Tree-ring analysis of *Juniperus excelsa* from the northern Oman mountains

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Introduction

Background

Oman has a rich history of irrigation agriculture which was largely shaped by changes in climate conditions throughout the last millennia. The historical development of oasis agriculture in the mountainous north of the country reflects changes in settlement patterns that are thought to be strongly related to recurrent droughts (Siebert et al. 2004). To study (i) the driving role of climate, i.e. rainfall for the oasis agriculture in the past and (ii) the effects of possible changes in climate on the still existing oases long climate records are needed. However, for the whole Arabian Peninsula such records are scarce and – if available - only date back until the last century, when the British established the first weather stations in the region.

The only published climate archive which fulfils the requirements of longevity and high resolution originates from a varved sediment core of the NE Arabian Sea (von Rad et al. 1999). This 5,000-yr record was dated at an extraordinary precision (about one order of magnitude smaller than typical AMS ^{14}C data) and allowed to reconstruct the strength of both the winter and the late summer monsoon affecting the area. Nevertheless this record may be of only limited value for Oman with its more arid climate largely influenced by the Indian Summer Monsoon. The recent stalagmite records of Fleitmann et al. (2007) in contrast are from northern Oman and cover a timespan of 10,000 years but their resolution is limited.

Potential of Dendrochronology

Dendrochronological studies on long-live tree species have the potential to provide long time series that reflect changes in climate conditions. In the high altitude Al Jabal al Akhdar mountains of Oman extended *Juniperus excelsa* stands exist growing under suitable site conditions. Tree-ring analysis of comparable material has been successfully conducted in both tropical and dry (mountainous) forests in Africa (Fichtler et al. 2004; Couralet et al. 2005; Schöngart et al. 2006, Trouet et al. 2006). Based on initial observations we assumed that these juniper trees form annual rings as they grow under harsh climatic conditions in the dry mountainous forests with a single pronounced dry season. Also a preliminary study by

Fisher et al. (1994) on *J. excelsa* from Oman suggested that *Juniperus excelsor* has potential for dendrochronology.

However, uncertainty remained about the periodicity of ring formation in trees growing under extremely dry conditions (Wils & Eshetu 2007) Theoretically both false or double rings and missing rings may occur in juniper (Couralet et al. 2005). False rings may be caused by a bimodal rainfall distribution in certain years due to winter rains and a strong monsoon event in any one year. Missing or partly missing rings (=wedging rings), in contrast, are frequently formed during years with little rainfall.

Objectives

In this study we therefore addressed the following research questions: (1) Does *Juniperus excelsa* from Oman form clearly distinguishable growth layers? (2) What is the mean annual growth level and estimated age of juniper in the study area? (3) Is cross-dating of tree-ring series between different trees possible? And ultimately (4) what is the potential of *Juniperus excelsa* for the reconstruction of climate records?

Materials and methods

Study site and sample material

The sampling area is located in the Jabal al Akhdar mountain range in the northern part of Oman (Fig. 1a). Unfortunately, the only climate records from Oman are available from the coast at Muscat (Fig. 1b). The climate diagram from Muscat indicates a dry seasonal climate with a prolonged dry season from April to mid November during which drought conditions can be expected.

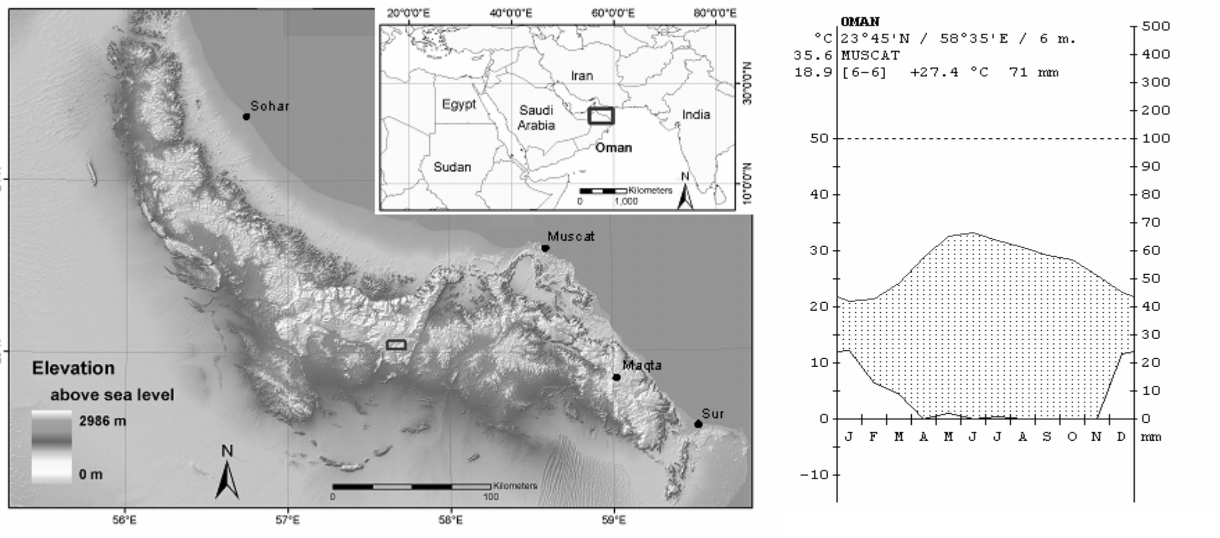

Figure 1: Location with the old Juniperus excelsa stands (see marked square on the insert) on Al-Jabal-al-Akhdar mountain range of northern Oman (left). Climate diagram from Muscat (Seeb Airport, right).

The climate at the high mountain study location is considerably cooler with a long term annual average air temperature of 18.1°C, a minimum of -3.6°C and a maximum of 36.3°C, the coolest and hottest month being January and June, respectively (Department of Civil

Aviation and Meteorology, Muscat, Oman). The juniper trees (*Juniperus excelsa* ubsp. *Polycarpos)* are growing at about 2,300 m a.s.l. in an open dry mountainous forest. The trees are strongly protected which makes cutting of trees for sample collection impossible. However, in addition to 12 cored trees, from which two cores were taken at breast height in January 2004, four stem disks were available from trees cut due to recent road construction.

Cross-dating of tree-ring series

According to the above mentioned tree ring uncertainties (double rings, missing rings), the measured tree-ring series were visually crossdated in a stepwise hierarchical order: Starting with comparisons of series from the cores of the same tree we identified disagreements and went back to the wood surface to check the wood structure in the problematic area. In order to adjust the series, the single tree-ring series were edited in TSAP by adding missing rings and merging false or double rings. The corrected tree-ring series were then averaged into *tree chronologies,* which were visually checked and corrected as in the previous tree-level-check. After successful cross-dating the corrected tree-ring series were combined into a *site chronology*. The final result of the visual cross-dating were statistically verified by running correlation analysis performed with the software program COFECHA (Holmes 1983).

^{14}C dating

As tree-ring formation in juniper from Oman is expected to be very spurious we decided to use *^{14}C* dating to check whether dendrochronological detection of tree rings coincides with the age suggested by *^{14}C* dating. For that purpose *^{14}C* dating was done on the 10 innermost tree rings of the three samples with most tree rings (111, 105, disk 27 in table 1) and compared to the result of the dendro-dating after measuring and cross dating of two radii.

Age determination and statistical description of tree-ring series

The number of measured (and corrected) tree rings indicates the minimum tree age. An exact age determination is, however, only possible if cores include the pith (=centre of the tree) and if reliable corrections for the missing rings according to the sampling heights can be made. The mean tree-ring width (and the standard deviation) describes the general growth level and the variability in tree-ring width and gives an indication about the chance of missing rings in the tree-ring record. Mean sensitivity and autocorrelation of first order are standard parameters in dendrochronology to describe the changes in tree-ring width from year to year and the persistence of the tree-ring pattern (Cook & Kairiukstis 1990).

$\delta^{18}O$ analyses

Many tree-ring series show alternating phases of high-frequency dominated or low-frequency dominated variation with the enhanced high–frequency signal being caused by the regular occurrence of very narrow rings. It is, however, well possible that these narrow rings resemble density variations, that is second growth phases that occur in periods with a strong bimodal rainfall distribution (Fig. 1b). This growth behaviour has been proved for many species growing under dry condition, such as in the Mediterranean’s where temporary dry spells cause a bimodal growth pattern with a recovery of growth after a summer drought (Cherubini et al. 2003). If so, changes in spectral behaviour of the tree-ring series can be used to point out shifts in large-scale climate-driving factors such as monsoon activity that trigger the amount and the distribution of rainfall throughout the year. $\delta^{18}O$ is known to be a sensitive indicator of changes in water availability and hence rainfall patterns. To study whether or not changes in the spectral behaviour of a tree-ring series are corresponding with the isotopic ($\delta^{18}O$) composition, $\delta^{18}O$ was measured in altogether 50 ring layers of sample 27. 25 consecutive tree rings bridging 1905 to 1930 the change from a high–frequency signal period to a period with moderate variability and b) 25 layers from the more recent (moderate as well) period 1975 to 2000.

Results and Discussion

Does Juniperus excelsa from Oman form clearly distinguishable growth layers?

Wood anatomical characteristics of Juniperus excelsa

As in case of conifers from regions with non-ambiguous annual tree rings, the growth rings in juniper are mostly defined by the sharply edged contrast between the last few rows of flattened and thick-walled late-wood tracheids and the larger and thin-walled early-wood tracheids of the next growth ring. These rings could be clearly identified and measured. However, some small rings consisted of only a few cell rows of early and late-wood with a less typically contrast in cell size but clear and sharp edges to the previous or next ring. These layers could not be clearly identified as density fluctuations, false rings or real “annual” rings (Fig. 2).

Figure 2: Cross section of Juniperus excelsa *from with distinct tree rings. The dark part (late wood) and light part (early wood) constitute a single annual growth layer (left). Partly missing rings and density variations in* Juniperus excelsa *(right).*

What is the mean annual growth level and estimated age of juniper in the study area?

The growth of the juniper trees from Al Jabal al Akhdar was very slow with an average of 0.52 mm (Tab. 1). However, it varied considerably between trees. The high variability indicates that growth conditions of the juniper trees are affected by different micro-site conditions such as surface slope-dependent water supply, matching the observations by Fisher & Gardner (1995).

Table 1. *(Statistical) description of tree-ring series. No. rings = number of measured tree rings, Mean TRW = mean tree-ring width [mm], Stdv = Standard deviation, AC(1)= 1st order autocorrelation, MS = mean sensitivity.*

Tree no.	Sampling date	No. rings	Mean TRW	Stdv	AC(1)	MS(%)
101	2004	214	1.37	1.154	0.02	91
102	2004	207	0.57	0.387	0.35	64
103	2004	172	0.58	0.357	0.43	51
104	2004	364	0.52	0.334	0.10	69
105	2004	604	0.27	0.144	0.21	55
106	2004	306	0.57	0.405	0.10	72
107	2004	392	0.34	0.173	0.20	53
108	2004	213	0.27	0.163	0.40	51
109	2004	482	0.24	0.141	0.52	45
110	2004	387	0.67	0.508	0.13	82
111	2004	783	0.21	0.154	0.34	59
112	2004	267	0.38	0.229	0.20	65
Disk 1	2005	306	0.46	0.415	0.34	64
Disk 2	2005	100	1.10	1.132	0.49	56
Disk 3	2005	146	0.48	0.303	0.27	59
Disk 27	2003	622	0.39	0.301	0.23	71

The number of measured tree rings provided an indication of minimum tree (pith-) age and varied considerably between the sample trees with tree 111 being the oldest tree (783 rings) with the lowest growth level and tree 'disk 2' being the youngest tree with 100 measured rings. However, as most samples did not include the pith, an unknown number of inner rings might have been omitted. The number of measured tree rings shows that junipers in this area can get very old which makes them highly valuable for climate reconstruction. Nevertheless, it has to be noticed that radial growth – especially in old individuals - under these extremely harsh climate and edaphic conditions can be extremely slow and might even stop for several (consecutive) years.

Comparison between ^{14}C dating and tree ring measurements

The ^{14}C dating of the juniper sample showed that there was at least – according to the youngest border of the 95.4 % probability level, Oxcal Calibration - a difference between the ^{14}C date and the dendro date of 30, 25 and 20 tree rings, respectively, for the three samples covering 783, 622 and 604 years. This indicates that some more missing rings have to be expected in the measured tree-ring series.

Is cross-dating of tree-ring series between different trees possible?

Tree-ring characteristics and tree-ring patterns

Tree-ring formation in the juniper trees from Al Jabal al Akhdar was very irregular with abrupt changes between wider rings and extremely small rings (Fig. 2). Wedging, that is partly missing rings, was frequently visible on the cores which suggests that a considerable number of missing rings can be expected (Fig. 2). Double rings, that is density variations, only occured on wide tree rings (>1.5 mm). This leads to a generally high sensitivity and low autocorrelation in tree-ring series (Tab. 1).

Unfortunately the tree-ring patterns from two cores of the same tree differed considerably. This was likely due to the eccentric growth pattern of the trees whereby wood formation around the circumference was very variable and made tree-ring analysis based on two cores difficult (Fig. 2). Cross-dating between two (or three) cores of the same tree showed that sometimes up to 30 rings were missing in one tree-ring record. Missing rings mainly occur during phases of depressed growth. However, we also observed that tree rings disappeared during phases of apparently normal growth. Given the fact that double rings most often occurred in wide tree rings, it was assumed that shifts in tree-ring series are mainly due to missing rings. The tree-ring series were corrected by tracing well-matching parts in two tree-ring series and fitting tree rings in until both series matched well. This extremely time-consuming process was applied to all 12 samples and the samples of the stem disks separately. Eventually all samples were matched and combined into a site chronology.

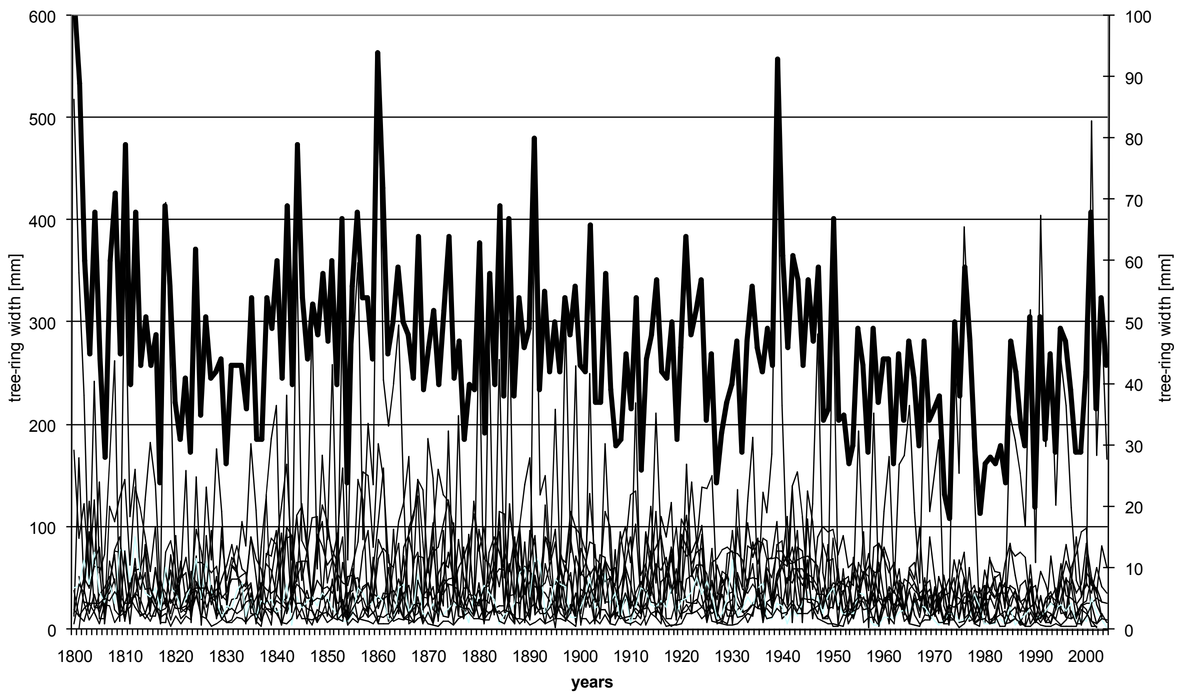

Figure 3: Cross-dated tree-ring series of 12 juniper trees from Al-Jabal-al-Akhdar together with the chronology (shifted, on top).

Calculation of a (preliminary) site chronology and description of tree-ring series

Figure 3 shows the cross-dated and corrected tree-ring series of 12 juniper trees (trees101-112) with the site chronology on top. The fact that such a site chronology could be developed demonstrates that the tree-ring series of single trees show periods of striking similarity. Figures 3 illustrates the tree-ring patterns in the period from 1800 to 2003 only. Cross-dating was possible throughout the whole period where at least two tree-ring series overlapped (1400-2004).

The single tree-ring series exhibited no clear age trend. Instead all trees showed a very sensitive growth pattern whereby phases of wider tree rings alternated with depressed tree growth. Obvious growth depressions occured in the 1860ies, around 1915 and around 1980. However, the trees were apparently able to recover from these depressions and there also was no indication of a prolonged decline in growth activity in recent decades.

Changes in spectral behaviour – δ^{18}O *isotope composition*

In single tree ring series striking changes in spectral behaviour of tree-ring widths could be detected. Phases of high sensitivity alternate with phases of dominant low frequency. In can be seen in sample 27 (Fig. 4), where a slight tendency towards more decadal variations was observed after the major depression in c. 1910. However, also in the chronology it was possible to distinguish phases that either contained more high frequency (annual) variation or more decadal variation (Fig. 3). In view of this, the δ^{18}O analyses on two 25-year periods in sample 27 yielded interesting results. The major switch in spectral behaviour of the tree-ring width, recorded around 1913, was related to a shift in the δ^{18}O-isotope composition towards significantly higher values known to reflect more humid conditions. The isotope composition of the second sample taken in the more recent period from 1975 to 2000 shows the same high values of δ^{18}O. Although these results need much more support by additional studies they indicate that frequency changes in tree-ring width are related to changes in the hydrological regime, which in turn could be related to changes in the amount or distribution of precipitation throughout the year.

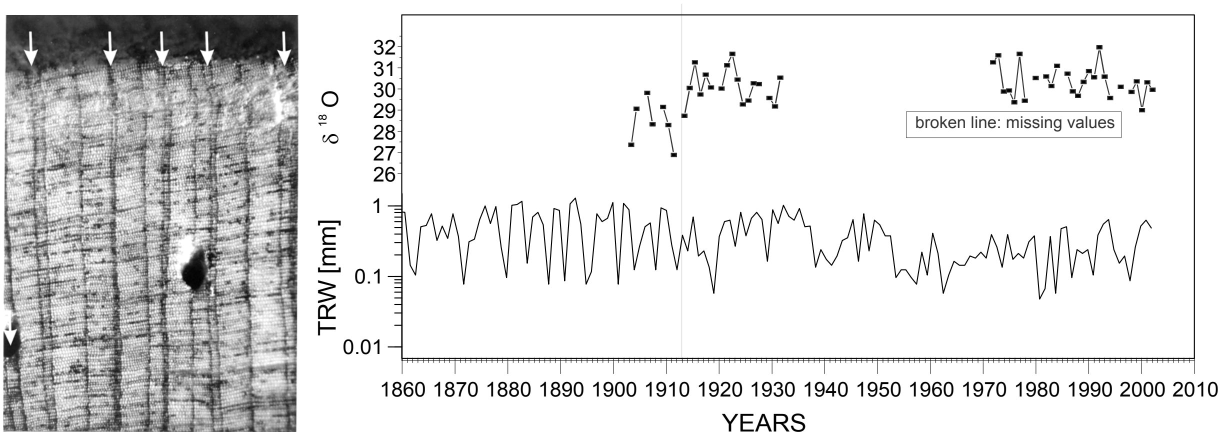

Figure 4. Typical growth pattern with small rings in 2-3 layers distance during a high frequency growth period. The interpretation of the small layers as annual rings, double rings or extreme density fluctuations is unclear (left). Tree-ring series of sample 27 with a shift between a phase with high frequency variation due to occurrence of small rings and more low- frequency variation. The δ^{18}*O composition data (above curves) of two 25-year segments indicate a strong and persistent increase in humidity from c. 1915 onwards (right).*

What is the potential to use Juniperus excelsa for climate reconstruction?

The calculated site chronology has to be regarded as preliminary. It certainly needs further support by integrating more material from – preferably - stem disks. However, as the juniper trees are strongly protected in Oman it is not likely that it will be possible to collect enough such material to considerably complement our samples. But even if stem-disk collection would not be such a major problem, it is still questionable if this material is appropriate to build up long tree-ring chronologies with the classical dendrochronological techniques that have been used in these and other studies. Juniper from Oman has proved to be very difficult material for several reasons: (1) the trees are generally slow growing; (2) show a very irregular growth pattern with alternating phases of sensitive (mainly annual variation) and very complacent (mainly decadal variation) growth; real tree-ring boundaries are often difficult to distinguish from density variations, that is double rings frequently occur; (4) (partly) missing rings are a very common phenomenon. The last point causes major trouble and the ^{14}C analyses suggested that even after thorough crossdating, that already resulted in tracing many (partly) missing rings, there still were rings that could not be detected.

Taking into account these aspects the following recommendations can be made:

Tree-ring analysis with juniper from Oman needs support by additional techniques. ^{14}C Wiggle matching (Kuzmin et al. 2004) is essential in order to check whether all missing trees can be traced via cross dating of tree-ring series. A carefully selection of samples, preferably stem disks, that undergo extensive wiggle matching could provide the exact time frame for verifying dendrochronological dating.

Once the preliminary chronology is supported by using these techniques the study material will provide a unique record to study (changes in) rainfall dynamics of up to 900 years in this region strongly susceptible for climate change. Integration with already existing networks of juniper chronologies in Pakistan (Esper 2000, Treydte et al. 2006) and Tibet (Bräuning 1999, 2001) and other (paleo)records, such as speleothems (Fleitmann et al. 2002, 2003, 2007) and varves and turbidites (Berger & Rad 2002) will contribute to a better understanding of large scale climate circulation patterns and their changes on the Arabian Peninsula throughout the last millennium. For Oman a reconstruction of rainfall will be of paramount importance to further elucidate the historic development of oasis agriculture.

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