A water Stress History of an *Acacia erioloba* (Kameeldoring) tree from the Koichab

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1. Introduction

The drinking water of Luderitz, Namibia, is derived from a wellfield situated in Koichab valley approximately 100 km NE of the town. At the point of abstraction the water is 6000 years to 8000 years old (Heaton et al. 1981) and flows in an aquifer located in the Koichab palaeochannel. The flow rate in the aquifer was calculated from the groundwater reserve to be between 33 m/yr and 83 m/yr but radiocarbon age profiles suggests that the value is 13 m/yr (Geyh et al. 1994). This has a significant impact on the theoretical sustainable levels of water abstraction. Between 1967 and 1992 the hydrological surface dropped by 5m over an elliptical area 5.5x7.0 km in extent (Geyh et al. 1994). The implicit exceedence of the abstraction rate over the recharge rate implies that the abstraction rate is not indefinitely sustainable, and could potentially impact on the hydrological and biological functioning of the system.

The reported death of mature *Acacia erioloba* (Kameeldoring) trees in the riverbed could be caused by the depression of the hydrological surface in the vicinity. This report assesses the history of water stress in one *Acacia erioloba* specimen (figure 1) in order to determine if there is an association between groundwater levels, and water stress in the trees.

![Figure 1. The Acacia erioloba specimen analysed in this report after the sample disk had been removed (reproduced with the kind permission of N du Plessis)](image)

2. Rationale for measuring isotopes in trees

A way in which water stress histories can be determined in trees is through the carbon isotopic ratio of the wood in the annual growth rings. It is broadly accepted that stable carbon isotopes in trees correlate with the rate of photosynthesis (carboxylation) because of the common dependence on stomatal conductance (Farquar & Richards...
In schematic terms trees close their stomata during periods of water stress, which forces them to use more of the CO₂ that is trapped within the leaves for carbohydrate synthesis than they would if the stomata were open. Instead of selectively using ¹³CO₂ the tree must make more use of ¹²CO₂. At the same time the reduced stomatal conductance prevents the replacement of CO₂ within the leaves and the enzymatic reaction that is central to photosynthesis, is halted. Thus in times of high water stress it is anticipated that trees will form tissue at a slower rate, and that the tissue will have a higher ratio of ¹³C/¹²C than in times of reduced water stress. Using delta notation to denote the ratio of ¹³C/¹²C the control of leaf isotopic composition is given by the equation:

\[
\delta^{13}C_{leaf} = \delta^{13}C_{atm} - a - (b - a) \frac{c_i}{c_a}
\]  

(Farquar et al. 1982)

Where \(a\) and \(b\) are fractionation constants and \(\delta^{13}C_{atm}\) represents the isotopic ratio of the air which is also more-or-less constant. Therefore the term \(c_i/c_a\), the ratio of intercellular to atmospheric CO₂ concentration that is controlled by stomatal conductance, is directly related to the stable carbon isotope ratio. Using a comparative approach it is possible to measure the stable carbon isotope ratio of different growth rings within a tree and by subtracting the values the constants in the above equation cancel one another. The difference between \(\delta^{13}C\) values is determined by the ratio \(c_i/c_a\) and is a reflection of different stomatal conductance regimes.

3. Terms of Reference for the project

This project was commissioned by N. du Plessis on behalf of Namwater. The terms are to determine a water stress history of a tree from the Koicab that would be shipped to Pretoria by Namwater. The necessary sample preparation and analyses for the last 100 years of growth would be conducted and suitable high resolution radiocarbon dates would be obtained to verify the time frame. These data were to be compared with groundwater levels and rainfall data provided by N. du Plessis to determine if the tree specimen had died from high water stress.

4. Previous Carbon isotope studies on Acacia erioloba

The carbon isotope fractionation mechanism operates at the scale of individual stomata. It is possible that the density of stomata can be regulated to compensate for changes in water availability instead of stomatal regulation and so carbon isotopes may not reflect water stress. For this reason it is important to test the carbon isotope response to water availability for each tree species that is studied. This is accomplished by comparing the diachronic record of carbon isotopes recorded in annual growth rings with correlated rainfall or groundwater levels depending on the water source of the tree.

A baseline study was conducted in the vicinity of Askam in the Northern Cape, South Africa were an invasive tree species, Prosopis spp. trees (common name: mesquite), was considered the cause of the death of many mature Acacia erioloba trees. The impact on the water reserve was estimated at 192 million m³/year in 1998 (Versveld et
al. 1998, Le Maitre et al. 2000). As this is an extremely arid region the availability of water is a limiting factor in tree growth. It is immediately apparent when traveling in the area that trees are mostly distributed in and alongside the apparently dry riverbeds, presumably because of their dependence on groundwater.

A number of trees were felled and disks cut from the trunks, the annual growth rings were identified on polished sections, and the annual $\delta^{13}$C history of the trees was measured. High-resolution radiocarbon analysis (yielding precision of ± 1 year) of the large growth ring of 1974/75 was used to fix the time frame of the rings. The results for *Prosopis* specimens P1 and P5 (green lines) and *Acacia erioloba* specimens E4 and E9 (blue lines) are presented graphically in figure 2 with the associated rainfall. The dependence of carbon isotope ratios on water availability is confirmed by the extremely negative $\delta^{13}$C values in both species following the two major rainfall events in the summers of 1975/76 and 1987/88.

![Figure 2. Carbon isotope values (plotted on left scale) of annual rings of 2 Acacia erioloba trees (blue lines) and 2 Prosopis spp. Trees (green lines) from the Askham area of the Kalahari Desert. The annual rainfall is plotted on the lower graph (right scale) showing that negative excursions in the carbon isotope history are associated with times of reduced water stress.](image-url)

On the basis of the comparison between water stress histories of the *Prosopis* and *Acacia erioloba* trees, and also with additional oxygen isotope measurements not presented here, it was suggested that the latter is dependent exclusively on groundwater from the saturated zone (Woodborne & Robertson 2000, 2001). At the onset of the water stress the *Acacia erioloba* tree minimised its impact on the groundwater by entering a dormant state in which its stomata were closed and
photosynthesis was at a minimum. In contrast the *Prosopis* trees were extremely opportunistic and it developed a shallow root system to exploit the water available in the unsaturated zone when this was available, and then shifted to a deep root system exploiting the saturated zone when the shallow water was no longer available.

This study demonstrated that the exotic species has an adaptive advantage over the local species that is manifest in the opportunistic adaptation that allows *Prosopis spp.* to exploit shallow water when it is available, and deep water in times of drought. The ability to intercept rainwater before it recharges the water table allows *Prosopis spp.* trees to germinate and mature even when rainfall is marginal. In contrast *Acacia erioloba* trees are not able to exploit shallow water and their recruitment is linked to flood events that saturate the evaporation zone and significantly recharge the groundwater levels in the area. As a result of this difference the recruitment success of *Prosopis spp.* is greater than that of *Acacia erioloba* and a much greater demand for water evolves as the *Prosopis spp.* trees invade the dry rivers of the Kalahari to form very dense stands. The isotopic data also suggest that *Acacia erioloba* adopt a conservative strategy akin to dormancy when the water table drops. *Prosopis spp.* trees also adopt a conservative strategy but only when the water table has dropped well below the threshold for *Acacia erioloba*. In its dormant state the indigenous trees cannot invest in their roots and they die from water stress.

5. The Koichab *Acacia erioloba*

A mature *Acacia erioloba* tree that had recently died was felled by N. du Plessis and a slice of the trunk was sent to the Quaternary Dating Research Unit, CSIR, Pretoria for an isotopic analysis of the last 100 years of growth. The selected time frame was presumed to span from before water abstraction commenced until the very recent past, and that the water stress profile could be linked to the impact of water mining in the area.

Borehole water level monitoring data was provided by N du Plessis. The data provides a critical baseline for comparison with the water stress history of the tree, but it is also difficult to reconcile data from different boreholes that commenced operation at different times. In order to overcome this, the data was separated into three periods – pre- June 1991 (approximately 24 years), June 1991-June 2002 (11 years) and post-June 2002 (2 years), and only borehole data that covered the relevant time ranges were used. The extent to which the water level dropped in each period is presented in figure 2. Because of the different time frames the drawdown data cannot be compared as drawdown rates, but they still demonstrate that a substantial cone of depression in the hydrological surface has developed. The *Acacia erioloba* specimen was taken from a point very close to the centre of the cone of depression where the total water drawdown has been in the order of 25m.
Figure 3. The Koichab valley drains approximately East to West allowing the latitude of boreholes to give a relative transect through the aquifer. The relative drop in borehole water levels in the period pre- June 1991, June 1991-June 2002, and post June 2002 is presented. This demonstrates the development of a substantial cone of depression in the hydrological surface as a result of water abstraction.

6. Sample preparation

The disk was polished using progressively finer sandpaper until a 1200 grit was used (see Orvis and Grissino-Mayer 2002) yielding a glass smooth finish. This surface was analysed under a binocular microscope to identify the parenchyma bands that have been shown to be annually resolved (Gourlay & Kanowski 1991). Sampling the rings individually was not feasible in this study, and a set of fine drillings (2mm diameter) were made in two offset transects immediately adjacent to one another (figure 4).

Figure 4. The parenchyma lines were identified on a polished surface and scored with a utility knife. Samples were drilled in two adjacent transects covering 100 rings using a 2mm drill bit. Chalk dust has been added after sampling to highlight the details.
The sample preparation process of Epstein et al. (1976) does not allow large sample numbers to be processed in a reasonable time, and so an ethanol/toluene Soxhlet distillation was used on the drillings to remove the mobile resin fractions (Loader et al. 1997). They were then carefully weighed and combusted on-line in an elemental analyser (Thermoquest EA 1110) coupled to a stable light isotope mass spectrometer (SIRA). Each sample was measured at least twice, and if the precision on replicates was unacceptable, further analyses were conducted. A beet sugar standard, and project specific sawdust standard were used to correct for sample size effects of the elemental analyser. The average precision on replicate results was <0.2‰.

7. Isotope measurement and nomenclature

Stable carbon isotope ratios are measured as deviations from standard reference materials using “delta” (δ) notation on a per mille (‰) scale. The equation used to derive the δ¹³C value is

\[ \delta = \left( \frac{R_{\text{sample}} - R_{\text{stand}}}{R_{\text{stand}}} \right) \times 1000 \]

where \( R = \frac{^{13}C}{^{12}C} \). Carbon isotopes are reported relative to PeeDee Belemnite (PDB) standard.

Although the Austral summer spans two calendar years, the convention used in assigning a growth ring to a year is to use the annum in which the ring started growing. When this data is to be compared with annual rainfall, it is necessary to annualize monthly rainfall figures from July to June to match the growing season. The rainfall is also attributed to the year in which the cycle commences.

8. Dating

Two growth rings were dated with high precision using radiocarbon dating to verify the ring count and to fix the year of death of the tree. Using the convention of counting rings backwards from the bark towards the centre of the tree, the two rings were number -10 and -25. These were selected in anticipation that they would correlate with approximately AD 1990 and AD 1975 respectively. Ultra-high precision radiocarbon analyses were done on the samples and the results were compared with the Pretoria high resolution record of atmospheric radiocarbon concentrations (Vogel et al. 2002). This is a direct measure of atmospheric radiocarbon levels and where ultra-high precision dates are obtained for a single growth ring it is possible to calculate with a precision of 1 year the date in which the ring grew. The corresponding dates emerged as either AD 1963 or AD 1972 (two possibilities) for ring -10 and AD 1957 for ring -25 (table 1). Given the 15 year anticipated difference between rings -10 and -25, the corresponding years are likely to be AD 1972 and AD 1957 respectively. Taking into account the 9 rings that grew after 1972 his implies that the last growth ring correlates with AD 1981 or more specifically the summer of Ad 1981/1982.
Discussions with N du Plessis suggest that the tree may have had green leaves more recently than 1982. The study of the Kalahari *Acacia erioloba* specimens from the Kalahari Desert indicated that the trees may assume a state of dormancy during times of extreme stress, and in this time their vitality is manifest in small fluorescence of leaves, but there is no substantial growth and the tree does not lay down a growth ring. Dead leaves recovered from the tree were also radiocarbon dated to test when the last fluorescence took place. When compared with the Pretoria air record the result suggests that the leaves were formed in either in the summer of AD 1958/1959 or the summer of AD 1998/1999. The context implies that the tree continued to flush new leaves 18 years after it had ceased to lay down growth rings in the trunk.

### Table 1. Radiocarbon analyses of the Koichab Acacia erioloba tree.

<table>
<thead>
<tr>
<th>Anal. No (Pta-)</th>
<th>Sample designation</th>
<th>( \delta^{13} \text{C} ) (( %_{\text{PDB}} ))</th>
<th>14C (pmc)</th>
<th>Calibrated Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>9084</td>
<td>Koichab Tree Ring -10</td>
<td>-25.3</td>
<td>148.2±0.3</td>
<td>AD 1963 or 1972</td>
</tr>
<tr>
<td>9095</td>
<td>Koichab Tree Ring -25</td>
<td>-26.4</td>
<td>105.8±0.3</td>
<td>AD 1957</td>
</tr>
<tr>
<td>9223</td>
<td>Koichab Tree leaves</td>
<td>-28.2</td>
<td>110.0±0.3</td>
<td>AD 1958 or 1999</td>
</tr>
</tbody>
</table>

Because the tree remained dormant for a protracted period of time it becomes difficult to argue the true date of the last 10 rings. Since 1972 the tree laid down 9 growth rings, and 18 rings are not represented. It is assumed that the 10 growth rings were laid down in the period AD 1972 to AD 1982 because of the continuous record in the preceding 15 years (established by the radiocarbon dates) and the fact that good rain was recorded during this period (see figure 5). Accordingly the dormancy of the tree is presumed to have been continuous since AD 1982.

In order to compare the impact of depressing the water table on the trees it is necessary to have overlapping data. Since water abstraction started in 1967 the only overlapping datasets for water table and water stress in the Koichab Acacia erioloba comes from the last 15 rings of the tree. Of these 15 rings the last 10 are assumed to be continuous but their age is not unequivocally established.

### 9. Results

The sample drillings used for the isotope analyses were occasionally from a single growth ring, but more often they cover several rings. In this circumstance the result obtained would be a weighted mean of the relative contribution of wood from each ring. In addition the “date” associated with each drilling is not a single value but rather a range. Accordingly the plot of \( \delta^{13} \text{C} \) variability through time (figure 5) has error bars on the \( \delta^{13} \text{C} \) values that are associated with the variability of duplicate measurements, and date range values on the date values associated with the range of rings intercepted by the drilling. The effect is to average out variability to some extent, but the overall pattern appears to be robust with long term trends (cycles) clearly portrayed.

The \( \delta^{13} \text{C} \) isotopes for the Koichab *Acacia erioloba* vary between -25 % to -27 % with two excursions that are more negative than this. This is substantially less variable than the values from the Kalahari trees which varied between -22 % and -27 %. The
Figure 5. The upper part of the illustration depicts the positioning of sample drillings relative to the parenchyma lines of the Koichab Acacia erioloba tree. The relative thickness of the growth rings influences the number of years that are sampled in each drilling and so there is some distortion of the X-scale to convert it into Julian years. This is compensated for by depicting the age values as a range (appears to be an X-error bar). The $\delta^{13}$C values are graphed in the centre using the left scale and the available rainfall data from Aus and Tsirub are presented in the lower graph using the right scale.

two negative excursions in the Koichab Acacia erioloba occurred in approximately AD 1894 and AD 1899 assuming no dormant periods in the early years. The values indicate that the stomata were excessively dilated in those years relative to the others. Convention suggests that this implies substantial water availability, but the 1 year duration in each case would imply no recharge or long-term effect. It is unlikely that these are flood events, and other explanations will need to be explored.

10. Discussion

The available rainfall records indicate relatively high rainfall in the years AD 1920, 1933, 1962 and from 1973-1975. There are indications that some of these were widespread rainfall events that would have led to substantial recharge of the desert aquifers. The 1933 rains were responsible for the biggest historical flood in the Swakop River (Stengel 1964). Incidentally the second biggest flood in the Swakop River occurred in 1893 which may correlate with the first of the two negative
excursions in the Koichab *erioloba*. The third biggest historical flood in the Swakop River took place in 1963 corresponding to the 1962 growth ring (the growth ring is dated according to the year in which it starts growing). Similarly the 1973-1975 rainfall event was the cause of the biggest flood event recorded in the Orange River and its effect is reflected in the rainfall of the Kalahari Desert (figure 2). With each of these rainfall events there is a negative shift in the stable carbon isotope values of the Koichab *Acacia erioloba* tree. The cyclicity in the δ¹³C values of the tree therefore seem to confirm the same pattern that was established in the Kalahari Desert in which major rainfall events lead to recharge of the soil water and negative shifts in the carbon isotope values. In intervening years the scarcity of rainfall leads to positive shifts in the carbon isotope values.

In the period 1967 to 1982, after the commencement of water abstraction, the carbon isotope values obtained for the Koichab *Acacia erioloba* tree show a cycle from low water stress to high water stress in 1972, and then returning to low water stress in 1982. The latter half of this cycle coincides with above average rainfall in the area. During this period the groundwater level dropped by about 1.5m from somewhere in the order of 11-14m depth. At the end of this period when the tree stopped laying down growth rings the water stress levels were not extreme in any way. No progressive increase in water stress can be linked to the progressive dropping of the water table at this time as the carbon isotope signal continues to show a rainfall driven response.

Oxygen isotope values for the wood sap taken from trees that are still alive in the area are consistent with the values obtained for water from the saturated zone. As the trees do not fractionate the water during uptake, this suggests that they are using the phreatic water. This appears to contradict the conclusion presented above based on the carbon isotope history of the dead tree. There are two areas to explore in trying to reconcile these positions. The first is that the oxygen isotope value of the water in the vadose zone is not known and so it cannot be demonstrated from the sap oxygen isotope values that the living trees are not using the vadose water. A second argument is that the use of phreatic water is opportunistic and the trees will use it when this is the only source. This would imply that the tapping of phreatic water would correspond to times of elevated water stress. Should there be any water available in the vadose zone (as a result of rainfall or flooding) the difference in water potential at the phreatic surface and in the vadose zone may be sufficient that the tree exploits shallower water. The difference between the two data sets is then a time resolution issue, and at present the trees are accessing the phreatic water. As reduced water stress appears to correlate with rainfall, the carbon isotope data suggests that the trees do respond to this source when it is available. The data also suggests that periods of low water stress occur sometimes for up to 10 years after good rain, which implies a long period of water retention in the soil before the trees shift to the deeper water source. A possible way to resolve this is to measure the oxygen isotope profile from the tree wood which reflects the changes in source water isotope values. Such an exercise was undertaken in the Kalahari study and the water stress cycle seen in the carbon isotopes was matched by a cycle in the oxygen isotopes implying a shift in water source.

The interpretations presented above suggest that the previous conclusion of Woodborne and Robertson (2001) that *Acacia erioloba* is exclusively phreatic water dependent is incorrect. At least in the Koichab Valley, the *Acacia erioloba* trees
Figure 6. Insect boring is noted in discoloured areas of the Koichab Acacia erioloba sapwood. This may indicate areas in which the bark has stopped growing, and where the insect attack may have contributed to the eventual demise of the tree.
Figure 7. A crack through the centre of the Koichab Acacia erioloba is flanked by wood that is discoloured and that has lost its ring structure. This is likely rotting and may also have contributed to the eventual death of the tree. Indeed, the enigmatic dormancy, which is presumably an ultra-high state of water stress, of this specimen following a time when the tree appeared to be under no stress is best explained in terms of a dual water-use strategy. The use of shallow water from above the water-table is a pragmatic energy saving approach that can be employed for as long as this reserve is available. This would obviously follow surface recharge events which in this case would be floods or rainfall that exceeds the evaporative potential. The results from both the Koichab and Kalahari specimens suggest that this reserve may last up to 10 years before water stress reoccurs. If in the interim the water table is depressed, then the switch from the shallow to the deeper water source may not be successful, and the tree immediately changes to its maximum state of water conservancy which is manifest as dormancy. This model predicts that the trees will invest in abstracting deeper water as the water table is reduced, but the first good rain cycle stops the investment in deep roots. When the shallow water source is depleted the tree is no longer able to access the deep water source, and there is a very rapid shift to hyper water stress conditions. The last growth rings of both the Koichab and Kalahari Acacia erioloba specimens reflect low water-stress carbon isotope signals, and they both occur when the shallow water supply following the first good rain cycle after water abstraction (synthetic lowering of the water table) had commenced. This model forecasts the onset of dormancy in Acacia erioloba as a result of water abstraction, and with no mechanism to adequately raise the water table again the tree will ultimately die.

The state of dormancy is, however, not sufficient to kill the tree, and the process will take many years before the tree dies directly from water-stress. During this time the tree is vulnerable because it is unable to grow woody tissue or bark which is essential to protect the tree from insect and bacterial attack. The final death of the tree is therefore unlikely to be from water-stress. The Koichab Acacia erioloba had evidence of prolific insect boring into its sapwood. It is clear that some areas of the sapwood had discoloured and had been subject to insect attack for some time (figure 6). The most likely reason for this is that the bark had been compromised and the tree was unable to heal itself. With the possibility that the tree had portions of healthy bark and portions that were dead, it may also happen that the growth rings would not be continuous around the circumference of the trunk. As the sampling transect was in an area in which the bark was compromised the possibility that the ring count (and stable carbon isotope analysis) may not have been fully representative. The parenchyma lines were traced from the sample transect to the area of the tree in which the bark was not compromised, and the same ring count was obtained.

Further evidence that may reflect on the reason for the death of the Koichab Acacia erioloba is rotting that is apparent in the polished section around a crack through the centre of the tree (figure 7). This area has not retained the parenchyma lines and the growth rings could not be traced back to the centre of the tree. The discolouration is similar to that of the sapwood where it was vulnerable to insect attack, and it may be that the tree had acquired an infection.
11. Conclusions

The water stress history of the Koichab _Acacia erioloba_ is established through a $\delta^{13}C$ proxy. Cyclicity between periods of high and low water stress appears to correlate with rainfall and not with groundwater level. This implies that this _Acacia erioloba_ tree was not exclusively dependent on accessing water from the saturated water table, but rather from the shallower vadose water that is replenished by rainwater.

The last growth ring of the tree did not have an isotope signal consistent with high water-stress, but immediately thereafter the tree nevertheless went into a protracted period of dormancy. The last flush of leaves was in AD 1999 and the tree probably died a year later. The rainfall record for the area does not include data for AD 1999, but records from Windhoek show that rainfall was above average in this year relative to the preceding years. This may have provided sufficient water for the last florescence of the tree, but bacterial infection and insect infestation was sufficiently advanced that the tree ultimately died.

The mechanism that induced the dormant state in the tree is presumed to be the progressive lowering of the water table through water abstraction. With the first good rain cycle the tree changed to a shallow water source for a few years and could not re-establish a sufficiently deep rooting system to exploit the ever deepening water table when the shallow water was depleted. This led to a protracted dormant state that could not be reversed while the water table continued to drop. This model can be tested by doing oxygen isotope analyses of the same wood samples used for the carbon isotope studies.

A shortcoming of this study in trying to address the impact of water abstraction on ecological functioning is the poor overlap between the growth record of the tree and the period of water abstraction. If the cyclic water stress response noted in this tree represents a shift between shallow soil water and deeper groundwater, then the impact of water abstraction will only be noted in the water stress conditions. In this study there is only one cycle of water stress during the water abstraction phase, and so it is not possible to determine if there was a progressive increase in baseline water stress as would be anticipated from a known decline in the water table.
12. References


