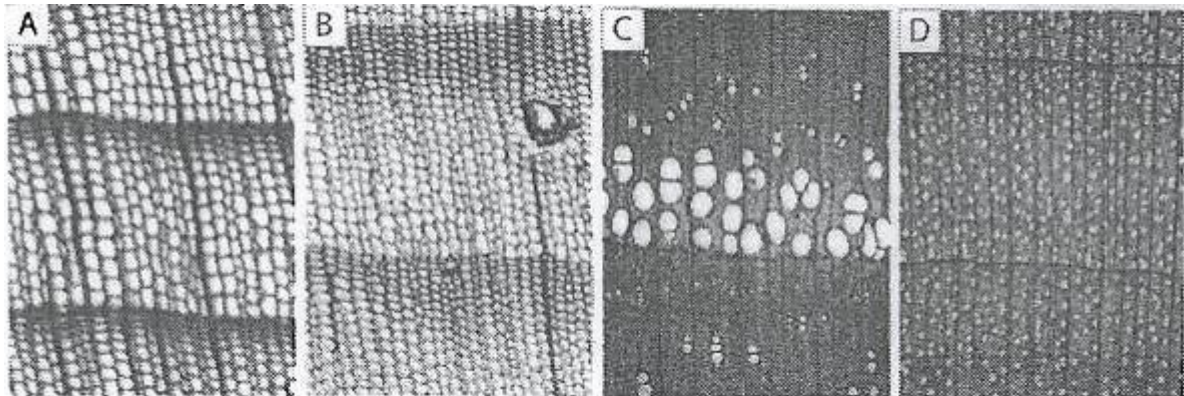


Figure 1: Micro-sections of different tree rings from conifer and broadleaved trees: In (A) *Picea abies* and (B) *Pinus cembra*. In (A) and (B) the bands of tracheids form the individual increment rings. In broadleaved trees tracheids and vessels are formed by the dividing cambium. Depending on the distribution of the vessel in the ring, a distinction between: (C) ring-porous (*Fraxinus excelsior*) and (D) diffuse-porous angiosperms (*Acer pseudoplatanus*) (Stoffel and Bollschweiler, 2008).

1.1.1 South African species in dendro-ecology

Some tree species are better suited for dendrochronology than others, since the growth and ring structure may differ significantly, with specific focus on false year rings and missing rings (Fritts, 1976; McNaughton and Tyson, 1979). A specific case study by Lilly (1977) in South Africa identified 108 tree species which would be potentially suitable for use dendrochronology (McNaughton and Tyson, 1979). However, very little research has been done on dendrochronology in South Africa. The earliest published dendroclimatological research was done on *Acacia erioloba* in south western Africa by Walter in 1940. This already showed some relationship between rainfall patterns and ring-widths.

In the past, *Podocarpus* species have been amongst the most frequently used species for dendrochronology research in South Africa (February & Stock, 1998). With the limited climate data in Southern Africa, it is imperative to first find a suitable species before long-term chronologies can be built. A multitude of methods, as described by Lilly (1977), McNaughton and Tyson (1979) and Fritts (1976), has been established to build chronologies

from stem samples as a surrogate for rainfall and climate data (February & Stock, 1998). Although most South African authors used *Podocarpus* species stem samples for their studies, there are still differing opinions (February & Stock, 1998) as to whether these species are actually suitable for use in building chronologies. It is argued by February and Stock (1998) that due to the amount of false- and converging year rings, that *Podocarpus* species cannot be dated accurately, and are therefore not suitable for dendrochronology.

Among the species that Lilly (1977) identified for the use in dendrochronology is the Cape Iron wood (*Olea capensis* spp. *Macrocarpa*) and the Candle wood tree (*Pterocelastrus tricuspidatus*). These species, along with *Podocarpus latifolius*, grow in the same area and can thus be compared for dendroecological fitness. These species were specifically selected from the list by Lily (1977) for their growth rates and because they are dominant (keystone) species within the Afrotropical forests.

As mentioned previously, some species are better suited for dendrochronology than others. Some gymnosperms form more distinguishable rings, whereas with some angiosperms the borders between tree rings can be less visible (Fig. 1).

Another issue to address is the validity of each year ring within a single tree. Tree growth is affected by both external sources such as climate, soil nutrients or available water, and internal factors which includes enzymes, growth regulators (Fritts, 1976). The latter are often correlated with tree age and ontogenetic differences. The problem is that limiting internal factors are often results of external situations which only reflect in the growth a year (one growing season) later (Worbes, 2004). This can cause misleading interpretation of the growth rings. In short but severe climate events, the tree can shut down for a very short period, and begin to grow again in the same season. This will cause a premature latewood formation in that year and after the conditions improved another zone of earlywood and latewood which makes it look like two growth rings in that same year. This phenomenon is called a 'false ring'. Similarly, a tree can experience conditions in which it does not grow at all during a season, and will therefore have a "missing ring". Obviously missing and false rings are a challenge for tree ring dating. The only method to ensure that these false and missing rings do not impact on the study is a cross-sectional analysis of many trees, preferably from multiple species in the same area or even to use multiple samples from the same tree, just taken at different aspects or heights (Pilcher and Munro, 1987).

Pointer years are used to link ring series of different individual trees to one another. Pointer years are years in which wide spread events affected all trees in the same region, e.g. exceptionally dry years or years with large scale insect defoliations (Fritts, 1976). In

chronology construction, pointer years should fall in line for feasible results. With pointer years one can then use a core from a living tree and a sample from roof trusses, partly fossilised trees or railway sleepers to construct a chronology for periods before a single tree's lifetime (Worbes, 2004). Each chronology can then be used to describe past climatic and abiotic events, assuming that the tree species reacts toward stresses to the same extent as previous generations (Uniformitarian principle by James Hutton).

The Kyoto protocol of 1997 clearly stated the significance of different forest systems on the global carbon balance. Because of this it is of cardinal importance to understand how the forest (dry-, woodland-, tropical-, temperate- and Taiga forests) will react to climate change. Understanding the base processes and reactions will enable one to model future scenarios and plan ahead into the ever changing climate change phenomenon (Either natural or caused by humans). This understanding of growth and resource allocation will help to maintain and improve carbon sinks around the world. Dendrochronology then forms a big part of this in building climate calendars, determining growth, understanding competition and much more. Modelling future scenarios will enable humans to better manage the natural resources instead of over-exploiting them due to a lack of understanding.

1.2 Dendrochronological principles and concepts

According to Fritts (1976) dendrochronology and here particularly dendroclimatology follows the following principles:

1. **The Uniformitarian principle:** This principle was originally proposed by James Hutton, 1785. It is commonly stated as "*The present is the key to the past*". This can be directly applied to dendrochronology. Occurrences, events and disasters affects the physiology of trees the same today as it would have in the past. This does not, however, mean that there was the same climate in the past than now, but simply that the effects are still the same. It is important to note is that if the present circumstances do not include those of the past, accurate extrapolations cannot be made on the tree ring data.
2. **Limiting Factor principle:** Various authors, such as Liebig (1840), wrote about the law of the minimum. This law states that any biological process is limited by the scarcest resource. As soon as one limiting resource is increased, growth will increase accordingly until the next factor is limiting. For dendrochronology, a limiting

factor must persist over a large enough geographical area for a significant amount of time to be used for crossdating. Latewood rings provide better information on limiting factors than the wider earlywood. In conditions with ample resources and little stress, trees would be limited by internal, rather than external factors. Because of this, these trees will not crossdate significantly.

3. **Sensitivity:** Some trees have a more severe reaction towards limiting factors than others. This is referred to as sensitivity, as opposed to complacency. This sensitivity is indicated by the variance in the widths of the latewood. For this reason certain species are also better suited for dendrochronology than others.
4. **Crossdating:** Within the field of dendrochronology crossdating is the most important verification tool. Worbes (2004) states that one of the best methods utilised for crossdating is the use of “pointer years”. These are years in which known events, such as severe drought or fires, occurred and left distinct patterns within the growth rings of the tree. Crossdating is done by firstly using samples within the same tree for comparison of the growth rings. The next step would be to compare samples of different trees within the same stand. And lastly to compare samples from various areas which was affected by the same climatic event. Crossdating itself is proof that climatic events or other limiting factors affect trees of multiple species in the same manner.
5. **Repetition:** By using various samples from the same area, neighbouring areas and samples within the same tree, one can more easily identify false year rings. Additional verification is obtained by using samples from other sources (other species; different localities) to confirm climatic findings.
6. **Standardization:** Due to differences in the growth rate of trees at different ages, as well as shaded vs. non-shaded trees, one should standardize the ring-width curve. This involves a mathematical detrending of the tree ring widths to remove the age-related trend and have only the tree ring signal of short term reactions to environmental variable left. Creating standard indices facilitates the comparisons of different samples across different age and strata classes.
7. **The principle of the aggregate tree growth model:** This principle states that tree will record everything that affects their growth within the lifetime in the annual rings. Cook (1985, 1992) conceptualised the idea of this model into an equation (equation

one), where R_t is the ring width at year t , G_t is the age- (or size-) related growth trend, C_t is the climate, D_1 is the endogenous disturbances in the stand, D_2 is the exogenous disturbance from without the stand and E_t is the error term factoring in the effects which are not captured by the aforementioned effects.

Equation 1: Aggregate tree growth model

$$R_t = f(G_t, C_t, D_1, D_2, E_t)$$

8. **The concept of auto-correlation:** Auto-correlation is the effect of a variable where it correlates with itself over time. All living creatures are subject to auto-correlation because they follow a linear path through time. Auto-correlation is then a measure of how the past affects current or future growth. In trees it can be applied that the previous years' climatic conditions will have an effect on how the tree growth in the current year. This can be seen by the fact that trees can store carbohydrates during times of stress, or create more complex root structures in search of water. The effect can then be perceived by the increased growth in a "good" year, with the larger root stock.
9. **The concept of ecological amplitude:** Ecological amplitude can be defined as the pattern which the vegetation occurs on a landscape. This is then influenced by the topography, slope aspect and other edaphic variables. Through this it can then be assumed that the vegetation will have minimal stress in the centre of the range, vs. the edges. It is therefore recommended that species selection is done at the edges of the range, so that one can more easily detect the climate variable to be tested. If multiple species are selected, multiple ranges where they all occur could be recommended.

1.3 Sampling and tree selection

Most commonly Pressler type increment borers are used to sample trees (Fig. 2), with some fewer studies using whole stem discs for these analyses (e.g. Seifert et al. 2010a). The main reason for the use of cores instead of discs is the ease of handling and obtaining the samples, as well as having a minimally invasive technique at hand that does not require the felling of trees. However, core sampling leaves a hole in the stem.



Figure 2: Haglof increment borer with extractor tray and core sample

According to Grissino-Mayer (2003) the method can nonetheless be regarded as non-destructive, since the created pockets are filled with resin quickly and the tree can compartmentalise the damage around the hole. Broadleaved species on the other hand are more susceptible to fungal attacks and discolouration within the wood. In cases such as these it is advisable to disinfect and seal the hole. Some studies on the other hand show that plugging the hole may in fact slow the process of compartmentalization and it is therefore advised against such procedures (Shigo, 1984). Sampling should in any case be done in periods when the risk of fungal attack is minimal (Grissino-Mayer, 2003) and all phytosanitary measures should be taken to prevent spreading of diseases through boring.

Non-destructive sampling is one of the most important factors when dealing with a potentially sensitive forest type or protected tree species. However, the use of cores generally should be tested on a species using stem discs first, where false and wedging tree rings might be detected more easily (McNaughton and Tyson, 1979).

Finally, trees for core sampling should be selected on sites or areas where the environmental factors to be tested are most likely limiting tree growth (Fritts, 1976) (see ecological amplitude above). On a chosen site one can then either select trees at random, use a stratified sampling across diameter classes or take samples from the biggest and therefore most likely oldest trees to extend the length of the chronology if that is the main objective. The tree borer is then used to extract the core, a small cylinder of wood, from the selected tree in a radial direction. To reduce directional slope bias (sunlight, lean) all the samples should be cored from the same aspect. To cater for cross-sectional stem form

irregularities two samples can be taken from each tree in different directions (North and East in the case of this study), preferably at 90 degrees. This will also increase the dating success because if both cores include the pith and were taken at the same height in different aspects the presence of false tree rings that do not encompass the full circumference of the tree ring can be detected by deviations in the ring numbers between the two cores.

After the core sample has been obtained infield, it can be safely stored for transport to the laboratory. The samples should then be removed in the lab to be dried and mounted on a sample tray. These trays can be manufactured from various materials, depending on the kind of analysis which will be used. With microscope analysis, there is little difference in the selection of the material used for the tray as long as the sample can be clearly seen.

1.4 Drought effects on sites and trees

According to the IPCC (2007), times of limiting nutrient resources and water stress (linked with drought events) is set to increase when climate changes as it is currently. Rapid climate change is said to have an extreme effect on plants which are not able to activate metabolic pathways or adapt fast enough to the changing conditions. Temperature stress (coupled with moisture stress) is one of the most severe stresses for plants, since it has a direct effect on the metabolic- and knock-on processes which directly affects the growth and resource allocation (Rennenberg, 2006).

Through the use of the aggregate tree growth model (Principle 7) it can be seen that there are two main influences which contributes to the growth of a tree; Internal- and external effects. Internal effects can be defined as genetics, species, adaptations and other intrinsic factors. External effects would then be competition, climate, pathogenic attacks and a multitude of environmental or human-caused factors.

1.4.1 Ecophysiological effects:

Two of the main processes in plants is photosynthesis and respiration. These two processes are predominantly influenced by moisture availability, humidity, transpiration and temperature (Kozlowski et al., 1991). The ideal temperature for photosynthesis is (in most cases, for C₃ metabolic plants) below that of 30°C (Rennenberg et al., 2006), with rare

exceptions of adaptations. It is known that high temperature has an inhibiting effect on different pathways in photosynthesis, by reducing the effectivity of Rubisco (1,5—biphosphate carboxylase/oxygenase) and photosystem II (Lea & Leegood, 1999; Berry & Bjorkman, 1980; Yordanov et al. 1986). In cases of stress the rate of respiration will surpass the rate of photosynthesis, causing the plant to exude more CO₂ than it can absorb.

Drought in itself does not directly reduce the efficiency of photosynthesis, but rather has an effect on how well the plant can absorb carbon dioxide into the chloroplasts. Additionally, with moisture stress, the stomata will close, reducing the effect of photosynthesis (Flexas et al., 2004). According to Rötzer et al. (2012), drought stress can be defined by intensity, duration, frequency and time of occurrence. Many authors agree that only prolonged drought events have a significant effect on biochemical reactions in plants and that moderate droughts have a reduced effect as soon as resistances and slight adaptations kick in (Bota et al., 2004; Tezara et al.; 1999; Flexas et.al, 2004).

Increased temperature and decreased water availability also have an effect on the potential nutrient uptake and availability of plants (Gessler et al., 2004a). Chapin et al. (1995) states that increased temperature could increase available nitrogen and phosphorous in a system due to enhanced microbial activity. However, this effect is completely opposite when the available moisture is reduced. Dise et al. (1998) mentions that throughfall is the main driver of nutrient fluctuations and thus availability at the soil surface (Generally for temperate forests). In South-African afrotemperate forests, water is seen as one of the biggest drivers of growth.

1.4.2 Competition effects

Competition can be seen as a negative effect on an individual whilst in the presence of another individual competing for the same resources (Seifert et al., 2014). Although this definition emphasises the negative aspects of interaction, there could also be direct and indirect positive effects stemming from tree–tree interaction. Mature trees protecting adolescent and developing trees from storms and severe winds would be an example of an indirect positive facilitation effect. Although multiple competition indices and models are available for less complex forests, the afrotemperate forest in South Africa has yet to be thoroughly researched. The reason for this is the immense amount of tree species (at least 102 according to the measurement data by SANParks, 2012). This complexity is aggravated

even more so by the inclusion of vines, sub-canopy bushes and brush/herbaceous floor plants and creepers.

When focussing on competition within tree species there are generally three factors, which one has to take into account. Firstly there is the competition for light. Generally light demanding species can be shade tolerant whilst young, but lose the tolerance as they age (Valladares & Niinemets, 2002). This, however, is not the case for all species as their light sensitivity can vary depending upon age, species and sub-species adaptations. Secondly there is the competition for nutrients. This is closely linked with the third factor, namely competition for water. Both of these factors rely heavily on the development of an individual tree's root system. It can be in conclusion said that there are two directions of interaction; competition for above and competition for below ground resources. Both forms of competition can then be quantified using multiple indices by using spatial and allometric measurements (Seifert et al., 2014).

1.4.3 Quantifying Drought

Drought can be described as a long period without precipitation although it is difficult to determine the severity, spread and duration. Though various drought indices are used, the subjective definition of drought has made it difficult to ensure universal and objective indices (Heim, 2002). In recent years, multiple authors (e.g. Gonza'lez and Valde's, 2006; Keyantash and Dracup, 2004; Wells et al., 2004; Tsakiris et al. 2007) have been creating and improving existing drought indices to ensure accurate and quantifiable periods of moisture stress. It can thus be concluded that the use of a specific drought index depends on the available data and the objectivity of the research.

1.5 Objectives and Key Questions

Larger and older trees should be less affected by drought and moisture stress than smaller trees, because of the increased size of the root system, which offers them access to deeper soil levels. On the other hand it could be argued that because of the sheltering effect created by the larger trees, the younger trees and saplings are protected and suffer less from transpiration stresses. With this complex relationship of differing microclimates, it is difficult

to gauge whether there would be a different reaction towards drought stress over the varying diameter classes.

The effect of differing diameter is amplified by the fact trees of different strata ranging from the forest floor to the upper canopy (Seydack et al., 2011). It could therefore be expected that some of the species would have different reactions during the drought and recovery thereafter according to the crown stratum they occupy.

The first objective of this study is to see whether the species will have different reactions towards drought with respect to resistance, recovery and resilience. Since each of the species has unique growth patterns and locations, it is necessary to see if they also differ when times of stress occurs.

The second objective is to see how each of the species reacts towards drought on two different sites. The sites are both afro-montane forests, but one has slightly more dry conditions. The drier conditions may either cause benefits for the tree species, or the highly increased moisture stress could inhibit growth completely.

2. Materials and Methods

2.1 Characterisation of the study area around Groenkop

The afro-temperate forest of South Africa occurs between Mossel Bay and Port Elizabeth in pockets ranging from <1ha up to large forests of 1000ha – 25800ha (Geldenhuys, 1991). These forests occur into three zones, namely upper mountain slopes, coastal platform and scarps along the coast and river valleys. Groenkop is classified as a dry-High forest/Medium moist forest mixture (Breitenbach 1974) and can be seen as a high coastal scarp forest. The following information originates from a report on the classification of indigenous forests in South Africa (DWAF 2003).

2.1.1 Geology and Soil

According to DWAF (2003) the coastal platform forests are generally situated on drier sites with lower rainfall and better drainage. Their altitude ranges from 340m – 1000m above sea level and they generally have a South to South-western aspect, but they do cover all aspects.

The soils are of Kaaimans formation, stabilised dunes, sandstone and shale types with widespread podzol forms in between. The sites are physiologically dry and generally have an above-average nutrient content. Soil pH ranges between 5.4 and 6.9.

2.1.2 Climate

The average annual rainfall for the Afrot temperate forests range from 500mm in the west to 1200mm in the centre of the forest range. The Groenkop site has a mean rainfall of 860mm over the past 40 years, where Diepwalle (being the more moist site) has had an average annual rainfall of over 1100mm. This is indicated by data obtained from the Agricultural

Research Council in 2012. Maximum temperature ranges from 15°C to 25°C while minimum temperature has a range of 9°C to 19°C (winter and summer respectively for both sites).

2.1.3 Forest structure

The forest structure of Afrotropical forests was classified by von Breitenbach in 1974. The forests in the Southern Cape are dominated by canopy species such as *Podocarpus latifolius*, *Podocarpus falcatus*, *Curtisia dentata* and *Apodytes dimidiata*. It is usually classified as high forests with a dominant height of 15m-25m. The Groenkop area, where some of the samples of this study have been taken, specifically is a Medium-moist high forest, but is on the border of being classified as a Dry-High forest. For this study, the site at Groenkop will be treated as a dry forest, when compared to the moister Diepwalle site. This site forms part of the Farleigh estate in the immediate vicinity east of George (Fig. 3). Diepwalle is situated north of Harkerville, on the R339 to Uniondale from Knysna.

The dry-high forest has sparse undergrowth, and is dominated mainly by *P. latifolius*, with infrequent occurrences of other tree species. Similar in composition to the specific dry-High forest, the medium-moist High forest is dominated by multiple species including *Olea capensis*, *Podocarpus latifolius* and *Pterocelastrus tricuspidatus*.

The Groenkop forest is then an ideal location to do a dendrochronological study on, since it is in a moisture deprived area. As mentioned before Fritts (1976) recommends that sites with a specific growth limiting factor (drought, soil nutrients, light) should be used in these studies because they react faster and more clearly towards changes in the specific limiting factor. This also relates back to the principle of ecological amplitude and Liebig's Law of the minimum. However, since multiple species were used, each with their different ecological distribution, both sites have been identified as potential "borders" of natural growth zones.

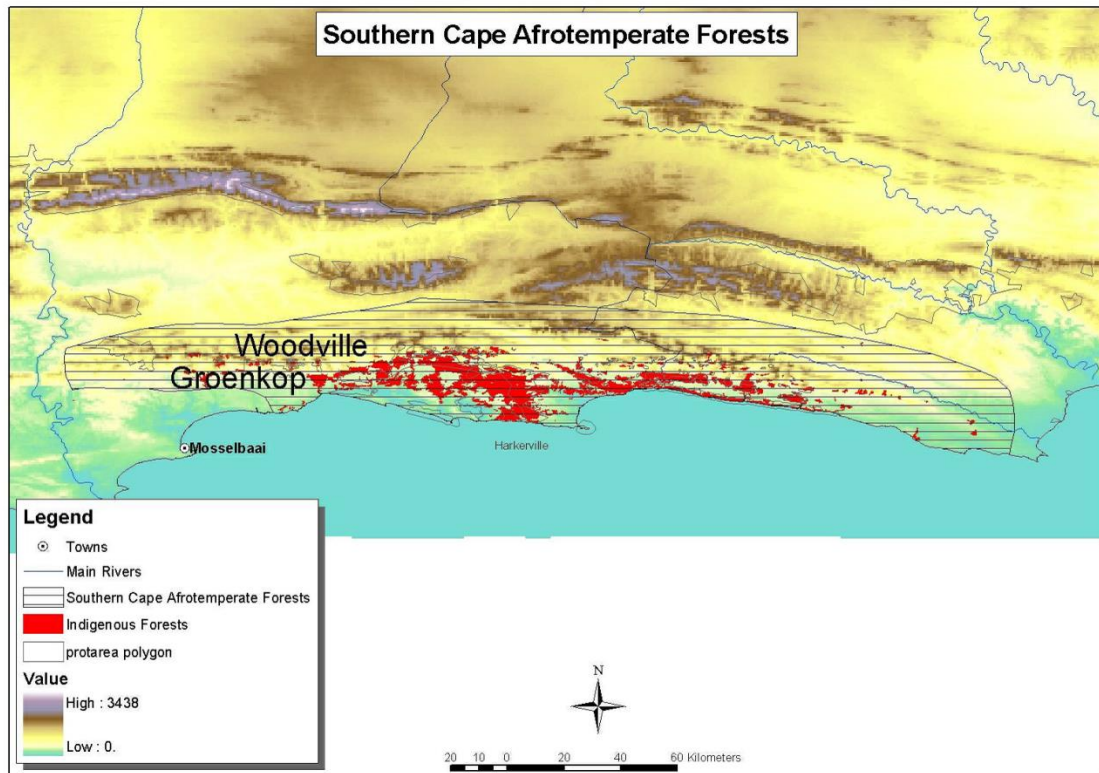


Figure 3: Location map for Groenkop and Diepwalle (Harkerville), taken from Classification System For South African Indigenous Forests (2003), Environmentek report ENV-P-C 2003-017, CSIR, Pretoria

The major difference between the Groenkop and Diepwalle sites could be seen as the rainfall patterns. This does have an effect on the density/sparseness of the forest, including the species distribution. The moisture deficit thus being the major differing climactic variable, these two sites could be seen as an ideal pair for a comparison.

2.2 Sampled tree statistics

This study was based on core samples, taken from multiple *Podocarpus latifolius*, *Olea capensis* and *Pterocelastrus tricuspidatus* trees in both Groenkop and Diepwalle. The average tree characteristics are displayed in Table 1.

Table 1: Sampled tree statistics

Species	Min diameter (cm)	Max. diameter (cm)	Mean diameter (cm)	Mean height (m)	Mean crown base height (m)
<i>Podocarpus latifolius</i>	16.2	78.5	37.8	23.8	10.2
<i>Olea capensis</i>	15	75.8	39.7	21.8	9.1
<i>Pterocelastrus tricuspidatus</i>	13.9	32.9	24.6	18.2	7.2

After the initial tree measurements were done, core sampling took place. In the following sections it is described how the steps follow and how analysis proceeds.

2.3 Principle steps of core sampling

A stepwise methodology (Fig. 4) shows the process and procedures for collection, preparation and analysis followed and presented in this thesis.

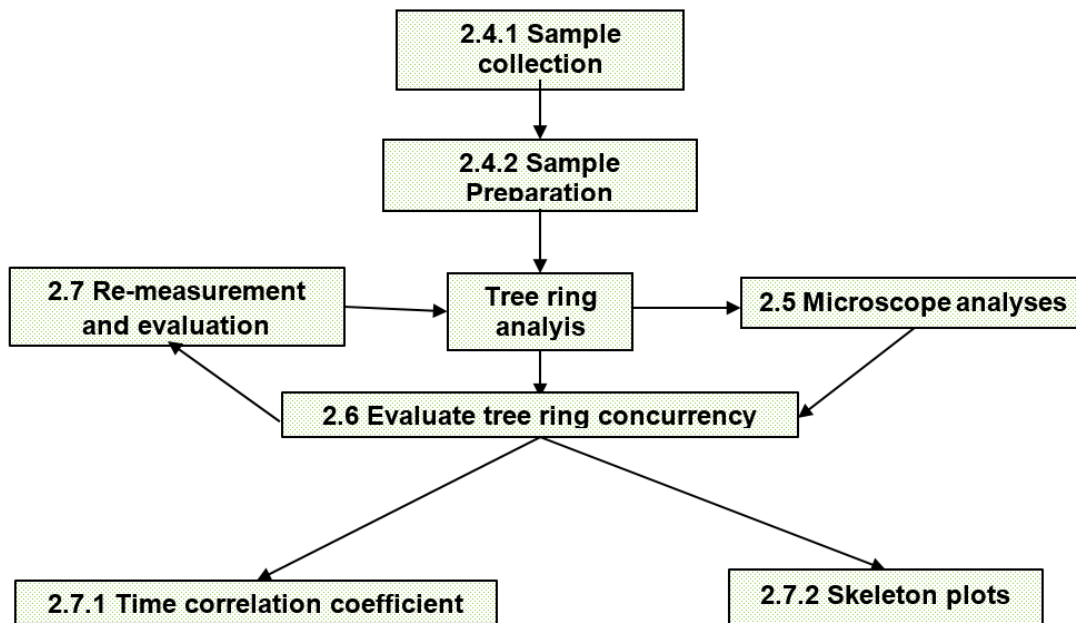


Figure 4: Sampling steps and methods

2.4 Sampling and sample preparation

2.4.1 Sample collection

To collect the sample a Pressler-type tree borer (Haglölf) was used. It consists of a threaded tip (Fig. 5), a handle and an extractor (Fig. 2). It packs up for easy storage and can be reassembled without difficulty (Fig. 6). Depending on the tree species, one will have to choose between a two-thread and a three-thread borer. A two-thread borer could be used for hardwoods while a three thread design works better for softwoods (Grissino-Mayer, 2003). With the selected species (*P. latifolius*) a three thread bores was used in accordance to Grissino-Mayer's (2003) recommendations. For both other species a two-thread borer was employed. Another aspect to consider while selecting the borer would be the diameter and length of the cores. Borer sizes range from 4 mm to 5 mm generally, but they do go up to a size of 12 mm. The chosen size will depend on the purpose of the study as well as the brittleness of the wood (Grissino-Mayer, 2003). Generally speaking, larger core diameters are easier to analyse.



Figure 5: Borer tip



Figure 6: Borer ready for storage/transport



Figure 7: Inserting borer into the tree

Figure 8: Extracting core tray

The borer should be held perpendicularly to the surface of the tree to ensure straight cores. Ideally one would sample the same tree from more than one direction in a 90 degrees angle to both increase the odds of sampling the pith and to be able to identify false (wedging) tree rings.

Cores should be taken at breast height (DBH). The tip of the borer should be pressed firmly into the bark of the sampled tree. Rotating the corer steadily clockwise will bore it into the tree until the required depth is reached (Fig. 7). To obtain cores of similar length, flagging (marking) can be done on the borer at a specific depth. Once the tip has reached the planned depth, the borer is turned slightly anti-clockwise to separate the core at the tip from the wood of the stem and the extractor is inserted at the end of the device (Fig. 8). Sliding the extractor to the tip of the core sample will lock it into place for extraction. The core is then removed along with the extractor. The core can then be marked and safely stored for transportation and preparation.

Some dendrologists use straws or flexible plastic pipes to store the samples during transport, after which they are dried and mounted on sample trays. The straws and pipes keep the moisture in the sample as well as provide support to reduce chances of breakage. They can also be marked easily without having to stain the sample.

The borer should then be removed from the tree quickly to reduce damage and to prevent it from getting stuck in the tree. A sterilisation of the borer (e.g. with ethanol) is often advisable to reduce the risk of an unintentional inoculation of further trees with fungi from the sample tree.



Figure 9: Hole left by borer

The hole left by the borer (Fig. 9) can be treated with resin or a filler to reduce chance of pathogens or insects invading the tree. In the case of conifers, this is usually not necessary since their own resin will quickly plug the hole, and the scar will occlude faster (Grissino-Mayer, 2003). One can also clean the wound and fill it, since these species are usually more susceptible to fungal invasion,

insect attacks and discoloration. Other studies (as previously mentioned) have shown that no treatment of the wound in both hard- and soft woods are preferable.

When cleaning the borer after use, care should be taken to not damage the tip of the auger or the thread, since chipped parts can break the core before the required length has been reached. Borer tips should also be sharpened after regular use to ensure good quality core samples in the future.

2.4.2 Sample preparation

In this study sample cores were mounted on wooden trays by using a hot glue gun (Fig. 10) as shown in Fig. 11. After the glue was spread, the samples were fastened onto the tray with the bark at the front end of the tray, and left over night to set (Fig. 12). It is of cardinal importance that the samples be aligned vertically in respect to the wood fibres. This will ease the polishing process as well as improve the visibility of the individual rings and most importantly grant a correct measurement. Trays should be made from material with a density in a similar range as that of the sample to avoid complications with X-ray penetration and absorption if computer tomography should be used for sample measurement. For microscope analysis the samples need to be planed and polished with sandpaper to make individual rings clear to the eye. Sometimes dyes are also used to further increase the visibility of the rings. According to Cook (1989) e.g. chalk dust also improves the visibility of the earlywood for visual analysis.



Figure 10: Glue Gun



Figure 11: Empty sample tray



Figure 12: Sample tray with rough cores

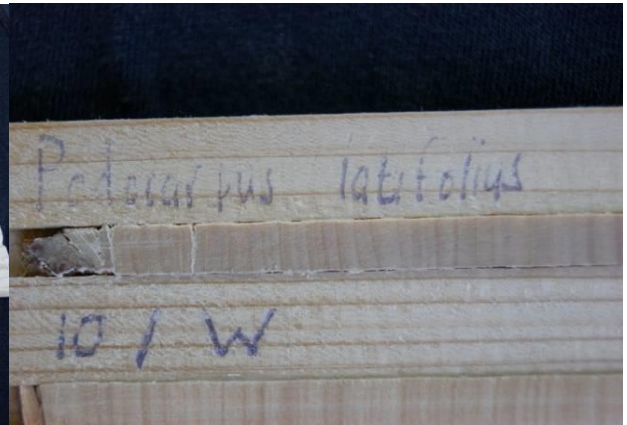


Figure 13: Processed samples

The sampled species *P. latifolius* is characterised by rather small, densely packed wood cells. For this reason all the samples were treated more intensely than for example pine samples, which show a particularly well defined latewood earlywood transition for the identification of tree ring borders. The hardwood species proved to be significantly more difficult to polish and measure due to different ring formation (diffuse porous). The samples were planed using a sharp razor blade and sanded down with 320pp sandpaper, followed by a 400pp and a 600pp. This wide range of sand papers ensures that no scarring is left and that the wood has a highly polished finish. The quality increase of the sample surface makes it easier for the naked eye to distinguish different individual growth rings (Fig. 13). Out of the three species, which were sampled for this study, the Yellow wood has the finest rings. The other two species, Candle wood and Iron wood respectively, have rings which are more distinguishable to the naked eye, but proved more difficult to identify during the microscope measurements. A complication arose while measuring the Iron wood trees, namely the occurrence of the heartwood. The change in the physiology of the wood made it difficult to distinguish rings within the heartwood, and especially at the heartwood-sapwood border.

2.5 Microscopic analyses:

The microscopic analysis is typically based on a standard reflective optical microscope. Once samples are prepared according to the methods described in Sub-chapter 2.4, measuring the rings through a microscope is a comparably simple process. Modern tree ring microscopes have many advantages over the traditional setup. They are connected to a digital video camera which enables tree ring inspection over a monitor without tiring the eyes



Figure 14: Eklund Apparatus

through looking in the microscope. The possibility of taking digital images for computer analyses is another advantage.

Instead of manually noting tree ring measurements the table of the microscope is mounted on a fine-thread spindle and an analogue-digital converter which reads out the table position with 0.01 mm accuracy and transfers the readings directly into the tree ring measurement software, where they are recorded with the respective dates.

While doing microscope measurements it is important to keep in mind that there are two types of accuracy one must observe throughout the process. The first form of accuracy is that of the physical precision of measurement. In dendro-ecological and dendro-climatological studies, this accuracy is of vital importance, since tree ring width and ring width index (ring width divided by the detrending function value) are directly used and their magnitude matters.

The second form of accuracy is the accuracy of the annual record. This accuracy is determined by the amount of false- and missing year rings. It is usually also only picked up as errors when the crossdating between samples is done. If these errors are not removed, it would be impossible to accurately date individual rings and it would invalidate the results obtained. The best way to avoid such errors is to do the measurement carefully and consistently, while looking for signs of possible false or missing rings. Evidently this is more difficult on cores than it is on discs, where wedging tree rings would be picked up more easily.

Both of these forms of accuracy depend on the experience and judgement of the operator. This also applies during the crossdating of samples and correction of possible measurement errors.

The system used for this study was a modified Eklund apparatus, improved at the Chair of Forest Growth and Yield Science at Technische Universität München. The equipment

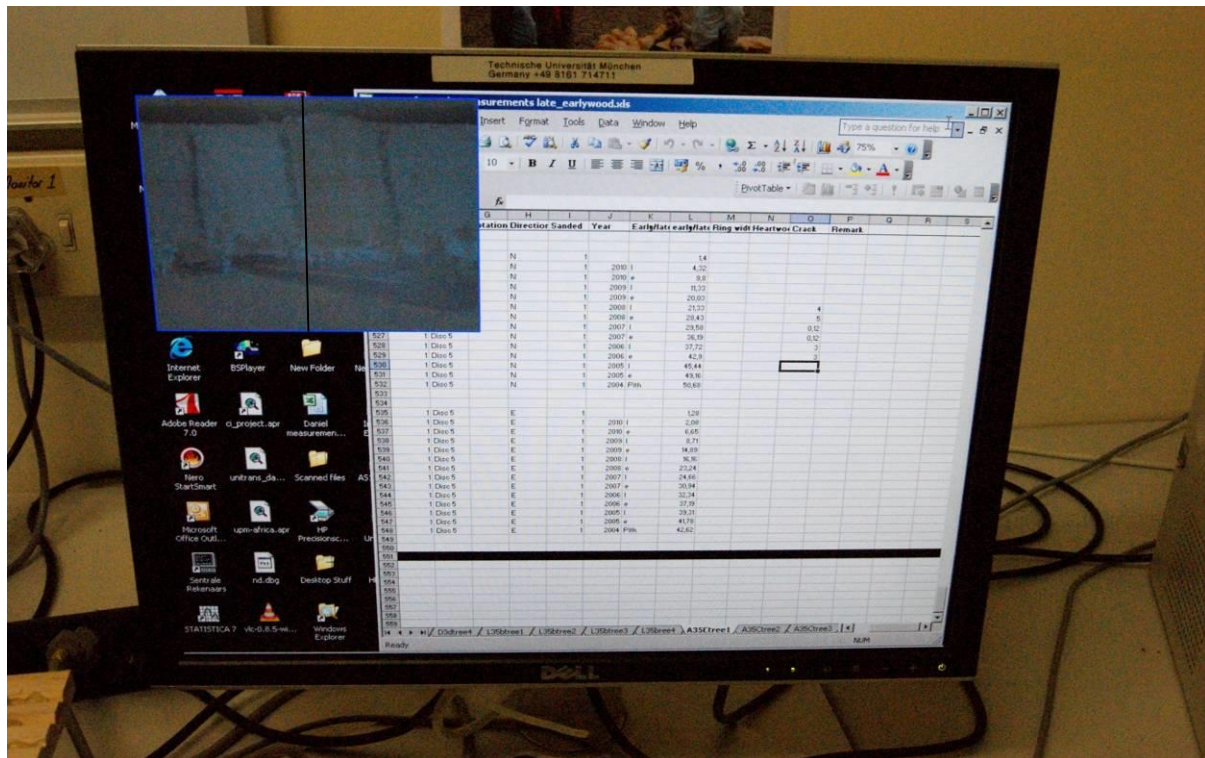


Figure 15: Output monitor

operates with a manually propelled moving plate to place the sample onto, and a microscope above the plate (Fig. 14). The microscope is connected to a digital video camera, which displays the microscope image as a picture in picture together with the measured data on the same monitor. During measurement, the sample is placed with the bark side directly underneath the microscope, and measurement is started from the bark to the pith. The first occurrence of latewood marks the first complete year. Incomplete years are usually discarded or marked as incomplete in the dataset. That is why it is essential to know the exact sampling date and to have an idea about the cambial activity of the species. The sample on the plate is then moved manually with a small handwheel along the microscope. The fine-thread spindle where the plate is attached to allows for accurate movements logged to 0.01 mm accuracy. On the output monitor one can clearly see individual year rings, with a specific marking (cross-hair) on the monitor where measurements take place for each ring (Fig. 15). Using a setup such as this is ideal since there is no microscope ocular inspection necessary, which would be increasing the fatigue of the operator during measurement. This

system also improves stability of the sample and with electronic measurement it improves the validity of the data. Although the measurement is time consuming, the ease of access and simplicity of use together with low costs of application makes it a feasible method.

Additionally, a LinTab (Rinntech) measuring device was obtained by the Department of Forest- and Wood science at Stellenbosch, which is an improved version of the above mentioned device. Although it does not work with an output monitor, but rather ocular (Microscope) measurement, it is deemed a more accurate and convenient device as it couples with purpose built dendro-software. A simple comparison was made between the samples measured on both devices to verify whether they were similarly accurate. It was seen that the measurements on the different machine did differ, but not to such an extent where re-measurement was deemed necessary.

2.6 Data correction

Measurement was done using both the Eklund apparatus and the Lintab devices. From the Eklund apparatus, the data was exported to Microsoft excel, where graphs were drawn of the two samples per tree for comparison. This enables one to see how well the ring profiles of the samples from the same tree goes together. The samples should be highly similar. Differences in the graphs can then be used to identify mistakes in the measurement. A visual analysis of each sample next to the graphs was then done, to find where the possible measurement mistake was made. A similar process was followed when using the Lintab device, with the exception that TSAPWin was used instead of MS Excel. TSAPWin facilitates a comparison of the ring patterns directly after measurement, while giving statistical information such as the GLK (Time correlatioin coefficient, Gleichlaeufigkeit) and significance of concurrency (Fig. 17). By knowing the sampling year (the outer most ring) the program will align the two samples from which mistakes can be found. Under the Lintab microscope the error was then identified by the operator and the rings series was remeasured in the respective region by simply editing in the correct measurements to replace to previous measurement.

Crossdating and data editing

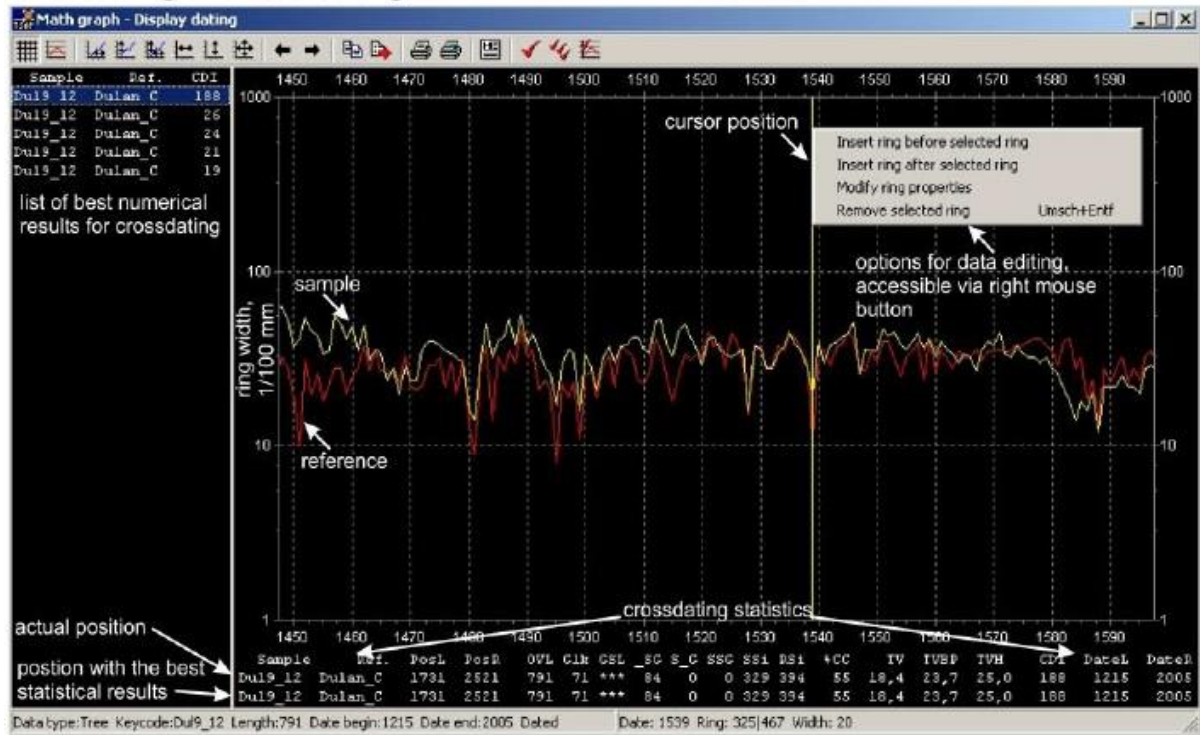


Figure 16: Taken from "Working with TSAP" by Diana Bretting

The Lintab device was a more productive system, since it had a program linked to it directly which can show errors and build full tree chronologies. While comparing the core samples with each other to find mistakes, with TSAPWin the GLK was displayed and recalculated with every change made to the data. For the amount of years looked at during this study, a minimum GLK value of 60% was needed for the samples to be significantly concurrent at a 95% confidence interval.

The next step to verify whether the data is correct was through the use of skeleton plots. These plots show, in order of severity, where there are specific years in which the tree grew dramatically different compared to the years around it. This difference in growth can be either positive (highly improved growth) or negative (extremely decreased growth). On the skeleton plot however, only the severity of the different growth is shown, and not whether it is positive or negative. For different samples, these "pointer years" on the skeleton plots should then align to indicate that they are indeed following the same pattern.

Using these pointer years was however simply a visual identification and verification process, and was not used to gauge the severity of specific events. The verification process was done by comparing the different plots to see whether the rings line up. The identification process was to see if there were specific years across all samples where there was a big

difference in growth. These identified periods were then compared to weather data to see if there was a stress event in the time around the period.

In certain cases (especially for the *Olea capensis*) some samples were vastly different, and it was nearly impossible to establish which of the samples were measured incorrectly. In cases such as these, both cores were remeasured to ensure that the data was sound. If the measurement results turned out to not match any of the measured samples, the sample was left out for more in depth analysis, to see if it was a core not suitable for the study (as described above).

After it has been determined that the cores were correctly measured, the cores from the same tree were combined into a single tree chronology to be compared to the other trees. Comparing these chronologies also enables one to see if certain trees formed false growth rings, or if they had “missing” rings. By identifying growth periods such as those the quality of the data was also improved.

The actual drought periods were defined by looking at the SPEI values for the two sites. The SPEI values are indicative of the severity of the drought. Each of the drought periods would also (as expected at least) align with the periods of different growth.

It also needs to be pointed out that the weather and SPEI data did not influence the correction of the data, as that would cause a bias in the results. Although it can be expected that severe drought periods would have an effect on growth, the severity and kind of effect cannot be predicted without aligning the correct years for each tree. Precipitation data would then be used at a later stadium in time to determine the kind of effect each tree species undergoes during these periods of stress.

2.7 Analyses to compare and verify sample growth concurrency

Before data analysis, the worksheet containing the data was restructured. This modification will put the data in the correct format for analyses. It also serves to compare samples with one another to see if any distinct measurement errors were made. The removal of these errors depends on the judgement of the researcher (as mentioned in Cook and Kairiukstis, 1990, p. 43) (Also see section 2.6).

The dplR (Dendrochronology Program Library in R package (Bunn, 2008) of the statistical package R (R Core Developer Team 2011) was used for data analysis. With multiple dendrochronologists and programmers working on this package, it is a comprehensive tool for tree ring analyses.

One of the useful functions of the dplR package is the ability to read in both raw ring-width data and .rwl files (ring-width library). The decadal .rwl files include Tucson, Heidelberg, compact and tridas formats and cover some of the most frequently used data formats in dendrochronology data bases. For the purpose of this study however, simple raw data in a comma-delineated format was used. Other functionalities of the dplR library include detrending of ring-widths, crossdating, chronology building and the creation of skeleton plots.

Detrending is a form of standardization used to remove the age effects of growth in trees. It is done by fitting a curve to the ring-width data, then dividing each of the values with their respective predicted values. This creates an index for the ring-widths which is centred around the value of one (Fritts, 1976). Each of the samples was detrended before analyses were done on them. Various authors (Cook, 1990; Fritts, 1976) recommend that two detrending functions are applied to the ring data to completely remove the age related autocorrelation within the data. The two functions used most often is a log-linearization and spline functions. Both of these were calculated in R for this study.

The purpose built software TSAPWin, in accordance with the LinTab device, was then later used as a replacement for the dplR package, as it also contains the same functionality of growth and indication verification. This program does however bring another benefit that the R-package does not offer; visual graph comparison and live editing. The ability to compare and edit data whilst in graph form eased the process of data correction and finding of errors. This was done by having multiple samples under the microscope together while visually comparing the graphs. When clear differences or mistakes were identified, one could look directly at the rings where the mistake could have happened as well as easily remeasure only a small part of a sample.

2.7.1 Time correlation coefficient (GLK)

To analyse the data one first has to determine if 1) samples from the same tree and 2) samples from different trees display similar growth patterns. This is done to ensure that the dating is correct and false or missing tree rings do not jeopardize the later correlation of ring widths and climatic factors. A Gleichlaeufigkeit's (GLK) index is a nonparametric

measurement which is used to analyse the similarities in tree ring patterns (as used by Treydte et al, 2001 and Levanic, 1999). The Gleichlaeufigkeits index (GLK, or time correlation coefficient) was run through R on the data matrix to compare all samples with one another. Afterwards, a mean GLK was obtained to see the correlation between all the samples. Eckstein and Bauch (1969) proposed that the GLK would give a percentage correlation for different samples or a set of samples. They described three confidence intervals of 99.9%, 99% and 95%, over the GLK% for a certain amount of years, measured in the sample (Fig. 17).

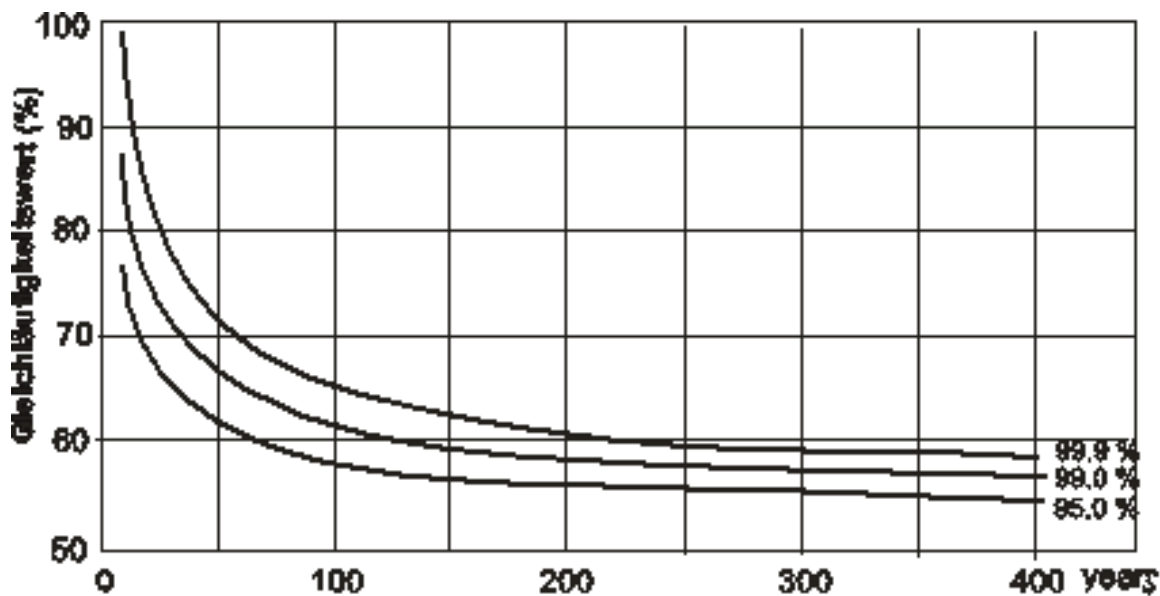


Figure 17: GLK correlation graph taken from Eckstein, D., Bauch J. (1969) Beitrag zur Rationalisierung eines dendrochronologischen Verfahrens und zur Analyse seiner Aussagesicherheit. Y-axis: GLK% X-axis: Years measured – Correlation percentage over the mount

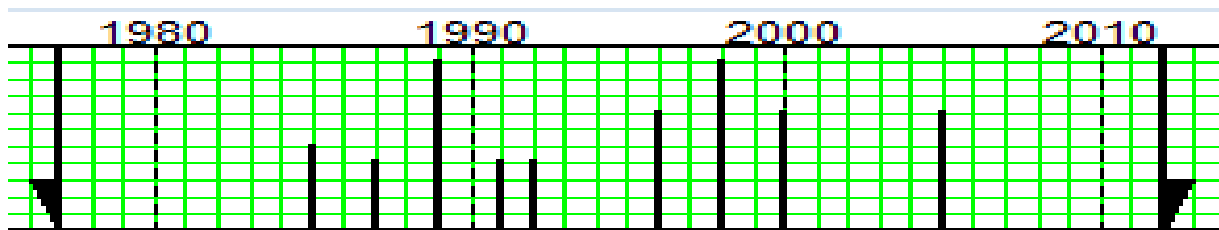
For the use of 42 years on average in the sample set, an obtained GLK% of 60 would be needed at a confidence level of 95% to be able to state that significant concurrent growth occurs.

2.7.2 Skeleton plots (Plot 1)

The next step in the process would be to use years of extraordinary different growth (so called pointer years as described by Worbes (2004) to determine if the samples match the pointer years in dates. With this procedure conclusions can be drawn to see whether these samples were accurately measured and whether they crossdate well. To see these pointer years, a skeleton plot was drawn for each individual sample, and then cross-compared to all

the remaining samples. The skeleton plot was proposed by Andrew E. Douglas in the early 1900's. It is a simple technique of plotting the thinnest tree rings relative to those next to them. The size of the plotted line indicates the severity of the size difference in the ring-widths. Each of these plotted lines should line up with those of a different sample from the same age to be able to crossdate the samples. Multiple samples with known ages can be used to build a master skeleton plot chronology, which could be used to crossdate additional samples with (Williams, 2007).

Pointer lines in the different plots should fall in the exact same range; otherwise samples cannot be used to build a chronology.



Plot 1: Example of a skeleton plot

2.8 Identifying Drought

Depending on the available data, identifying periods of drought can prove to be difficult. One method is to use historical records and hear-say to determine which periods in time had the most "severe" droughts. An issue with this method is that one can never judge the accuracy of the accounts, nor attach an indexed value to it. This makes the historical method unreliable and difficult to gauge. The best option would be to use existing drought indices, depending on the data which is available since the subjective element of human interpretation is excluded. In the case of this study, only precipitation data was available for both study sites. This limited the drought indices to ones which could work with either modelled transpiration data or the precipitation data alone.

The only model, which would work with precipitation data alone was the Standardised precipitation index (SPI). The SPI delimitates the rainfall data and then creates an index around zero. The values to this index can be interpreted as follows (Table 2) according to McKee et al. (1993):

Table 2: SPI drought interpretation values

Exceptionally moist:	$SPI \geq 2.0$
Extremely moist:	$1.60 \leq SPI < 1.99$
Very moist:	$1.30 \leq SPI < 1.59$
Moderately moist:	$0.80 \leq SPI < 1.29$
Abnormally moist:	$0.51 \leq SPI < 0.79$
Near normal:	$-0.50 \leq SPI \leq 0.50$
Abnormally dry:	$-0.79 \leq SPI < -0.51$
Moderately dry:	$-1.29 \leq SPI < -0.80$
Severely dry:	$-1.59 \leq SPI < -1.30$
Extremely dry:	$-1.99 \leq SPI < -1.60$
Exceptionally dry:	$SPI \leq -2.0$

Droughts were then identified by using the SPI output values according to the precipitation. No temperature or evaporation data was available for use though, so simply using the SPI could have resulted in a bias within the data. For this reason specifically a better index was used, namely the standardised precipitation and evapotranspiration index (SPEI) (Vicente-Serrano et al., 2010). These two indices use the same scale of indexing (as seen above), but the SPEI includes temperature and A-pan evaporation data as well. Because of this, the SPEI is a more reliable index to use. Data for this was found on the SPEIbase by Vicente-Serrano et al. (2010) and Begueria et al. (2010). Using the SPEIbase a total of five drought periods were selected for the two sites. On the Groenkop site 1988 and 1998 were seen to be two drought years with SPI values of -1.2 and -0.72 respectively. On the Diepwalle three drought periods were identified in 1984, 1999 and 2009 with -2.28, -0.76 and -2.43

respectively. For both sites thus, it can be seen that abnormally to exceptionally dry periods were observed.

2.9 Stress Indices

Lloret et al. (2011) devised an indexing method to determine how trees would react towards different levels of stress. Their study focussed specifically on drought, but it could also be applied to other forms of stress, such as fire and periodic disease.

The purpose of these indices is to gauge the difference in growth before, during and after the event. Firstly there is the resistance (Rt), which looks at the inverse effect the stress event has on the growth of a tree, thus the difference in growth before and during the event. Secondly the recovery (Rc) is the difference in growth for during and after the event. Third there is the resilience (Rs) of the tree, which measures the capacity for each tree to reach pre-event growth conditions. Lastly there is relative resilience (RRs) which is a weighted damage index based on the damage suffered by the tree during the stress event.

Mainly there are three values used to determine the indices. These are the pre-event growth values, during-event growth values, and post-event growth values. The pre- and post-event values are calculated by taking the average value of a selected amount of years around the event year. In the case of this study, three years were used to avoid overlapping of drought

Equation 2: Lloret et al. (2011) formulas

$$\mathbf{Resistance} = \frac{\mathbf{Event}}{\mathbf{Pre\ Event}}$$

$$\mathbf{Recovery} = \frac{\mathbf{Post\ Event}}{\mathbf{Event}}$$

$$\mathbf{Resilience} = \frac{\mathbf{Post\ Event}}{\mathbf{Pre\ Event}}$$

$$\mathbf{Relative\ Resilience} = \frac{(\mathbf{Post\ Event} - \mathbf{Event})}{(\mathbf{Pre\ Event})}$$

Pre-event is the average basal area increment of the three years preceding the drought event.

Event is the basal area increment during the drought event.

Post-event is the averaged basal are increment of the three years following the drought event.

events. The ring width of each year is taken and scaled up to the basal area increment for the periods in question. From these values either single tree, averaged tree or total stand areas can be used to determine the overall index values. The formulas to calculate each of the index values are as shown above in Equation 2.

Each of the index values can be interpreted to see how the trees react during the different periods of drought, and then lastly to see, relatively, how well the tree is adapted to handle the stress. Resistance, recovery and resilience are each values centred around one. Values of one and higher indicate good reactions, where lower values indicates weaker reactions. Relative resilience on the other hand is centred on zero, where zero indicates no recovery in growth after the drought event. Relative resilience values lower than zero indicates lower growth than before and during the drought event. In such cases more in depth analysis of the data will be needed.

The last step of using the drought indices is to verify whether they differ significantly across different species or sites. Generalized linear mixed models (GLMM's) based on the GlmmPQL package of R (Venebles & Ripley, 2002) with the gamma distribution and a loglink function were used in R to determine whether the growth and index values of the different species were significantly different. It was expected to see a significant difference between the growth rate of all the species and a possible difference in indexed reactions.

```
The following script indicates the base commands used in the DPLR package of R for
statistical and visual analysis. Detrending spline:      detrend(mydata, y.name =
names(mydata), make.plot = FALSE,
                method = c("Spline"), nyrs = NULL,
                f = 0.5, pos.slope = FALSE)
Skeleton plots in PDF format: pdf(file="Skelplots.pdf")
                for (i in 2:ncol(DT)) (
                skel.plot(DT[,i])
                )
                dev.off()
Gleichläufigkeit value and mean: GLK=glk(DT)
                mean(GLK, na.rm = TRUE)
Mixed model for growth comparison: M.1 = glmmPQL (Rt ~ Gr_D+Species,
                random = ~1 | Site, family = Gamma(link = "log"),
                data = Mydata)
```

Script 1: R commands used for analyses

3. Results and discussions

During the study, various problems and difficulties were managed and overcome. First and foremost was obtaining permission for sampling in the protected indigenous forests of the Southern Cape. After the sampling was completed a full analysis on the samples was conducted. The measurements were compared with precipitation data and statistically analysed to see the full effect of drought on the tree species in the indigenous forests.

3.1 Sampling and tree ring description

Sampling for the study occurred from the 10th to the 21st of December 2012. An average of 30 samples could be extracted per day, along with height, diameter and crown data. The trees were visually identified and marked with red tape to ensure the correct trees and species were sampled. Diameters of lower than 10cm were excluded from the study. On each site 30 trees per species were identified, with diameter classes stretching from 10 cm-80 cm. Two cores per tree was extracted in a North and East aspect where possible. According to Cook (1990) sampling from the same aspects is not always important in highly mixed forests such as these, but the procedure was followed to be consistent.

After sampling, the extracted cores were left to air-dry for two weeks, after which they were mounted on wooden trays for measurement. The polishing process started with a 100pp grit sanding paper, and went up to 600 for a smooth finish. Another problem was encountered at this point, as some of the samples had rings, which were difficult if not impossible to discern under the microscope. Due to this, only half the samples from the Iron wood could be used. Almost all the Iron wood cores from the Groenkop site had rings with extremely fuzzy tree ring borders that could not be distinguished. This caused the Groenkop site's Iron wood samples to be left out, because of too few samples to be statistically significant. Table 3 shows the amount of trees available in each site for analysis.

Table 3: Amount of trees for analysis

Species	Site	Amount	Mean height
<i>Podocarpus latifolius</i>	Diepwalle	28	25.34m
	Groenkop	25	18.91m
<i>Olea capensis</i>	Diepwalle	19	21.85m
	Groenkop	NA	20.4m
<i>Pterocelastrus tricuspidatus</i>	Diepwalle	23	18.27m
	Groenkop	22	18.16m

Reasons for the inability to measure the rings could stem from two possibilities. The first of which is extremely slow growth rates in an area where there is no specific time where the trees stop growth (i.e. no cold/dry time of year). Secondly, it could be the kind of rings the trees form. Iron wood has diffuse porous rings, which are some of the most difficult types of rings to measure accurately. The ring structure, coupled with the extreme visual change from sap-wood to heart-wood, is the most likely explanation for the difficulties in measurement.

3.2 Response to precipitation

. Response to precipitation can be analysed with help of detrended data only because otherwise the age trend of the tree will bias the correlation of growth signal and precipitation. The detrended residuals were thus used to effectively remove any age effect each individual tree could have on the results.

For all three species the regressions of residuals against precipitation were tested for significance. It was found that all the trends were significant, but with the low R^2 values should not be used for modelling. To interpret the figures, the most important value to look at would be the slope. A positive slope would indicate that with higher moisture availability,

higher growth would be possible. A negative, or flat slope, could be seen as improved growth during periods of drought or as an indifferent reaction.

Table 4 indicates the sensitivity values for each of the following species and sites. Each of the values are discussed individually within the text, each separated per species and site.

Table 4: Precipitation sensitivity values and confidence intervals

Species	Site	Slope	Inversed slope	Intercept	Lower confidence interval (5%)	Upper confidence interval (95%)
<i>Podocarpus latifolius</i>	Diepwalle	0.002	253.64	-0.2	0.00135	0.00544
	Groenkop	0.00019	219.84	-0.023	0.0001	0.000157
<i>Pterocelastrus tricuspidatus</i>	Diepwalle	0.0003	539.54	-0.033	0.00012	0.00062
	Groenkop	0.000197	215.98	-0.0098	0.000177	0.00097
<i>Olea capensis</i>	Diepwalle	-0.000003	-46.38	0.031	-0.00000348	-0.00000286

3.2.1 *Podocarpus latifolius* sensitivity to precipitation

The *Podocarpus latifolius*, which was regularly spread over both sites was the easiest of the core samples to measure. The fact that it is a conifer makes the growth rings much more visible and contrasting. The *Podocarpus latifolius* is also one of the most prominent upper canopy species in both forest types. Being some of the biggest trees could also imply that they have bigger root systems and could thus possibly be more resistant towards periods of moisture stress due to deeper water access. One could also argue that because they have access to the direct atmosphere, not only the forest micro-climate, they will therefore suffer from more transpiration stress for being in more direct contact with wind and higher temperatures (direct sunlight). This direct heat could also cause their stomata to close, further reducing their capacity to grow.

Diepwalle

The Diepwalle site can be seen as one of the originating points for the *Podocarpus latifolius* as it is in the epicentre of the distribution range for the species. Cook (1990) recommends

that trees be sampled closer to the edge of their natural spread, because they would be more susceptible to environmental stress in such areas. By using two sites (Groenkop and Diepwalle) one can compare the ideal ecological range of the species with the trees at the edges of the range. This is explained fully in the section containing the information on *Ecological amplitude* (1.2.9).

In Figure 18 one can see a positive correlation of growth residuals and precipitation. This can be interpreted as better growth for periods of improved moisture availability. This reaction is a normal and expected reaction for most plants. The slope value for this 0.002 (Table 4)

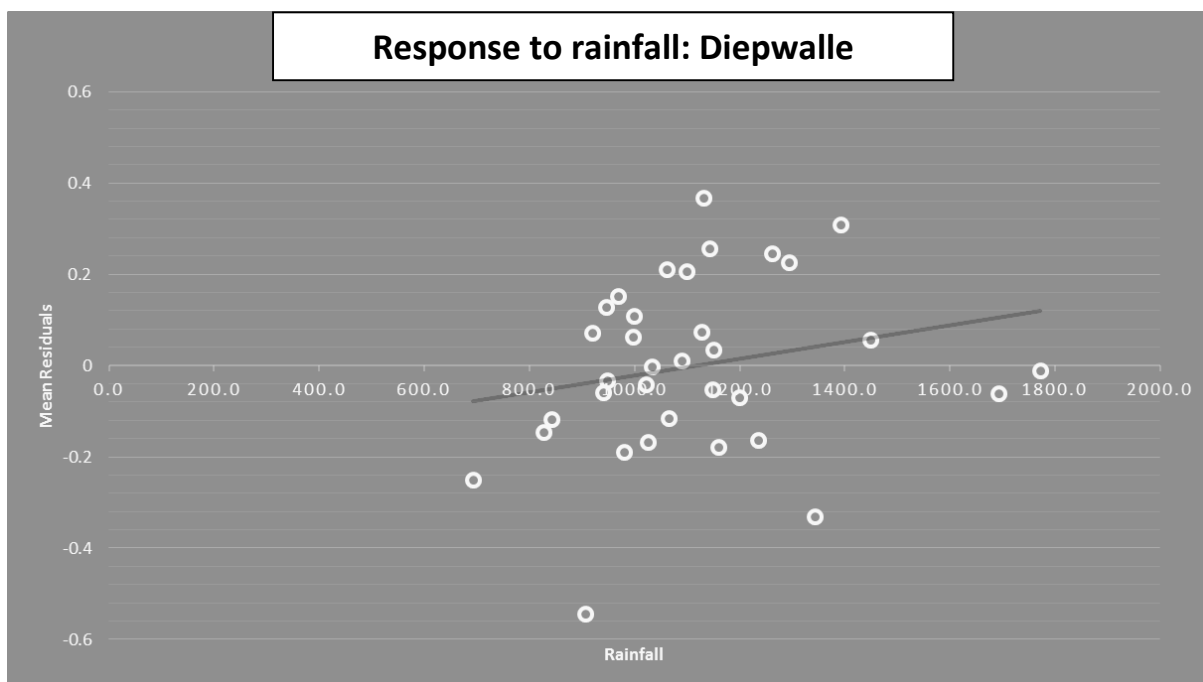


Figure 18: Growth and precipitation at Diepwalle. Standardised residuals compared to precipitation

Groenkop

As mentioned above, Groenkop is the site at the ecological “edge” of the natural distribution for *Podocarpus latifolius*. Groenkop is also a drier site, but has the same forest type classification as Diepwalle. This would explain a slower growth. On the other hand trees exposed to latent drought stress on a drier site could have developed a specific adaptation and resistance when faced with extreme drought events.

Figure 19 shows how the *Podocarpus latifolius* grows with differing rainfall. The result is very similar to that of Diepwalle, with only a slight difference in the slope. The slope on this figure is 0.00019 (Table 4). Comparing the slopes of the two sites indicates that the Groenkop site should have a form of adaptation as it handles the lower rainfall better.

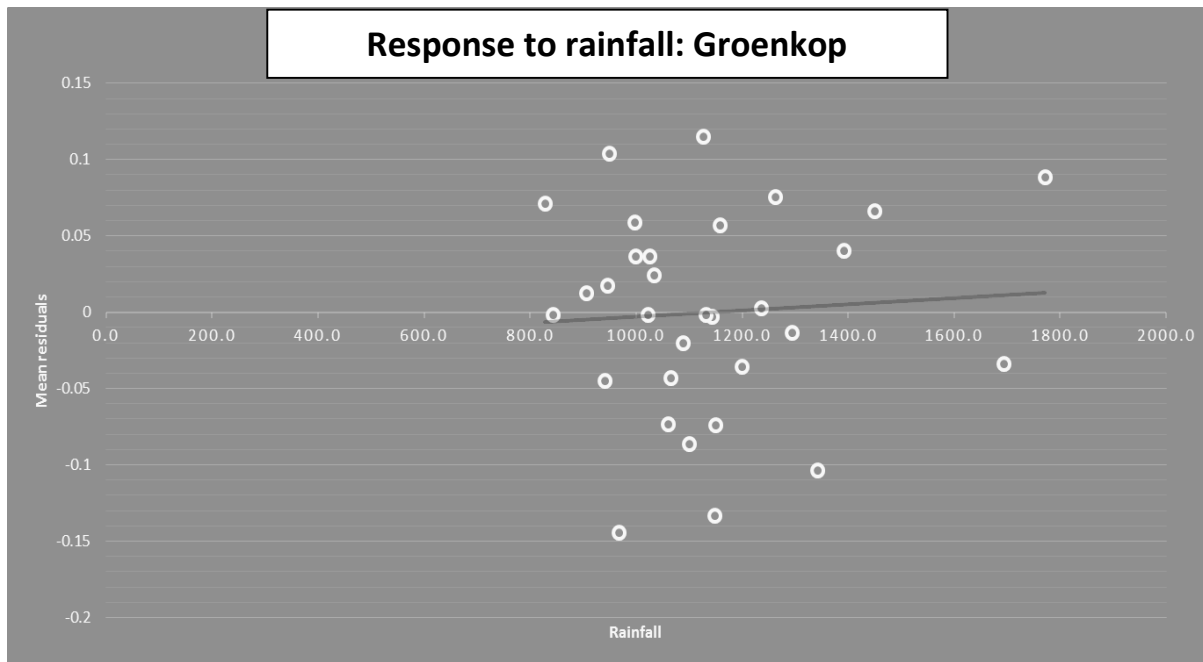


Figure 19: Growth and precipitation at Groenkop. Standardised residuals compared with precipitation

Discussing Podocarpus latifolius sensitivity to precipitation

From what can be seen above in figures 18 and 19, it seems that there are only minor differences in the response to growth when the trees are subjugated to periods of moisture stress. When looking at the confidence interval values of the two sites (Table 4), it is shown that the intervals have an overlap, indicating that there is no significant difference between the reactions on the two sites. The trees at the Groenkop site seem to have a mechanism to deal better with drought stress, although this cannot be confirmed by simply looking at the regression slopes. The mean diameter growth at Diepwalle is 1.09 mm per year whereas the growth at Groenkop is better with a mean of 1.18 mm per year. The mean growth and the trends does then point in the same direction that the *Podocarpus latifolius* trees have an adaptation to grow better in the drier site at Groenkop.

3.2.2 *Pterocelastrus tricuspidatus* sensitivity to precipitation

The ecological range of *Pterocelastrus tricuspidatus* is naturally more west than that of *Podocarpus latifolius*. It has a higher density in the drier Groenkop area and it is more sparsely found at Diepwalle. These trees also have a distinct red or pink coloured wood, with tree rings that can be identified fairly easily after proper polishing. *Pterocelastrus tricuspidatus* is also a tree that does not dominate the upper canopy, but rather sits in the sub-canopy, where it is less exposed to the harsh sunlight and dryness outside of the forest micro-climate. Because they are generally smaller than the *Podocarpus latifolius* and *Olea capensis* trees it could be assumed that they would be out competed during times of moisture stress. However, because they are not directly in the air above the canopy, they suffer less from transpiration stress (wind and humidity caused). There are thus two possibilities in the reaction towards drought for this species as well.

Diepwalle

Diepwalle is not at the exact ecological spread edge of the growth spectrum for the *Pterocelastrus tricuspidatus* trees, but it is at a point where they could be more affected by the higher amount of moisture and clay in the soil. The dominant height at Diepwalle is also 2-5 meters higher than that of Groenkop, which means that the smaller *Pterocelastrus tricuspidatus* trees can be outcompeted and overshadowed at Diepwalle.

Figure 20 indicates a positive reaction for the *Pterocelastrus tricuspidatus*' growth relative to the rainfall. It shows that higher rainfall/moisture improves growth. This reaction is very similar to that of the *Podocarpus latifolius* at Diepwalle. The slope difference is 0.0003, this is indicative of a substantial susceptibility to moisture stress (compared to *Podocarpus latifolius*).

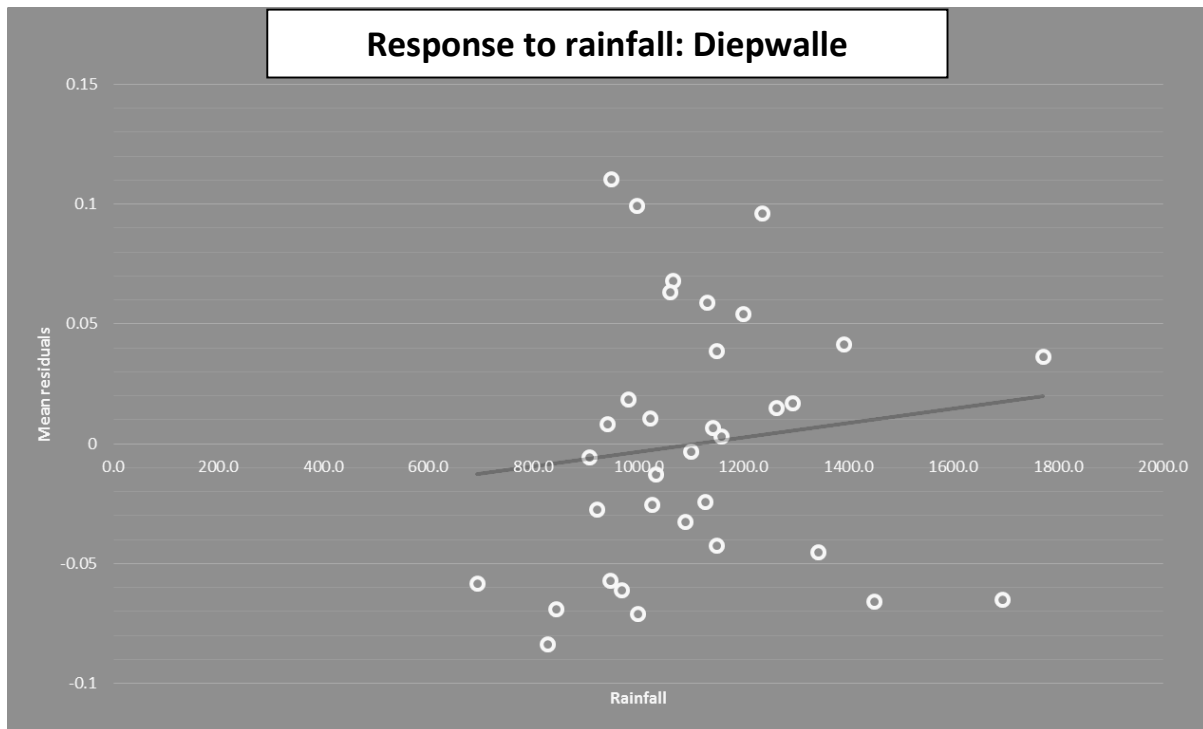


Figure 20: Growth and precipitation for Diepwalle. Standardised residuals compared with Precipitation

Groenkop

The Groenkop site is a more suitable area for the *Pterocelastrus tricuspidatus* to grow than that of Diepwalle. This is indicated by the larger presence of the species in the forest. The forests' understorey is more sparse at Groenkop meaning less small competition for water for the canopy trees. With the canopy also a bit lower than that of Diepwalle, the *Pterocelastrus* trees would get more direct sunlight and outer atmosphere contact. The trees should be able to compete better for resources at this site because they are of similar size than the *Podocarpus latifolius* and *Olea capensis* (Table 3). Additionally there is the added effect of a greater amount of nutrients available in Groenkop, according to SANParks. If this is taken into account along with the more similarly sized trees, it would make sense that the trees would be able to compete on a similar level to that of the other two species.

Figure 21 is that of the *Pterocelastrus tricuspidatus* trees reacting to precipitation. A positive correlation is also present at this site, but there is a great difference in the slope. The slope at this site is much flatter than at Diepwalle, indicating that the trees at Groenkop have better growth and adaptations when in times of moisture stress. The slope is 0.000197, which is slightly lower than that of the Diepwalle site. The result clearly shows that *Pterocelastrus tricuspidatus* is better adapted to moisture stress at the Groenkop site. The table above

(Table 4) shows that there is no overlap in the confidence intervals or the regressions. It therefore has a significantly different reaction towards growth on the two different sites.

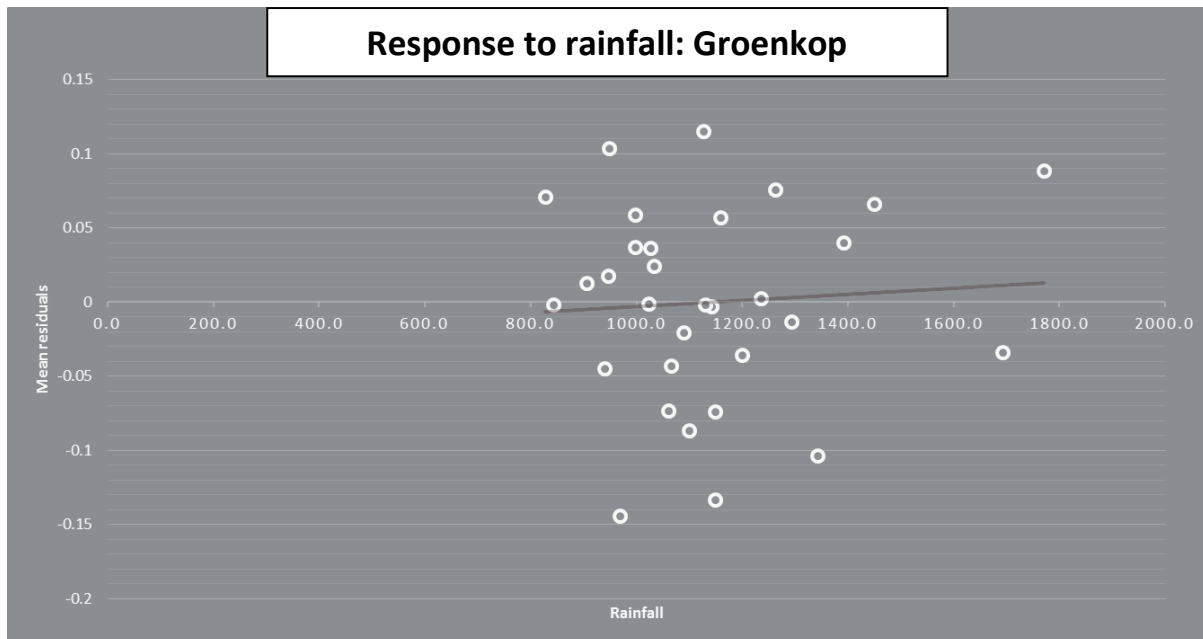


Figure 21: Growth and precipitation for Groenkop. Standardised residuals compared with precipitation

Discussing Pterocelastrus tricuspidatus sensitivity to precipitation

The precipitation-growth correlation for the *Pterocelastrus tricuspidatus* indicates a good difference with respect to reactions towards moisture stress. This could be attributed to two main things. First, the ideal growth site for the trees are at the Groenkop site. At this site they seem able to compete better for resources as well as being at their ecological epicentre. Secondly, the trees are overshadowed and outcompeted at the Diepwalle site. There is also more competition from various under growth plants. The mean diameter growth for *Pterocelastrus tricuspidatus* at Diepwalle is 0.489 mm per year. At the Groenkop site it is 0.503 mm diameter growth per year. With the growth being very similar over the two sites one could expect a difference in drought resistance and possibly recovery when looking only at what the correlations between growth and precipitation indicate.

3.2.3 *Olea capensis* sensitivity to precipitation

Olea capensis is a species, which is found throughout the whole Southern coast of South Africa. Determining where its ideal ecological amplitude is would prove to be a difficult matter. These trees are generally high canopy species, sometimes even standing out above the canopy as emergents. These trees are identified by their characteristic cork-like bark. They also have great amounts of water stored inside the trunk, as demonstrated during the sampling process where a full stream poured out of a few for several minutes. The wood is extremely hard and dense, and thus caused difficulties in the sampling process. There is also a distinct colour separation between the heart- and softwood. This separation makes the measurements of the rings fairly difficult. This measurement difficulty is also aided by the fact that the growth rings do not form very clearly and are difficult to distinguish under a microscope.

The difficulties with sampling and measurement of this species led to only the Diepwalle site having sufficient data to utilise in this study.

Figure 22 indicates the peculiar growth reaction when this species is subjected to moisture stress at the Diepwalle site. The general expectation is to see an increase in growth along with an increase in moisture availability. This is especially true for most trees, which are dominant forest canopy species, such as the *Podocarpus latifolius*. The *Olea capensis* on the other hand displays a negative slope, indicating that it grows better with less moisture (Table 4). One possibility for this phenomenon could be that the *Olea capensis* is already under moisture stress (too wet conditions) on the Diepwalle site. Periods of less moisture availability then increases the growth potential for the tree due to some of the stress being relieved.

The observed slope in Figure 22 is -0.000003. The mean growth for the *Olea capensis* at the Diepwalle site is 1.31 mm diameter growth per year, making it the fastest growing species in this study.

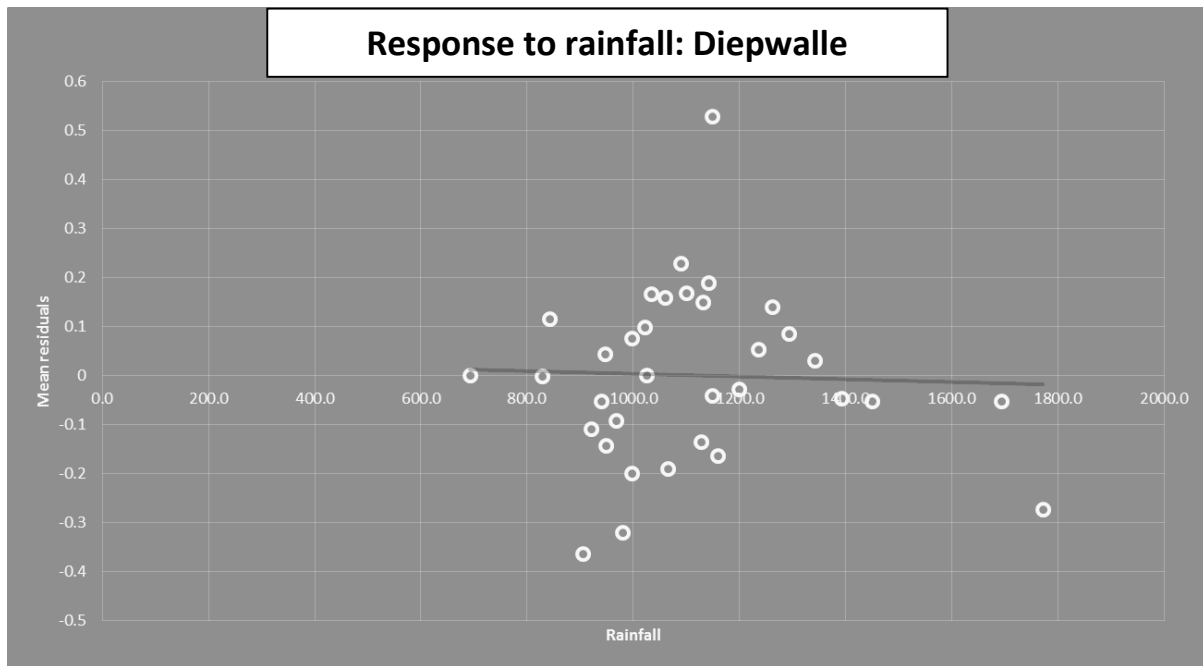


Figure 22: Growth and precipitation for Diepwalle. Standardised residuals compared with Precipitation

3.3 Growth Response during drought periods: stress indices

The indices according to Lloret et al. (2011) give, in combination, a clear idea of how trees react in times of stress. The indices makes use of pre-drought, drought and post-drought basal area increment (iBA) values to describe growth responses. These indices are categorised under resistance towards drought (R_t), recovery after drought (R_c), resilience during drought (R_s) and relative resilience (RRS) as a value to describe how the R_t , R_c and R_s interact with each other.

Tabled values for each of the species and for each of the drought periods were calculated for comparison. These values were used to discern how each of the individual species reacts towards drought in the different years.

3.3.1 Growth response of *Podocarpus latifolius*

The *Podocarpus latifolius* displayed an expected result in reaction towards drought according to the correlation pattern shown in Section 3.3. This reaction towards drought can be explained by looking at the Lloret et al. (2011) index values (Table 6).

When one looks at the resistance values for the *Podocarpus latifolius* over the two sites, it can be seen that there are slightly higher values for the Groenkop site than for Diepwalle, with the exception of the year 1984. This was also shown by the correlation pattern, that the *Podocarpus latifolius* trees have a higher tolerance towards moisture stress at Groenkop. The severely low resistance in 1984 could be explained by an additional stress which accompanied the severe drought. On average it is seen that the *Podocarpus latifolius* has a moderate drought resistance (Relative to various authors such as Pretzsch 2012 and Lloret 2011) with a mean value of 0.8 (or 0.87 when disregarding the year 1984).

Table 5: *Podocarpus latifolius* stress index values

Site	Year	Rt	Rc	Rs	RRs	SPEI	Precipitation
Diepwalle	1984	0.493	2.102	1.037	0.544	-2.28	905
	1999	0.777	1.063	0.826	0.049	-0.76	842.1
	2009	0.779	1.297	1.010	0.231	-2.43	693
Groenkop	1988	0.992	1.086	1.076	0.085	-1.19	641
	1998	0.968	1.147	1.110	0.143	-0.72	690

The recovery after drought for the *Podocarpus latifolius* averages fairly close to 1 (1.33). This value could be biased though because of a screwed recovery after the severe lack of growth in 1984. It is also possible that during 1984 that the trees selectively grew more in the roots and stored nutrients. This could have caused much higher growth in the successive years due to additional root area and available nutrients. Without the exceptional year, the mean recovery value is 1.14. Between the two sites, one can also see almost no difference in the post-drought recovery of the trees.

Resilience is a value to determine tendency for the tree to reach “normal” growth rates after the drought has passed. In the case of the *Podocarpus latifolius* the resilience towards drought is above one. This means that within three years after the drought has occurred pre-drought growth conditions are reached again. The mean resilience value for this tree then is 1.012. It can be seen that even though the resistance towards drought in 1984 was low, the

recovery made up for the lost growth, and the trees still reached pre-drought growth levels within a short amount of time, comparable with the other years.

Finally looking at relative resilience one can see that the values are fairly spread between 0.05 and 0.50.

Figures 23 to 27 are graphical illustrations of how the basal area of the trees were affected during the drought periods. The first segment of the figure is the pre-drought basal area growth. This then drops into the single period of drought, followed by the post-drought basal area increments. The variation between years can clearly be seen, as well the differences across sites.

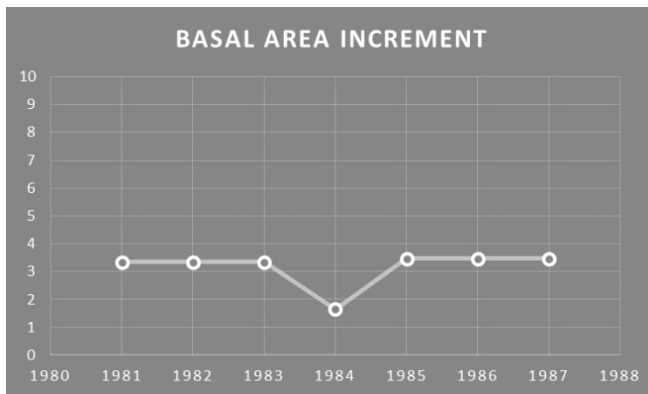


Figure 23: Diepwalle drought of 1984

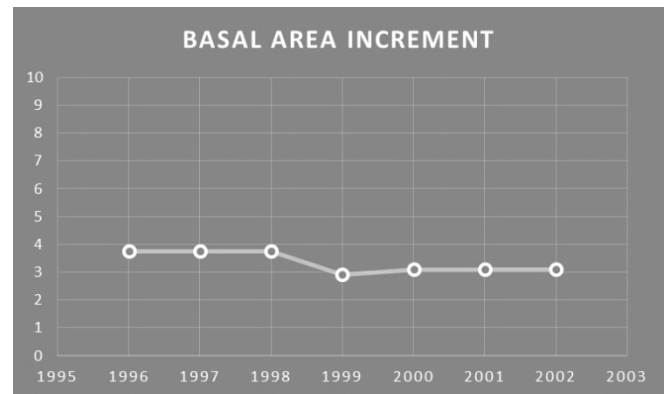


Figure 24: Diepwalle drought of 1999

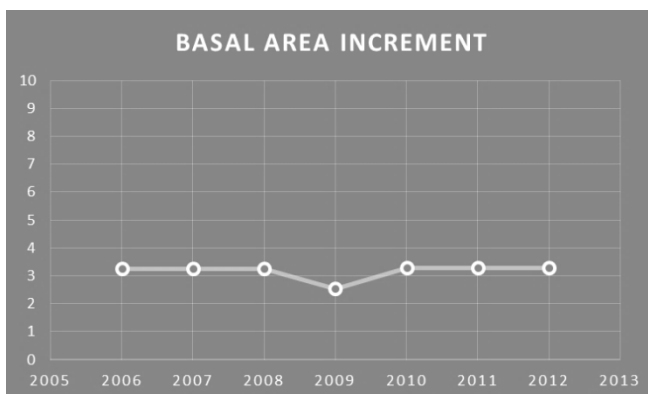


Figure 25: Diepwalle drought of 2009

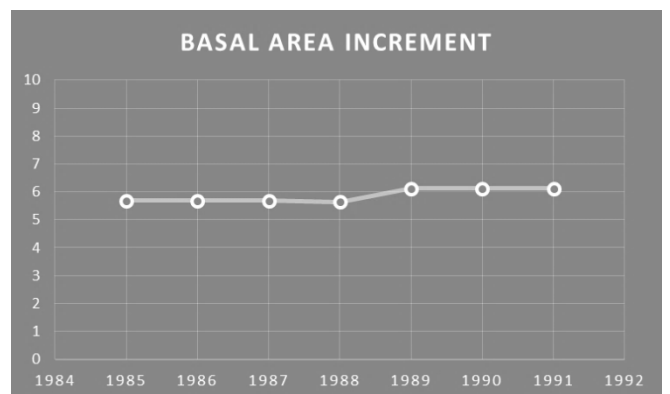


Figure 26: Groenkop drought of 1988

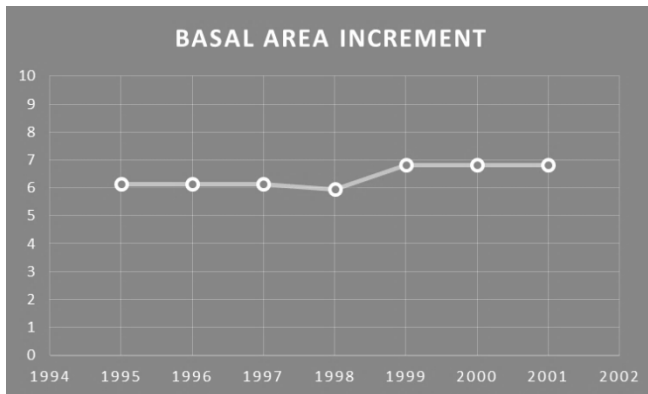


Figure 27: Groenkop drought of 1998

The biggest “dip” in growth can clearly be seen at the Diepwalle site in the year 1984. For the rest of the years at Diepwalle a normal recovery to normal growing condition can be observed with the exception of 1999, where proper growth only returned in 2003. In the case of Groenkop, it can be seen that for both of the drought periods there was a very good recovery to a slightly higher growth after the drought than before it. This is the reason for the relatively high resilience.

3.3.2 Growth response of *Pterocelastrus tricuspidatus*

Pterocelastrus tricuspidatus trees seems to be fairly drought resistant when looking at the correlation pattern in Section 3.3 this drought resistance however is only seen on the Groenkop site, where they seem to have an existing adaptation to prevent a great loss of diameter growth during these moisture stress events. At the Diepwalle site, it was seen that they are fairly sensitive to a large change in moisture availability when only looking at the precipitation. There are, however, other factors that need to be looked at.

P. tricuspidatus trees are smaller, under canopy trees which makes them less susceptible to dry atmospheric conditions. This also gives them some coverage from strong winds and harsh sunlight.

The Lloret index values are shown in Table 7. The values in this table will then confirm or contradict the observed pattern in Section 3.3 with explanations following each of the index values.

The resistance towards drought on both sites is higher than that of the *Podocarpus latifolius*. This confirmed the growth -precipitation correlations indicated that this would be the case for Groenkop, but also that it should be lower for Diepwalle. As mentioned, secondary effects besides the precipitation had an influence on how these trees react when faced with a moisture deficit. The possibility the micro-climatic protection from the upper canopy might offer a potential explanation. Their mean resistance to drought is 0.889. The slightly lower value for 1998 in Groenkop could also have been an additional external influence causing a restricted resistance towards drought. The value is not significantly different from the other values.

Table 6: *Pterocelastrus tricuspidatus* stressindex values

Site	Year	Rt	Rc	Rs	RRs	SPEI	Precipitation
Diepwalle	1984	0.914	1.017	0.930	0.015	-2.28	905
	1999	0.888	1.176	1.045	0.156	-0.76	842.1
	2009	0.974	1.119	1.090	0.116	-2.43	693
Groenkop	1988	0.942	1.007	0.949	0.007	-1.19	641
	1998	0.724	1.236	0.895	0.171	-0.72	690

The recovery values for the *Pterocelastrus tricuspidatus* are all above 1, which shows they all recovered at a reasonable rate directly after the drought. As with the *Podocarpus latifolius* as well, the single year where resistance towards drought was the lowest has shown the highest recovery. This implies that the external effect causing the reduced resistance was temporary, seeing that the tree had shown great recovery.

Resilience values for the *Pterocelastrus tricuspidatus* were centred around one with three of the values being below. This is an indication that these trees take more than a single year after the drought event to return to their pre-drought diameter growth rates. It was only for two years (1999 and 2009) at the Diepwalle site where regular growth returned almost directly after the events. It is possible that for those drought periods a temporary lagging dryness simulated similar conditions as seen in normal growth periods of Groenkop. This effect could then describe why these two years had a good resilience. The mean resilience for *Pterocelastrus tricuspidatus* is 0.982. It can thus be expected that after any drought period they will take a longer time to fully recover growth.

The relative resilience of these trees are however grouped much better than that of the *Podocarpus latifolius*. The lowest value is 0.007 and the highest is at 0.171. They average at 0.093 which serves as an indication that these trees are resistant towards drought, but will take longer to recover.

Figures 28 to 32 describe how the *Pterocelastrus tricuspidatus* trees reacted in the drought periods over both sites. As with *Podocarpus latifolius* the lines indicates pre-drought, drought and post-drought basal area increments.

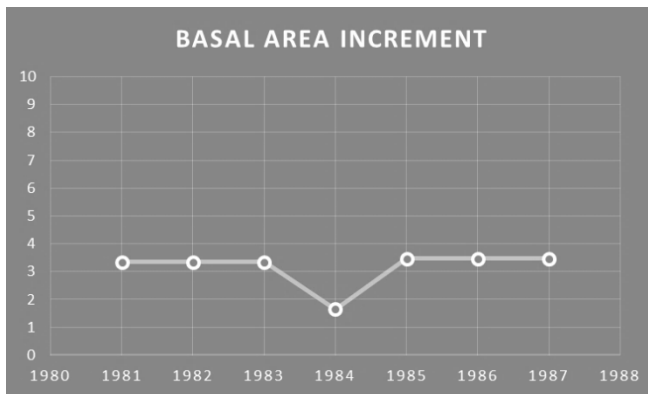


Figure 28: Diepwalle drought of 1984

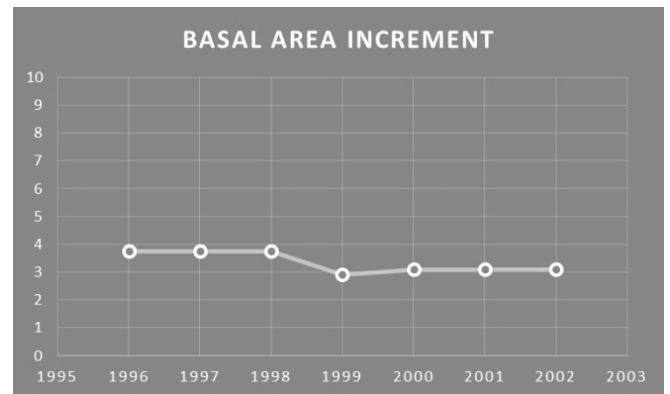


Figure 29: Diepwalle drought of 1999

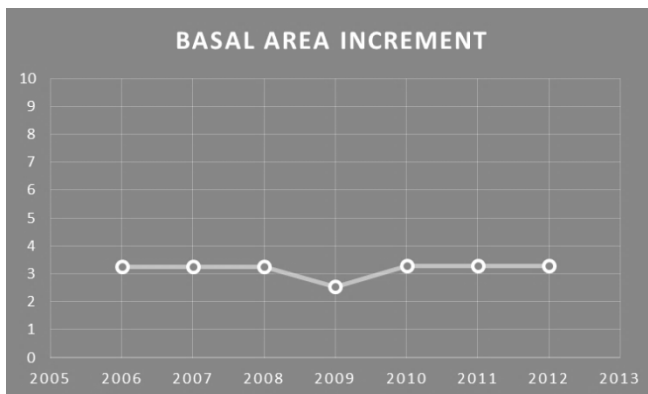


Figure 30: Diepwalle drought of 2009

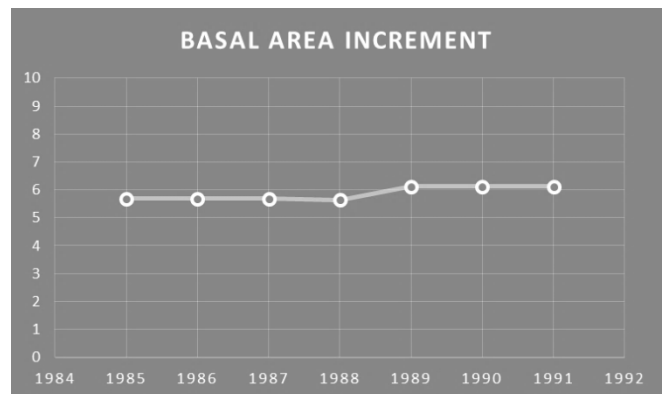


Figure 31: Groenkop drought of 1988

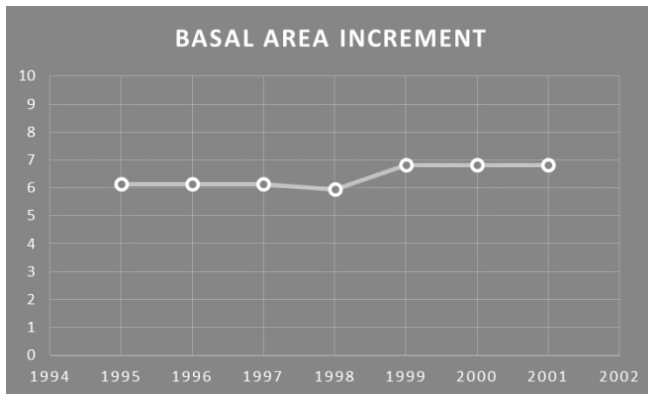


Figure 32: Groenkop drought of 1998

As the *Pterocelastrus tricuspidatus* is the slowest growing species used in this study, there is very little variance seen in their growth during drought periods. Their reactions however are similar to that of the other species indicating a significant reduction in growth during the periods. The biggest “dip” in growth can be observed in Groenkop, 1998. This largest reduction in growth is specifically the year and site where the lowest resistance was observed. Temporary external growth modifiers affecting the growth could have been pollution, pests or extreme temperatures.

3.3.3 Growth response of *Olea capensis*

The most peculiar reaction seen in the growth-precipitation trends were that of the *Olea capensis*. It was shown that a lack of precipitation had little to no effect on the growth of this species. The first possibility to this could be the answer to one of the research questions. It could be possible that on the Diepwalle site *Olea capensis* is already water logged, or oversaturated with the available amount of water. During times of drought it is relieved of the additional moisture stress and can grow better. The *Olea* trees were also observed to be growing in the middle of the canopy, with some trees penetrating it and becoming emergent. They are generally large trees, with widespread root systems. They could therefore be very susceptible to overly wet soils.

If one looks at the Lloret index values calculated for *Olea capensis* (Table 8), it can be seen that the reactions enforce the odd growth pattern during moisture stressed periods. Only for 1984 all four of the index values are as one would expect it to be normally. The other two (1999 and 2009) years have values that would contradict the usual way of thinking.

The resistance did only react normally to drought in the year 1984 for the *Olea capensis*. For the years 1999 and 2009 there is a resistance of more than one. This means in effect that the trees did indeed grow better during the years of drought than it did in the pre-drought years. With 1984 being the only outlier, it can be assumed that as with the *Podocarpus latifolius* there was a specific event which caused these two species to have severely lower growth than during usual drought periods.

Table 7: *Olea capensis* Lloret et al. (2011) index values

Site	Year	Rt	Rc	Rs	RRs	SPEI	Precipitation
Diepwalle	1984	0.804	1.563	1.257	0.453	-2.28	905
	1999	1.015	0.916	0.926	-0.086	-0.76	842.1
	2009	1.030	0.915	0.942	-0.088	-2.43	693

The recovery of the *Olea capensis* trees are subsequently also strange during the droughts of 1999 and 2009. Recovery values of less than one indicate that trees grew less after the stress event than what they did during. It is again only 1984 that would fit the “normal” growth reaction. The low recovery value is of course directly linked to the increase in growth during the drought year, with a subsequent return to the normal growth of pre-drought periods.

The resilience in 1984 is the highest recorded resilience of all years and species for this study. This is explained by seeing that the trees did not return to their pre-drought growth, but instead had a much higher growth vigour. The much higher growth difference between the pre- and post-drought periods indicates that although 1984 seems to follow patterns one would expect, that there is still a difference between the reactions of the *Olea* vs the reactions of the other species.

Lastly the relative resilience is at a fairly high value for 1984, but has distinctly strange values for 1999 and 2009. Negative relative resilience values indicated that droughts actually increases the growth vigour of the trees. There are very few explanations as to how or why a tree would grow in this strange fashion One has been mentioned before (existing excessive amounts of moisture),

The following illustrations (Figures 33 to 35) show graphically how the *Olea capensis* reacted in the three periods of drought. When compared to the forms of the other species' illustrations it can be seen that they are completely different.

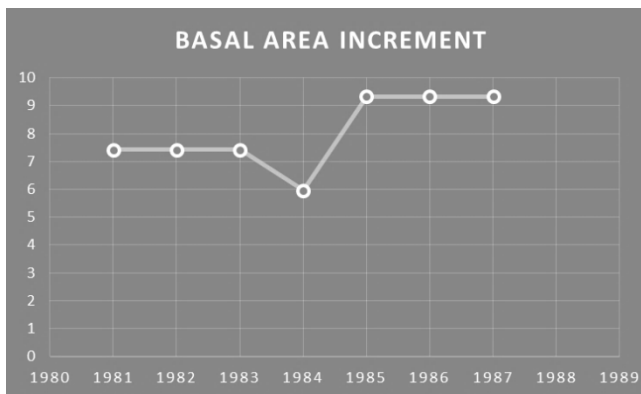


Figure 33: Diepwalle drought of 1984

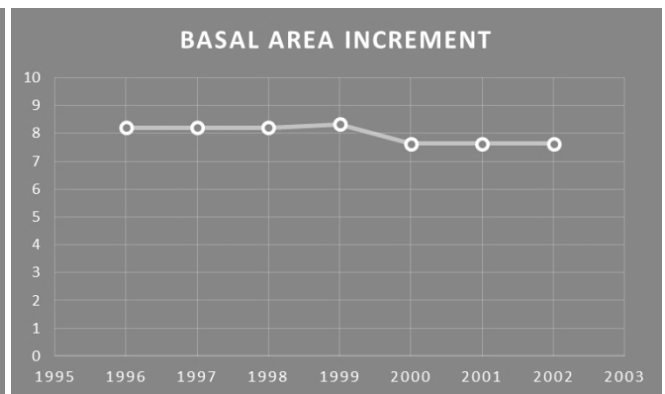


Figure 34: Diepwalle drought of 1999

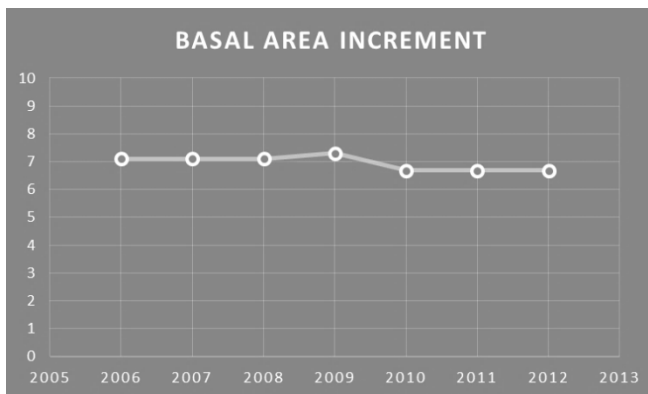


Figure 35: Diepwalle drought of 2009

In figures 34 and 35 it can be seen that there is an increase in growth during the respective periods of drought. The post-drought periods then has growth that is reduced to an even lower level than the pre-drought basal area growth. The excessive high growth after the drought in 1984 was also an indicator that the *Olea capensis* does not react to drought the same way as the other species.

A different approach was then used to evaluate how these trees react towards the drought. The basal area growth of the drought year was compared to the previous and successive years. A noticeable dip in growth in the year following the drought was recorded.

Using the year following the drought, additional Lloret index values were calculated (Table 9). Because growth-ring measurements are taken on an “annual” basis, the method does not take into account whether different species have different periods of growth during the year. After excluding a dating mistake, the reason that the reactions of *Olea capensis* can only be seen in the following year could be caused by a different growing season than that of the

other two species. It can be seen in Table 9 that besides 1984, the other two years now have what one would describe as normal reaction index values.

Table 8: *Olea capensis* Lloret et al. (2011) index values for one year after drought events

Site	Year	Rt	Rc	Rs	RRs
Diepwalle	2000	1.217	0.988	1.202	-0.015
	2010	0.810	1.214	0.983	0.173

In the resistance column it can be seen that the resistance towards drought now fits with the values of the other two species. It is again the 1984 drought year (1985 tested index value) which is an outlier. The other two resistance values of 0.810 and 0.965 respectively thus indicate this species' true resistance towards drought.

For the recovery a fairly high value was recorded for the 1999 drought (2000 tested index value) but this value was within the normal range relative to the other species. The reverse of what is expected is seen in the 1984 (1985 tested index value) as there is then again a peak in growth with only slightly reduced growth two years after the drought event (1986).

The resilience value for the drought of 2009 shows that the trees returned to their original growth patterns more than three years after the event. This is also the same as for the other species, which had normal growth return within 3 years after the growth depression event (Drought year in the case of *Podocarpus latifolius* and *Pterocelastrus tricuspidatus*). The drought of 1999 on the other hand had to take more time to return to the pre-drought growth patterns.

The relative resilience for the 1999 and 2009 drought years are what was expected in the years of the drought, but was only expressed in the year after.

Figures 36 and 37 indicates how the *Olea capensis* trees reacted toward the respective droughts **one year after the event**.

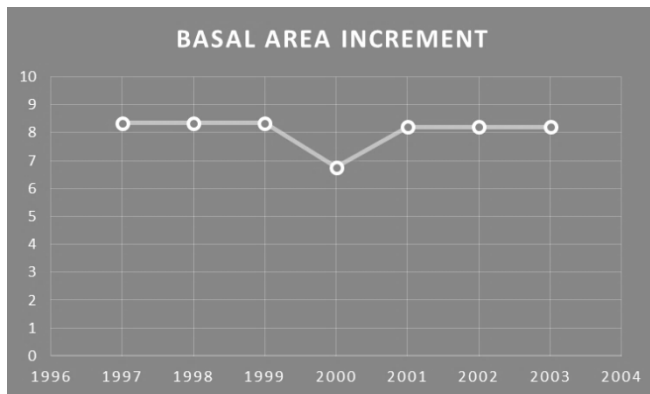


Figure 36: Diepwalle drought of 1999

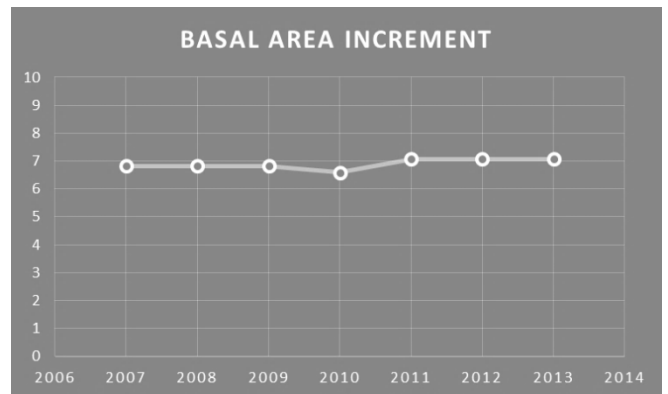


Figure 37: Diepwalle drought of 2009

It is thus observed that the *Olea capensis* trees do not react in the year of the drought event, but instead one year afterwards. It can also be said that this does not happen because of existing high moisture stress, but rather because of another existing adaptation. The most likely explanation for this would be a leaf shedding and fertilization effect. The *Olea capensis* trees could be dropping leaves to preserve energy and prevent moisture loss. By doing this they are fertilizing the remaining trees, reducing the stress during the drought.

3.3.4 Species comparison

The first test done was to see how each of the three species on the Diepwalle site differ. First, the growth rate was tested, which yielded a significant difference level of 99.9% (p-value of less than 0.001). From this value, it is stated that all three species in the one site significantly differed in basal area increment in the years before, during and after drought events. In a complex forest system, such as the one at Diepwalle, one can expect to see many tree species with vastly different growth rates and forms. Because of the different growing spaces and light tolerances, this result was expected.

The next step on the species level was to see how each of the species differed in their reaction towards the droughts. In the year of the drought, all three species had significantly differing resistance values. The *Podocarpus latifolius* had the least resistance against drought, whereas the *Pterocelastrus tricuspidatus* was well adapted against it. The *Olea*

capensis was the only species with a resistance above one, and was thus also different. The significance of the differing R_t values was at 95% (A p-value of less than 0.05). The reason for this difference could be the low-resistance outlier of the *Podocarpus latifolius* trees. The test without the outlier yielded no big difference and the species remained at a 95% confidence difference. If one uses the values of the *Olea capensis* one year after the drought event, it was not significantly different from either the *Podocarpus latifolius*' or the *Pterocelastrus tricuspidatus*' resistance. The other two species still remained different. Because this reaction is only seen a year after, the values could not be compared. Instead values of the same years had to be used. The result was great differences in all the species.

For recovery after drought and resilience towards drought, it was seen that *Podocarpus latifolius* was adapted the best to reach pre-drought growth rates. *Pterocelastrus tricuspidatus* had a similar (albeit slightly lower) recovery value which did not differ significantly from *Podocarpus latifolius*. It did however have resilience values below one, implying that it took longer to reach pre-drought growth rates. The *Olea capensis* again had a completely different approach as the reactions only happened during the following year.

Concluding the difference between species, it can be said that the *Podocarpus latifolius* had the lowest resistance towards drought but could quickly recover afterwards. The *Pterocelastrus tricuspidatus* trees had a very good resistance towards drought, but took a much longer time to recover the resources and energy to be able to reach normal growing conditions. *Olea capensis* only reacted to the drought a year after the event. The reaction in the following year is very comparable with the *Podocarpus latifolius* during the drought year, although it would have slightly higher resistance values.

3.3.5 Comparison of site influence

When the sites were compared three main aspects were used. The first was the rainfall, which had a significant difference. The mean rainfall at Groenkop was 860mm per annum with droughts as low as 641mm in the timeframe of this study. The moister site, Diepwalle, had a mean rainfall of 1100mm per annum with droughts down to 690mm for the 2009 drought. Although the drought levels for two of the periods were similar, the mean annual precipitation (MAP) was significantly different over the two sites.

The second aspect which was compared over the two sites were the basal area growth rates of the species present on both sites (standardised growth rates). It was seen that the

Groenkop site had significantly higher growth rates than that of Diepwalle for both species. The mean basal area growth for *Pterocelastrus tricuspidatus* was 2.1cm² at Groenkop and 1.89cm² at Diepwalle per year. The *Podocarpus latifolius* had mean basal area growth of 3.36cm² at Diepwalle and 6.19cm² at Groenkop.

The last aspect looked at were the Lloret stress index values. While the growth rates between sites had big differences, the reactions (indexed values) had no significant difference at all. This means that even though the trees on each site have different growing conditions and moisture availability, that they still reacted similarly when faced with similar forms of stress.

It can thus be concluded that the site differences include weather and absolute growth, but not to the reaction pattern of the trees.

3.3.6 Comparing the drought periods

Five drought periods were observed in the total of forty years. There were two droughts on the Groenkop site, and three at Diepwalle. The severity of the droughts ranged from abnormally dry (SPEI values of -0.79 to -0.51), moderately dry (SPEI values of -1.29 to -0.8) and exceptionally dry (SPEI values of <-2.0).

The difference in drought periods were tested on two levels namely growth rate during the drought and reactions towards the drought. Although there were slight differences in both the growth rate and the index values, neither proved to be significant.

Concluding the comparison of drought periods, it was seen that there was no significant difference in growth with the drought classes ranging severely. The same was observed when looking at how the trees reacted in times of moisture stress. There were almost no difference between the reactions to drought in any of the specific periods.

3.4 Discussion

In the case of this study, a paper by Lilly (1977) was used to select species suited for the purposes of this study. During the course of the study a difference in conclusions arose due to the difficulty during the measurement of the *Olea capensis* samples.

3.4.1 Critical appraisal of methods and data

There are multiple methods available for various purposes in dendrochronological studies. A large amount of these had to be evaluated for possible suitability of use in this study. The first of which was how to quantify the effect of drought. To do this one first had to look at available data and how it could be transformed into indexed values comparable with the growth of trees. The best two methods stood out as the Palmer drought sensitivity index (PDSI) and the standardised precipitation and evapotranspiration index (SPEI). Both of these indices would have been able to indicate specific drought periods, but for the suitability of use and the data, the SPEI was selected.

The SPEI takes in to account the precipitation and then calculates a base values of water which could be available to the plants. It then corrects the base value with temperature and transpiration values to ensure a more representative index value is used. These calculated index values then gave good insight into how each year during the past 40 had experienced precipitation quantities relative to the plant available water. These values thus enabled one to select specific drought years, which did not have overlapping effects from previous droughts or flooding years to compare tree growth of the selected year to these surrounding years. The SPEI data was a mixture of measured and modelled values. They were supplied by both the Agricultural Research Council (ARC) and the international SPEI database (SPEIbase, 2010). The data was additionally compared to ensure that there were no discrepancies between the two different sources.

Tree selection was done in accordance to the principles listed in Section 1.2. There was looked at their ecological amplitude and importance within the forests. As some of the trees, and the forests in general, are protected, special permission to sample had to be obtained. There were also issues with the selected species, and it thus had to be adapted to suit both the selection principles and the legislation of SANParks. This did luckily not pose major

problems, as most of the selected species were not specifically protected and could thus be sampled with our minimal invasive coring procedure.

Coring and measurement methods could be seen as standard, and thus little selection was done here. There are various opinions on how to treat trees after coring, but it was decided to not treat the wounds extensively with sealants, but rather with a simple anti-fungal paste. This only ensured that no outside infection would enter the tree before it compartmentalised the damage by itself. Ideally the devices for tree ring measurement should have been the same from the start, but only the available equipment could be used. The program TSAPWin along with the Lintab measurement device was a very efficient combination to measure and analyse the core samples.

Two steps within the methodology is seen in the literature as cardinal to most tree ring studies. The time correlation coefficient and the skeleton plots. Although there are a few time correlations coefficients available for use, most all researchers use the GLK for its ease of use and simplicity. Skeleton plots on the other hand is an older method, which is seldom used these days. These plots are good indicators of concurrent growth, but have almost fully been replaced by the correlation coefficients. They were however of great help while doing visual comparison of samples and (re-)measuring data. As they indicate ring size differences, non-overlapping cores could not only be identified easily, but the specific first occurrence of the break in correlations could be detected. The GLK along with the skeleton plots were thus excellent methods to use together as their results complemented each other.

After measurement it was seen that the *P. latifolius* had a frequent occurrence of false rings, but due to the nature of conifer ring formation, was easy to measure. The false rings could also be identified and removed through comparison with all the other samples. It was thus seen that this was a well selected species for this study. Similarly, the *P. tricuspoidatus* had rings fairly easy to measure, but in some of the samples little to no rings could be seen. This caused a loss of data and a smaller pool to do analysis on. The *O. capensis* proved to be the most difficult to work with. It was the most difficult species to sample due to the hardness of the wood as well as to prepare and polish it. During the measurement of this species it was also seen that the heartwood-sapwood border caused problems. On one of the sites, only a minimal amount could be measured at all, thus causing one species to be lost for analysis on one of the sites. On the Diepwalle site enough samples could be measured to do analysis on, but not as much as that of the other two species. *O. capensis*, in contrast to what Lily (1977) indicated, is, according to the experience gained in this study, not one of the best species to use for dendro-ecological studies. A possibility to overcome these difficulties

could be to use other methods of ring identification and measurement, such as CT scanning or by use of the whole stem disc as shown by Seifert et al. (2010).

To see the effect drought have on the diameter growth of the trees, two methods were employed. In many studies, such as that of Pretzsch et al. (2012), the Lloret (2011) growth reaction indices were sufficient to describe and compare the growth situations on comparable sites and species. By using growth-precipitation correlations and additional preliminary verification, expected reactions could be seen. These pattern on their own do not mean much, but by combining what can be seen with that of the Lloret index reactions created a bigger and more complete picture of how the trees react towards moisture availability.

3.4.2 Results and indicated responses

It was seen in the results section that each of the selected species had a completely different reaction towards the drought stress. Although it could also be seen that for two of the species there was a definite different growth over the two sites, there was no significant difference in how they reacted towards the periods of drought. This indicated that even though they are not closely genetically related they show similar adaptation patterns to drought.

It could clearly be seen that *P. latifolius* had the most “expected” reaction towards drought periods. It had the biggest reduction in growth during the year of the drought, but then recovered to full potential growth within a short period after the event. *P. tricuspoidatus* also reacted in a similar way as could be expected, but it had a much bigger resistance to the drought, expressed in lower growth reductions. This high resistance could in that case also be seen as the reason for the slower return to potential growth, due to the trees using more energy in the drought year to keep on growing. This reaction could be an evolutionary way in which this specific species gains an “edge” on the other trees to ensure it is not out competed by the bigger species when normal precipitation and temperature conditions return.

The *O. capensis* had the most interesting reactions towards periods of drought, as it had slightly better growth during the years of drought as indicated by the Lloret index values and the trends. Through deeper investigation it was seen that this species only properly reacted to the drought one year after the event. Two possibilities for this reaction were discussed.

The first was one where this species is already under a stress due to an oversupply of moisture in the soil. The drought period could then relieve some of this stress, being the cause for the increased growth during the event. The second possibility was that it was a co-evolutionary reaction where it facilitates the stress on the forest caused by the drought event. This facilitation could distribute the required resources over a longer period, instead of having all the stress from a drought affect all of the trees at the same time. During the event these species would then use more internal resources as well as water to build up supply for the following year. The year after only, it would suffer reduced growth while the rest of the trees started to recover. By doing this, the available resources during the event is more evenly split across two years, instead of causing severe competition during the drought.

When comparing how each of the species reacted relative to each other and across the sites, multiple differences and similarities were observed. It could be said that the *P. tricuspidatus* is facilitated during periods of stress by being shielded from harsher environments. The *P. latifolius* then takes the full effect of the drought, but has the ability to recover better after the event. This effect could be because the *Podocarpus latifolius* should have a more developed root system than that of the *Pterocelastrus tricuspidatus* and can thus be more efficient with its resources in the years following the event. *O. capensis* then buffers the effect of the drought further by only reacting to the event a year after the event.

Using three species of different size classes and strata occurrence along with ecological amplitude, gave one a good idea of how these forests react during times of drought. The problem though is that there are over 100 different tree species within these forests and that using three only is not fully indicative of the forest as a whole.

3.4.3 Key questions

Is there a difference in growth and reactions towards drought over multiple species?

The first objective of this study was to see whether different species have differing reactions during periods of drought. It was observed that each of the species had a significantly different growth. This difference in growth was also confirmed with the presence of a drought event, in which each of the species had a specific and significantly different reaction towards the drought. Each species excelled in either resistance, recovery or resilience towards drought. It was thus concluded that each of the species were completely different.

Was there a difference in growth and drought reactions seen over different forest types?

By comparing two of the species found on two different sites to each other, it was determined that growth over site differences were present. This difference could be expected due to different resource availability between the sites. Stand structure, density and undergrowth would also have played a role in this. Reactions towards drought however still remained similar over both the sites and species. The growth reductions are thus relatively the same indicating that these species are “genetically programmed” to react in certain manners when faced with stress. We thus see that although the diameter growth is completely different, that the relative growth reactions indicated by the resistance and the recovery to drought are very similar.

Could a difference between different size classes and strata be observed?

Due to some of the samples not being able to be measured, it was not possible to determine whether there are size-class differences in reactions to drought. There was, however, a difference observed in the two upper canopy species’ reactions relative to that of the low-canopy species. The *P. tricuspoidatus* seems to have been sheltered by the larger species, and thus had a lesser reaction to drought with a significantly higher resistance to the events. Due to the fact that these are different species, no conclusive result could be found for this question and further research would thus be necessary.

Could existing stresses be relieved through the presence of a drought event?

It was speculated during the preliminary part of the study that *O. capensis* already had too much moisture to deal with, and could thus indeed benefit from droughts. By looking at the trends presented, it could be seen that better growth is observed with less precipitation. It was instead seen that this species had specific adaptations to only react to droughts a year after they occurred. Specific stress was thus not relieved during drought periods, a delayed reaction to the drought rather caused the available nutrients to be split among species over a longer period.

3.4.4 Future research and management

Although this study found conclusive reactions towards drought in three different species, over two sites, the research on these reactions are far from complete. With the complexity of these forests, multiple future studies are recommended to gain a deeper understanding of afrotemperate forests as an ecosystem.

The first step would be to compile a tree-ring database for all the possible tree species, dating back as far as possible. This collected data should then be used to not only look at how droughts effect the forests, but also fires, pathogens and other external events.

Following the collection of more complete data, a large competition and growth index should be developed for these unique forests. Crown extension, direction and size, along with tree and canopy height and diameter should be collected for the same trees. This along with GPS coordinates would be the data needed to create competition profiles for the complete forest.

Taking then how each kind of event affects growth, as well as how each species interact with each other, a preliminary forest growth model could be created. To create a complete model would require additional biomass studies.

This research will also enable better management of these forests by being able to predict almost exact growth and future climatic reactions.

4. Conclusions and recommendations

This study originated from the lack of knowledge on certain reactions within the indigenous forests of South Africa. With an anticipation of a higher erraticness of precipitation and thus higher drought frequencies caused by climate change it is imperative to understand how these forests will react when faced with changing conditions. It was seen that the species selection for a study such as this is critical. Two of the three selected species were well sought out, but the third, namely *Olea capensis*, was not the ideal selection. It would be advisable to rather include another *Podocarpus latifolius* species as well as another crown species such as *Ocotea bullata*.

The methods used to sample, measure and analyse these species should also be constant to reduce the possible bias that could occur. When dealing with the analysis of tree rings, it is also important to have an experienced operator and analyst as much of the work depends on the perception and interpretations of this person.

The *Olea capensis* is considered one of the fastest growing trees in these forests. The *Podocarpus latifolius*, which is a medium to fast grower can only compete with the *Olea capensis* on sites where it has ideal growing conditions. Lastly the *Pterocelastrus tricuspidatus*, which is a slow to average growing tree and also the smallest of the three, represents the trees slower radial growth. The species selection was well planned as it covered the different strata found in all South African forests.

Observations and statistics indicated both differences in sites and in species. Although only two species could be used for the cross-site comparison, it could be expected that *Olea capensis* would have a similar reaction. This would only be the case though if it was not under specific stress as at the Diepwalle site, and assuming that there is not a physiologically different sub-species present at the Groenkop site.

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