

Long-term dynamics of *wadi* trees in a hyper-arid cultural landscape

Gidske L. Andersen



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“When the last tree is gone, it is the end of the world”

Bedja pastoralist, Sudan

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Abstract

This study focuses on the long-term dynamics of *wadi* (dry river valley) trees, in particular *Acacia tortilis* (Forssk.) Hayne, in the hyper-arid Eastern Desert of Egypt. The project was motivated by the importance of drought enduring trees for the local indigenous population, by the lack of studies on vegetation changes in hyper-arid areas, and in particular by the fact that understanding the long-term dynamics of trees is essential responding to ongoing changes effectively. Lack of data and methods offering appropriate spatial and temporal resolution has impeded research on long-term dynamics, so the use of high resolution, historical satellite data, ^{14}C content and the anatomy of wood to obtain the necessary data is emphasised.

Imagery from the first generation US reconnaissance satellite CORONA, taken already in 1965, offer a spatial (2.7 m) and temporal dimension for ecological information which other data sources cannot furnish at a comparable cost, coverage, resolution or accessibility. The vast majority of mature trees mapped in 2003 is identifiable in the imagery. A change analysis (1965-2003) reveals a negative trend in population size at most of the sites studied. Of mature trees 41 % have died. Recruitment was in general very poor at all sites, but the great capacity of saplings to resprout seems to be a major strategy to increase their persistence. A set of parameters related to water conditions, derived from the SRTM DEM, could not explain observed patterns in recruitment among sites, although it could explain some of the observed variation in mortality. Nevertheless, charcoal production seems to be the major cause of mortality.

A method was developed to assure that image-based mortality estimates derived without contemporaneous reference data can be applied with great confidence. This is of particular importance when appropriate management strategies are to be adopted.

The pre- and post-bomb ^{14}C content in *A. tortilis* wood is used to estimate age and growth. Annual growth varies in space and time (0.2 – 2.4 mm), and the ages of the trees studied seem to lie between 200 and 650 years. In combination with the low recruitment observed, this suggests that the landscape will need very long time to recover from the ongoing and rapid deforestation. If this current trend is to be arrested, urgent action is required and must take into account the traditional management practices of the pastoral nomads who for millennia have lived in and developed sustainable strategies in accordance with local climatic conditions and available resources.

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List of papers

This dissertation is based on the following four papers, which will be referred to by their roman numbers:

- I: Andersen, G.L. (2006) How to detect desert trees using CORONA images: Discovering historical ecological data. *Journal of Arid Environments*, **65**(3), 491-511.
- II: Andersen, G.L. & Krzywinski, K. (In press) Mortality, recruitment and change of desert tree populations in a hyper-arid environment. *PLoS ONE*.
- III: Andersen, G.L. Deforestation or not – how reliable are image based mortality estimates? Manuscript.
- IV: Andersen, G.L. & Krzywinski, K. Longevity and growth of *Acacia tortilis*; insights from ¹⁴C content and anatomy of wood. Submitted to *BMC Ecology*.

Introduction

We live in a world with an increasing population and an expanding demand for energy. There is a growing consensus that these processes are generating pressures which are adversely affecting our global climate, undermining common resources and disrupting regional environments. A major portion of our planet (41 % of its land area) consists of drylands and deserts that are the homes of peoples (2 billions in 2000) whose lives and cultures may be lost if they are unable to withstand these pressures. They need our support, but we cannot provide it unless we correctly understand their situation. Goodwill will not suffice. In the present context this means grasping the interplay between vegetation dynamics, in particular of *wadi* (dry river valley) trees, and cultural forces; and for the success of this undertaking research of the kind presented in this dissertation is fundamental.

Trees, due to their drought resistance (Noy-Meir, 1973), are the most dependable resource for local populations in arid environments: Indigenous people live in and of the land – with trees as a key resource (Ashkenazi, 1995; Eshete & Stahl, 1999; Gourlay, 1995b; Hall, 1992; Kenneni & van der Maarel, 1990; LeHouerou, 2000; Martin & Moss, 1997; Springuel & Mekki, 1994; Wyant & Reid, 1992). In the Eastern Desert (ED) of Egypt, their management and conservation of their resources are reflected both in the landscape, which can therefore be described as a *cultural landscape*, and in their traditional lifestyle, which has adapted to the environment over millennia (Krzywinski & Pierce, 2001). Nomadic strategies of migration and transhumance enable indigenous people to avoid overexploitation of their resource base. However, there has been a transformation process away from traditional lifestyle and management of resources (Geist & Lambin, 2004; Krzywinski & Pierce, 2001; Manger & Abd el Ati, 1996; Millenium Ecosystem Assessment, 2005). This transformation is mainly linked to social, economic and political developments within the society and the changing world outside; and one result of these developments is often degradation of the resource base and consequently of the environment, producing poverty instead of sustainable development (Geist & Lambin, 2004; Millenium Ecosystem Assessment, 2005).

The degradation of drylands, commonly known as *desertification* (Thomas & Middleton, 1994), was reported already in the nineteen thirties and has drawn attention to vegetation changes occurring in drylands. This attention peaked in the seventies when the “marching desert” (Lamprey, 1988) became a global environmental issue producing headlines such as “World deserts grow by 14 million acres” (New York Times, Aug. 28, 1977; as referred in Veron, Paruelo & Oesteheld, 2006). This has been followed up by discussions about the

causes of the process (climate or human) and about the process itself (Bassett & Zueli, 2000; Benjaminsen, 1993; Hein & de Ridder, 2006; Helldén, 1991; Herrmann & Hutchinson, 2005; Hutchinson et al., 2005; Nicholson, 2005; Olsson, Eklundh & Ardo, 2005; Rasmussen, Fog & Madsen, 2001; Thomas, 1997; Thomas & Middleton, 1994; Veron, Paruelo & Oesteheld, 2006; Warren, 2005). Rather than being one process, initially perceived as the marching desert, desertification must be seen as different land-degradation processes, e.g. deforestation and cropland expansion, with various proximate causes and underlying driving forces (Geist & Lambin, 2004; Millenium Ecosystem Assessment, 2005; Thomas & Middleton, 1994). While desertification is not presently as hot a topic as in the 70s, it is still recognized as among the greatest environmental challenges (Millenium Ecosystem Assessment, 2005); and the UN declared 2006 as the International Year of Deserts and Desertification.

The understanding of pastoral resource management played an essential role in bringing the desertification debate and the understanding of arid ecosystems forward. It led to a paradigmatic change from understanding arid ecosystems as equilibrium to non-equilibrium systems (Ellis & Swift, 1988; Warren, 1995). Underlying the equilibrium paradigm was the idea of the “stability of nature”, a philosophical idea that was well established in Greek science (Egerton, 1973) and became a fundamental theoretical concept within ecology (Peters, 1991). Arid ecosystems are now increasingly understood as event-driven/pulse-reserve systems, with water as the main resource pulse (Chesson et al., 2004; Noy-Meir, 1973; Schwinning & Sala, 2004). Within this framework the large temporal fluctuations in vegetation in the so-called Sahel zone, for a time perceived as the marching desert, can be understood as short-term rainfall induced variation, as confirmed by several broad scale satellite studies (Anyamba & Tucker, 2005; Lambin & Ehrlich, 1997; Tucker, Dregne & Newcomb, 1991; Tucker & Nicholson, 1999). These variations are mainly caused by the adaptation of ephemeral species to conclude their lifecycle within a short period after a rainfall event, and are not in contradiction with long-term ecosystem stability. The recently reported greening of the Sahara (Hutchinson et al., 2005; Olsson, Eklundh & Ardo, 2005; Pearce, 2002) must be understood within this framework. Moreover, the importance of the spatial and temporal scale of studies and of discriminating between degradation processes and between types of vegetation becomes evident within this framework.

While ephemeral species depend on pulse size (depth + duration) for initiating their lifecycle (Schwinning & Sala, 2004), long-lived species and in particular trees typically depend on several larger pulses of rainfall for successful seedling establishment (Chesson et al., 2004;

Krzywinski & Pierce, 2001; Wiegand, Jeltsch & Ward, 2004; Wilson & Witkowski, 1998). Such occasions are rare in dry environments, and increasingly so towards the desert extreme. Longevity is therefore an increasingly important strategy to secure the reproductive potential of a population over generations, i.e. the storage effect (Chesson et al., 2004; Warner & Chesson, 1985). Increased mortality of trees therefore introduces an additional factor into the equation of stability and change in arid environments, which implies long-term or permanent changes in the arid environment, i.e. deforestation. The outcome depends upon how resilient the system is confronted with factors introducing disturbance and stress in the system.

Although it has been recognized that perennial desert vegetation is very stable but “has no resilience” (Le Houérou, 1985), we possess inadequate knowledge not only about desert ecology, but in particular about the population dynamics of trees adapted to semi-arid and arid conditions (BenDavid-Novak & Schick, 1997; Chesson et al., 2004; Eshete & Stahl, 1999; Kadmon & HarariKremer, 1999; Kenneni & van der Maarel, 1990; Lahav-Ginott, Kadmon & Gersani, 2001; Martin & Moss, 1997; Noy-Meir, 1979/80, 1985; Ward & Rohner, 1997; Wiegand, Jeltsch & Ward, 1999, 2000, 2004; Wiegand et al., 2000b; Wiegand & Jeltsch, 2000; Wiegand & Milton, 1996; Wiegand, Milton & Wissel, 1995). Reliable predictions about deforestation and the development of sustainable conservation strategies are therefore made difficult until insight into the long-term dynamics of trees, i.e. into the processes of recruitment, growth and mortality, is improved. By studying recruitment, growth and mortality under extreme conditions, as found in the hyper-arid ED, results will also be applicable to a wide range of arid conditions. Moreover, selecting this study area contributes to reducing the lack of data on vegetation change in the long-neglected hyper-arid areas (Millenium Ecosystem Assessment, 2005).

It has been recognized that the complex dynamics of arid and semi-arid ecosystems and especially the mismatch between observation times (years) and time scales of vegetation change (centuries) makes it difficult to fully understand the long-term dynamics (Wiegand & Jeltsch, 2000). Also the spatial scale of available data limits insight into the long-term dynamics of scattered trees. Baseline data, with reference to which changes can be assessed and from which dynamics can be derived, must comply both with spatial and temporal requirements. For the success of this study, I have therefore applied high resolution imagery from the first generation US reconnaissance satellite CORONA. This is the first time this imagery has been applied to individually based tree mapping in hyper-arid conditions. Therefore, methodological aspects which focus on the potential of this imagery for tree

mapping and on securing reliable results have been particularly important. To achieve a longer temporal perspective on growth and longevity, pre- and post-bomb ^{14}C content of wood samples was used.

Objective

The overall objective of this study is to further our knowledge about the long-term dynamics of wadi trees, in particular on the processes of recruitment, growth and mortality. Focus here is on the hyper-arid ED, where trees are key resources for local nomads. Insights of the kind sought here are needed for proper conservation, management and monitoring of arid environments and therefore for the sustainable development of arid lands. For obtaining the required spatial and temporal resolution new data sources and methods have been examined and assessed, including the use of early, high resolution satellite imagery, pre- and post-bomb ^{14}C content and anatomy of wood. The study has been performed largely in the methodological framework of a Geographical Information System (GIS).

The **specific objectives** studied in the individual publications are:

- I. to investigate the potential and limitations of CORONA imagery for the study of arid arboreal vegetation ecology and dynamics. The potential is assessed on both a landscape and on a population scale.
- II. to quantify population change, mortality and recruitment of *Acacia tortilis* and *Balanites aegyptiaca* based on CORONA imagery (1965) and field maps (2003), and to assess the status of recruited individuals. Patterns in recruitment and mortality are related to water conditions and human intervention.
- III. to assess the reliability of image (CORONA) based mortality estimates when historical ground truth data are lacking.
- IV. to use pre- and post-bomb ^{14}C content in wood samples and the presence of narrow marginal parenchymatic bands in the wood to gain further insight into the age, growth and growth conditions of *A. tortilis*.

In the following the study area will be presented and thereafter two sections describe the main methods and data sources used to approach the long-term dynamics of the trees studied. Results from paper I and III are presented mainly in the first of these two sections. Results on the long-terms dynamics are presented thereafter, and before the conclusion and future perspectives these findings are put into a regional management context in a separate section.

Study area – the Eastern Desert of Egypt

The ED is the huge area between the green Nile-valley and the Red Sea coast. It has been selected as a study area due to its extreme aridity (Meigs, 1953) and wide variation in the topo-hydrology of its *wadi* system, where arboreal vegetation grows (cf. below). This variable topo-hydrology makes it possible to study how the dynamic processes of regeneration, growth and mortality are influenced along moisture gradients; and the application of historical data provides the required temporal aspect. The generally hyper-arid conditions allow these processes to be studied at their extreme limits.

The ED ranks among the most arid deserts in the world (the coefficient of variation in rainfall reaches 200 %, and the mean annual precipitation is < 30 mm; Andersen, 1999; Ayyad & Ghabbour, 1985). The Red Sea mountain range is a dominant feature that runs parallel to the Red Sea coast and constitutes the main watershed in the ED (Al-Izz, 1971; Ball, 1912). The study area is located in the mountainous south-eastern part of the ED (Fig. 1) where some of the mountain peaks are nearly 2,000 m asl. It is this combination of strong altitudinal gradients over short distances and the general proximity to the sea which occasionally brings moist air to the area and results in wide variation in the topo-hydrology of the characteristic and widespread wadi -system.

Because gauge measurements are lacking and meteorological stations are few and scattered, studies on the spatial and temporal distribution of water resources are rare (Abdel Moneim, 2005; Foody, Ghoneim & Arnell, 2004; Gheith & Sultan, 2002). Infrequent, short and intense rainstorms (e.g. less than 4 h, intensity of 30 mm/h) generate flash floods in the wadis, where soils have good infiltration capacity (Foody, Ghoneim & Arnell, 2004; Gheith & Sultan, 2002). A flood might last up to three days, be a main factor of erosion sometimes with destructive effects (e.g. on roads) and can be dangerous for both humans and animals (Anonymous, 1997; Foody, Ghoneim & Arnell, 2004; Hassib, 1951).

Wadis intersect large areas of rock outcrops where run-off is high. Water reaching a site is therefore often related to its upstream catchment size, and it is recognized that topo-hydrology is more important for the actual amount of water available than on the spot rainfall (Krzywinski, 1990; and as referred to in Furley & Newey, 1983). Torrents are rare, however, and other sources of water input such as smaller scattered showers, orographic rain, mist and fog are more important in some places. Moreover, the occurrence of dew and water vapour adsorption may contribute significantly (Agam & Berliner, 2006; Evenari, 1985). On several occasions during fieldwork we experienced nocturnal dew which dampened our blankets.

Such conditions are apparently not exceptional as Täckholm (1969) speculated after she had a similar experience in the ED.

Other factors essential for water conditions at a site are evaporation, transpiration, soil drainage and texture (Noy-Meir, 1973), and underground water seepage. When soil-texture and depth permit, a deeply seated, permanently wet soil layer will form (Batanouny & Abdel Wahab, 1973; Kassas, 1952, 1953; Kassas & Imam, 1954; Zahran & Willis, 1992). These optimal water conditions occur in the desert wadis and explain the “rich” vegetation that grows there (Kassas & Imam, 1954; Zahran & Willis, 1992). Together with its friendly topography it is easy to understand the importance of this landform for the nomadic people (Hobbs, 1989).

A. tortilis (Forssk.) Hayne and *B. aegyptiaca* (L.) Del. predominate in the wadis (Fig. 2). According to Boulos (1999) two subspecies of *A. tortilis* occur in the ED; i.e. ssp. *tortilis* and ssp. *raddiana* (Savi) Brenan. The majority of *A. tortilis* individuals recorded in this dissertation are ssp. *raddiana* (also considered as a separate species: *A. raddiana* Savi; Täckholm, 1974); but because gradual morphological transitions are found and desert dwellers shape the very morphology of trees and bushes by their management strategies (Krzywinski & Pierce, 2001), I refer to *A. tortilis* at the species level. Kenneni & van der Maarel (1990) too recognized that gradual morphological transitions make collection of data at the sub-specific level difficult. Growth form and the number of main trunks is a key feature used to distinguish between subspecies (Boulos, 1999; El Amin, 1990). The high frequency of sprouting in saplings (paper II) and its possible long-term effect on growth form also make such characters less reliable for discriminating between species (see also Archibald & Bond, 2003; Midgley & Bond, 2001).

The ED is interesting also apart from being a hyper-arid desert. It belongs to a region of great historical importance, both because of its strategic position and because of its rich resources in minerals and stones, e.g. gold, silver, emeralds, porphyry and *breccia verde antica* (Krzywinski & Pierce, 2001; Murray, 1951). Already in the Old Kingdom (3000 BC) caravans traversed the desert, and later immensely important Ptolemaic and Roman trade routes crossed the area (Krzywinski & Pierce, 2001). Remains of this historic activity are abundant in the area, e.g. mines and road stations. Also the ancestors of the Ababda who inhabit the area today, the Blemmyes, have left marks of their presence there, e.g. ancient cities, tombs and rockart reflecting their observations and perceptions of their landscape (Eide et al., 1994; Krzywinski & Pierce, 2001). There has been a depopulation of the ED since the end of the

nineteenth century, and in 1987 approximately 15,500 Ababda were living in the southern ED (as referred to in Briggs, Badri & Mekki, 1999).

Traditionally the Ababda have been nomads, who with their animals live in and rely upon the wadis and their resources, particularly trees. Their pastoral nomadic lifestyle and management

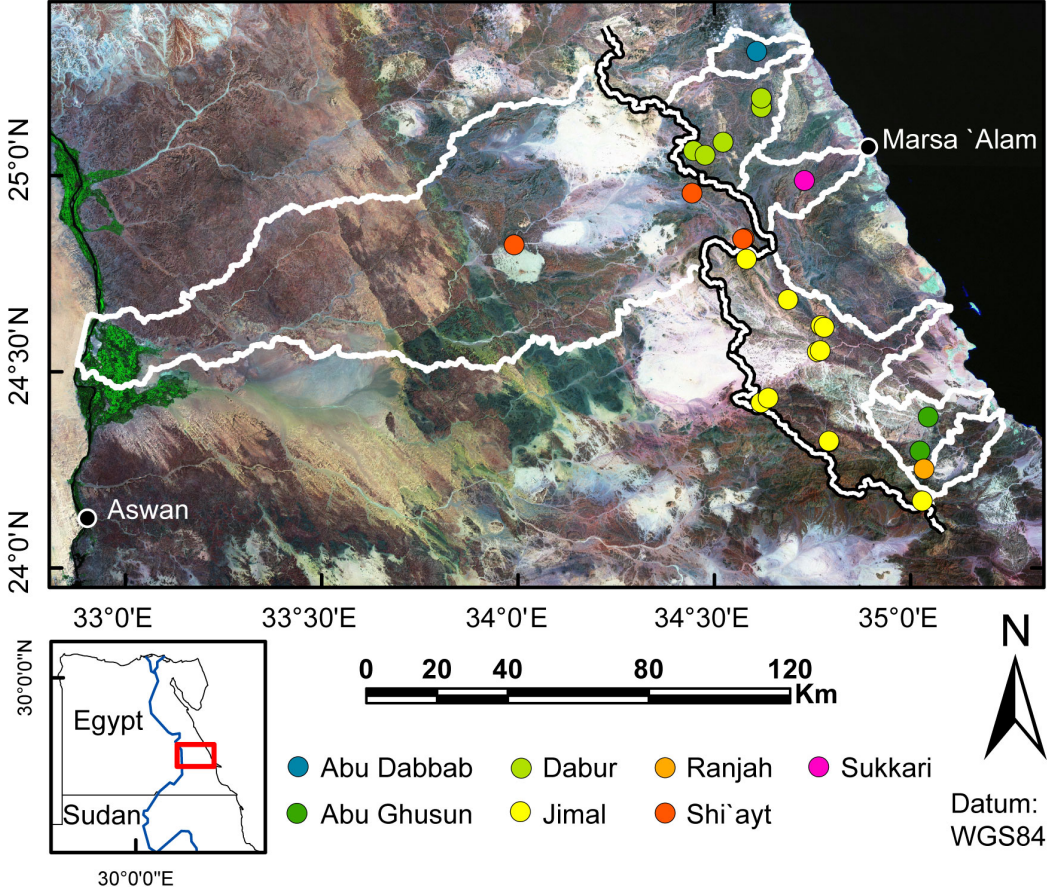


Figure 1: Study area. Sites studied in the field; the colors indicate which basin they are located in. Basins are outlined in white, and the main east-west water-divide is outlined in black and white.



Figure 2: Wadis (dry river valleys) are intersecting the mountainous landscape and trees can be abundant; here acacias predominate. Floyer (1893) described W. Durunkat as a “well-treed valley”.

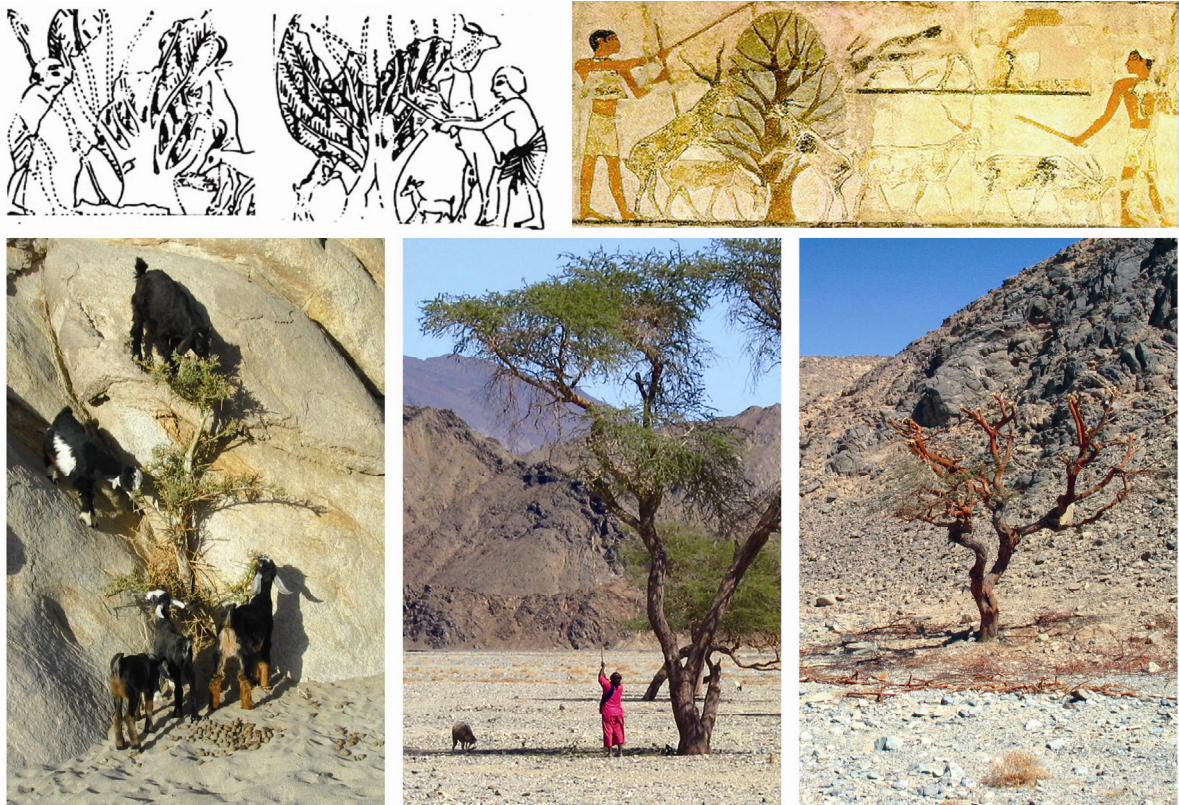


Figure 3: Traditional nomadic management strategies (direct browse, shaking branches and pollarding the trees), as depicted already in the Egyptian New Kingdom (upper panel). Modern inhabitants still use the trees the same way (lower panel).

strategies are essential for environmental conservation; and the persistent influence of such strategies has shaped this hyper-arid landscape throughout millennia (Hobbs, 1989; Krzywinski & Pierce, 2001; see Fig. 3). The continuity of these management practises indicates their sustainability, but the Ababda have also long been known as professional charcoal producers and the destructive effects of this activity on the environment and tree populations have been commented upon (Floyer, 1893; Krzywinski & Pierce, 2001; Täckholm, 1969; see Fig. 4). This is elaborated upon in paper I.

While earlier the ED attracted little interest from national authorities apart from its role as an area for mining and geological exploration, it is now valued for both its natural beauty and biodiversity and its potential for tourism. Tourism is a very important source of income for Egypt, estimated to be 1.9 % of the GNP but probably accounting for up to 10 % if secondary effects are taken into account. Along the Red Sea coast tourism already impact the ED, in particular in its northern parts, e.g. the Hurghada resorts; and further south the development of tourism is expanding at an alarming rate. Along the coast in the study area there has been a recent increase in tourist resorts, including an airport, pressure chambers for divers and high class hotels. The Red Sea with diving opportunities has, until recently, been the main



Figure 4: Charcoal production in W. Sartut

attraction; but tourism also increasingly is focusing on the inland desert environment. To a large degree this uncontrolled tourism has introduced a threat to the natural environment. The effect is caused both directly by tourist activities and indirectly by changing the cultural framework and the basis for the life of the desert dwellers and consequently their indigenous land-use and use of natural resources, *e.g.* trees. The Egyptian Red Sea Coastal and Marine Resource Management Project (1998) concluded that there was an urgent need to establish conservation zones to protect several habitats in the study area, among them certain wadis. The Wadi El Gemal – Hamata Protected Area was established in 2003, and 11 of the sites studied lie within this area.

Fieldwork

The fieldwork was performed in the period from February 5th to 24th and March 2nd to 24th, 2003. A total of 25 sites were mapped carefully. The spelling of these site names conforms to Egyptian General Survey Authority (EGSA) 1:50.000 maps from 1989. Individual trees were positioned, measured and described, including observations of traditional management and traces of charcoal production at the sites. Due to the limited coverage of the CORONA images



Figure 5: Sampling tree cores. To avoid destructive sampling of stem cross sections, sampling for both ^{14}C measurement and wood anatomy was based on increment coring. Due to logistic constraints a battery operated, solar-chargeable field setup was developed, including special steel corers designed to withstand the high torque.

subsequently purchased, a subset of these sites had to be selected for papers I to III.

In addition, 69 increment cores were drilled at 22 different sites (Fig. 5). A selection of these cores, based on tree location and core quality and length, were investigated in the study of longevity, growth-rate and variation in growth conditions in this hyper-arid environment (paper IV).

The logistic infrastructure of the study area is poorly developed, to the point of being almost completely lacking. While most foreign expeditions depend on logistics at high costs, our approach was to conduct the fieldwork with a minimum of expenditure and a maximal reliance on local resources. This approach brought us as fieldworkers in closer contact with the physical environment and the indigenous inhabitants. Spending days and nights out in the open also allowed us to observe the landscape continuously.

GIS and Remote Sensing in arid land ecology and vegetation science; methods and data to approach long-term dynamics

Spatial analysis has become the most rapidly growing field in ecology (Fortin & Dale, 2005). Landscapes, ecosystems and habitats are changing rapidly and thus the importance of time, space and scale has become clearer (Wiens, 1989), but our ability to actually incorporate and study spatial and temporal processes is largely connected to the recent development in computer and satellite technology. In particular Geographical Information Systems (GIS), Remote Sensing (RS) imagery and Global Positioning Systems (GPS) are presently important tools that have facilitated studies of spatial and temporal processes within ecology and vegetation science (Bassett & Zueli, 2000; Goodchild, 1994; Haines-Young, Green & Cousins, 1993; Johnston, 1998; Kerr & Ostrovsky, 2003; Linderholm, 2006; Pettorelli et al., 2005; Ringrose, Vanderpost & Matheson, 1996; Tucker, Dregne & Newcomb, 1991; Turner, Hiernaux & Schlecht, 2005; Wadsworth & Treweek, 1999). GIS has its strength in its ability to integrate geographical data from different sources such as RS images or GPS based field observations and in having available a set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world (Burrough & McDonnell, 1998).

The collection of well positioned spatial data for facilitating image interpretation and analysis was challenging and time-consuming in the first era of RS applications. In recent years, however, the collection of spatial data has been revolutionised by the US military satellite navigation system, officially named NAVSTAR GPS. Satellite navigation systems had their start already in the 1960s (US Transit); but it was not until the GPS was operational (1993;

fully operational 1995) and low cost, low power receivers became available that satellite based navigation became fast and easy to use for civilian users. A great advance came about in 2000 when the Selective Availability that intentionally reduced the positional accuracy of publicly available navigation signals was turned off (Clinton, 2000). This reduced the horizontal error from within about 100 m to within 22 m 95 % of the time (as referred in Campbell, 2002). However, this is probably a conservative measure (Campbell, 2002; D'Eon et al., 2002; Hengl et al., 2001; Liu, 2002). For civilian users even greater accuracy is possible if one applies principles of Differential GPS (down to centimetre accuracies possible), but the equipment needed is more expensive and often less user-friendly (Adrados et al., 2002). Another advance today is the combined use of the US GPS and the Russian GLONASS together with additional satellites and ground stations, e.g. the European EGNOS where the horizontal error is reduced to 5 m. For the collection of spatial data in the field I relied on signals from the GPS.

Since the evolution of civilian satellite based remote sensing in the 1970s, RS imagery has played an essential role in the worldwide focus on ecological and vegetation changes in arid lands. The NOAA AVHRR, primarily a weather satellite, with low spatial but high temporal resolution was used to monitor changes in African drylands (Sahel) on continental scale (Anyamba & Tucker, 2005; Lambin & Ehrlich, 1997; Tucker, Dregne & Newcomb, 1991). The first civilian earth observation satellite, Landsat MSS, had at that time a comparatively high spatial resolution, but a low temporal resolution, and was designed to monitor changes on landscape scale (Andersen, 1999; Matheson & Ringrose, 1994; Pickup, Chewings & Nelson, 1993). In recent years MODIS has started to follow up the NOAA AVHRR monitoring of changes across African drylands (Fensholt, 2004; Friedl et al., 2002; Zhang et al., 2005). These low spatial and high temporal resolution time series data, however, mainly reflect the greening and disappearance of ephemeral herbs' within short-term rainfall fluctuations (Anyamba & Tucker, 2005; Lambin & Ehrlich, 1997; Tucker, Dregne & Newcomb, 1991). Changes in desert tree populations are impossible to detect in such low spatial resolution data. In many cases even medium resolution LANDSAT MSS and TM imagery are too coarse to detect scattered trees in hyper-arid areas or to separate trees from ephemeral plant cover (Andersen, 1999; Saltz et al., 1999; Wiegand et al., 2000a; Williamson, 1994). It is only in high resolution aerial photos or satellite images that individual trees can be detected, and the potential of such imagery for studies of long-term vegetation changes in arid and semi-arid areas is acknowledged by many authors (Cole, 1989; Kadmon & HarariKremer, 1999; Lahav-Ginott, Kadmon & Gersani, 2001; Laliberte et al., 2004; Moustakas, 2006;

Tappan et al., 2000). Moreover, high resolution data in locally focused studies together with detailed, well-positioned ground truth data is needed to reveal the high spatial variability and the complex processes normally taking place (Bassett & Zueli, 2000; Geist & Lambin, 2004; Rasmussen, Fog & Madsen, 2001). A main challenge for insight into the long-term dynamics of long-lived species is, however, to acquire historical imagery that is old enough and has high enough spatial resolution. CORONA imagery fulfils these requirements.

CORONA imagery – retrieving reliable historical – ecological information

CORONA imagery is a Cold War product. CORONA was a first generation US photo-reconnaissance satellite system that operated between 1960 and 1972 and provided high-resolution imagery (Ruffner, 1995). In 1995 Clinton (1995) declassified the CORONA data, which can now be purchased at a low price from Earth Explorer (<http://edcsns17.cr.usgs.gov/EarthExplorer/>).

Large parts of the globe were monitored by CORONA, but its special focus was on communist controlled areas (McDonald, 1995). During its active period around 100 different missions were launched, some having different camera systems aboard (McDonald, 1995). In this study data from the KEYHOLE (KH) 4A camera system have been used. It acquired panchromatic, panorama data in stereo (see paper I for technical details), with a best resolution of about 2.7 m. The later KH-4B had a best resolution of 1.8 m. Imagery acquired was physically stored in film capsules that were deorbited from space and recovered in mid-air by a specially equipped aircraft (Ruffner, 1995).

CORONA KH-4A imagery from 1965 has been a main source of data because its high spatial resolution permits individual trees to be detected at the beginning of a period (1965-2003) which is long enough to give essential information on the long-term dynamics of these trees. To get excess to data of comparable date and spatial resolution, i.e. aerial photos, from Egyptian sources would have been time-consuming, difficult if not impossible and probably very expensive. Although the potential of this imagery for long-term environmental studies has been foreseen and to an increasing degree tested, there had been no application of the data for individually based vegetation mapping (Altmaier & Kany, 2002; Fowler, 2004a, b; Goslee et al., 2003; Kostka, 2002; Lorenz, 2004; McDonald, 1995; Philip et al., 2002; Rigina, 2003; Sohn, Kim & Yom, 2004; Tappan et al., 2000).

I have applied KH-4A imagery in papers I-III (Fig. 6). Paper I investigates the potential of this imagery, in particular for detailed vegetation mapping, and uses a spatial overlay of interpreted image structures with reference data from 2003 for assessing this potential. It also

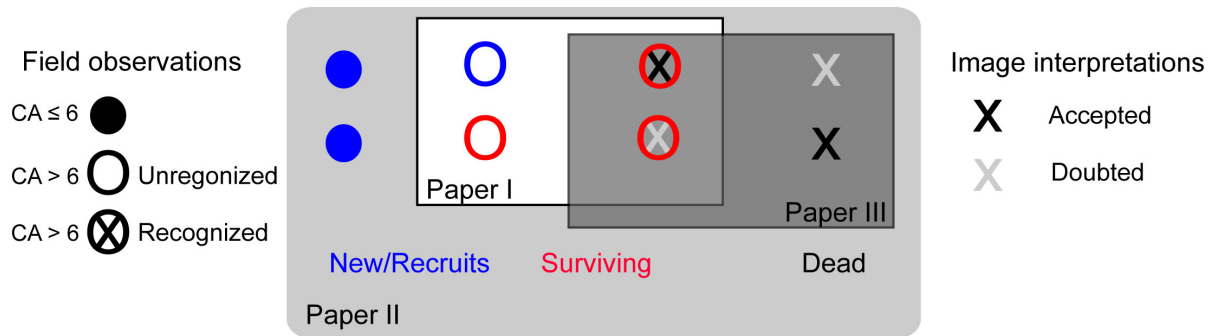


Figure 6: The relation between field observations (2003) and image interpretations (1965) and the three papers where CORONA images are applied. Paper I focuses on the larger trees mapped in the field (Canopy Area > 6 m²) and the ability to detect these in imagery. Trees are either recognized or unrecognized in the imagery, based upon a spatial criterion. In paper II the whole set of field observations and image interpretations are combined in order to derive estimates of recruitment and mortality of tree populations at 19 different sites. Paper III investigates the reliability of the mortality estimate derived by assessing the consistency of the image interpretation. For this, interpreted points are classified as either accepted or doubted.

discusses general aspects of image preprocessing. Paper II derives and quantifies tree recruitment and mortality from the image interpretations and field data from 2003, based on the resulting categorization of trees as *new*, *surviving* and *dead*. In paper III, I investigate how to assess the mortality estimates derived when reference data from 1965 is lacking. An important aspect of both papers I and III is therefore the quality/accuracy of the image interpretation and the information derived. This is elaborated upon below.

Derivation of information from RS data implies generalization and simplification of the data content. In this case, image structures resembling those generated by trees were represented by points in a visual interpretation. A typical generalization in other RS based studies lies in the generation of thematic maps based on various image classification algorithms (Foody, 2002; Tso & Mather, 2001). Although it is not always done in practise, it is widely accepted that generalized RS map products should be accompanied by data stating their quality, and for this standard methods exist (Congalton, 1988; Congalton, 1991; Foody, 2002; Stehman & Czaplewski, 1998). Such methods cannot, however, be directly applied to the historical maps derived here. Nevertheless, the accuracy of tree maps and estimates derived from CORONA should be assessed, in particular because this type of application of CORONA data has not previously been fully explored. It is also of importance for potential users that the data are reliable. Ground truth data from 1965 would be needed to assess fully the accuracy of the image interpretation made from CORONA, but such reference data are lacking. This lack of contemporaneous reference data is a general problem when using historical imagery (Okeke & Karnieli, 2006).

In paper I, data from 2003 is used as reference data, based on the assumption that at least the larger trees ($CA > 6 \text{ m}^2$) recorded in 2003 must have been present in 1965, and at a detectable size. This assumption was confirmed during fieldwork. A spatial overlay of interpreted CORONA maps (1965) and reference data (2003) was therefore used to evaluate our ability to detect trees from imagery. A spatial threshold (20 m) was applied to bypass the common problem of misregistration occurring when data from different sources are combined in a spatial overlay (Foody, 2002). Of larger trees mapped in 2003 (canopy area $> 6 \text{ m}^2$) 70 % were detected in the imagery. A specially designed spatial classification shows that between 9 and 55 % of the population at sites studied was concealed by landscape elements that reduce image contrast.

The proportion of the interpreted points (1965) that does not correspond to any individual present in 2003 is either a tree which has disappeared (dead) or a misinterpretation, i.e. an error of commission. If it is a misinterpretation, it will falsely increase the mortality estimate derived. Paper III presents, therefore, a method to test the reliability of the mortality estimate by assessing the consistency of the image interpretation. This relies upon the categorization of interpreted points into two Interpretation Classes (IC; independently of field observations); either accepted or doubted points. The frequency and characteristics of *surviving* and *dead* points within each IC are used to generate hypotheses testing the consistency of the image interpretation. The results show that the image interpretation is consistent for the majority of sites studied. Detected inconsistencies in image interpretation suggest at which sites mortality estimates should be interpreted with care. The suggested method successfully addresses challenges involved in visual photo interpretation of historical imagery, e.g. lack of reference data and varying degrees of certainty in interpretation, and supplies essential information about the reliability of the results, assuring that appropriate management measures can be taken.

Digital Elevation Model; data for topo-hydrological information

Landscape topography is a primary factor influencing water redistribution (Noy-Meir, 1973) and therefore the water available to trees in arid environments (Kassas, 1960). The actual amount of water available in an area can only be assessed directly by impractical, even impossible, digging or deep coring or expensive georadar profiles. Water availability should rather be approached by an indirect, relative method. Research over the past decades has demonstrated the feasibility of extracting hydrological information directly from DEMs (mathematical representations of landscape topography; Yin & Wang, 1999). Automated

procedures for deriving key variables such as catchment size, drainage density, wetness indices, slope, aspect, profile and plan curvature have been developed (Burrough & McDonnell, 1998; Eash, 1994; Garbrecht & Martz, 1993; Martz & Garbrecht, 1993; Tachikawa, Shiiba & Takasao, 1994; Tribe, 1992). Such procedures are integrated in several GIS-software packages, *e.g.* ArcGIS and GRASS.

Different optical RS sensors, *e.g.* ASTER, SPOT and CORONA, acquire stereo imagery allowing topographical information to be derived based on photogrammetrical methods (AlRousan et al., 1997; Altmaier & Kany, 2002; Fujisada et al., 2005; Giles & Franklin, 1996; Hirano, Welch & Lang, 2003; Lillesand & Kiefer, 2000; San & Suzen, 2005; Toutin, 1998; Welch et al., 1998). In the current project ASTER images were acquired and DEM processing started in ERDAS Imagine OrthoBASE ® based on ground control points from printed topographic maps (EGSA, 1:50.000, 1989). These points were not, however, of sufficient quality to produce a satisfactory model.

While working with the ASTER data the first, but unedited Shuttle Radar Topography Mission (SRTM) DEMs became available. During about 220 hours in February 2000 the SRTM instrument, on board the Space Shuttle Endeavour, collected topographical data from about 80 % of the earth's total landmass, based on Synthetic Aperture Radar interferometry, IFSAR (Gesch, Muller & Farr, 2006; Rabus et al., 2003; van Zyl, 2001). Different data products are freely available as a result of this mission (Gesch, Muller & Farr, 2006). In this dissertation I have applied the 3-arc second data, *i.e.* with approximately 90 m resolution, based on the C-band radar observations. Rodriguez, Morris & Belz (2006) showed that the SRTM met its horizontal (20 m) and vertical accuracy requirements (absolute of 16 m, relative of 10 m; linear error at 90 % confidence), and found even better than required accuracies for African data (11.9, 5.6, 9.8 m, respectively). Parameters used as indicators of regional and local water conditions such as catchment size, distance from stream, slope, aspect and elevation (paper II) were extracted or derived from this dataset.

The unedited SRTM data first released had gaps, or voids, of various sizes caused, for instance, by topographic shadowing. These voids must be filled before hydrological parameters such as catchment size and streams can be derived, and different methods exist to do this (Grohman, Kroenung & Strebeck, 2006). I used an algorithm based on Laplacian and LSQR iterations (Blackart 3.99: <http://www.terrainmap.com/>; Paige & Saunders, 1982). The number of iterations selected was based on when convergence occurred. Since computing time was not a serious problem, the final number of iterations was 3000 (Laplacian) and 300

(LSQR). A visual inspection of the result showed that the borders of basins derived were in good agreement with mountain ridges and other easily recognized water divides. To fill in sinks and derive hydrological parameters the algorithms in ArcGIS workstation were applied.

¹⁴C content and the anatomy of *A. tortilis* wood: methods to approach age and growth

A primary motivation for this study was to establish the age of desert trees. In temperate regions this would be no problem because age can be determined from annual rings that are easily detectable. However, the use of the anatomical features of wood for age determination in non-temperate regions is not straightforward, and little is therefore known about the age of trees in arid lands. There has been a general idea that trees in arid lands outlive the lifetime of researchers (Cody, 2000; February, Mader & Bond, 2006; Higgins, Bond & Trollope, 2000; Hobbs, 1989; Kenneni & van der Maarel, 1990; Wyant & Reid, 1992), but it has also been suggested that trees there are short lived (Gourlay, 1995b; Springuel & Mekki, 1994; Ward & Rohner, 1997). Because the long-term data needed to resolve this issue are so rare in many areas, the life-expectancies of many trees have remained unknown for many species. Indirect methods such as those based on mortality rates or size-age relationships from periodic size increment measurements are designed to avoid the problem of long-term data access, but such estimates may be very inaccurate (Martinez-Ramos & Alvarez-Buylla, 1998). Repeated photography, and historical aerial or space imagery in combination with recent data on tree distribution, can be used to address the issue of longevity, but this has to be done at an individual level and requires accurate spatial information. Moreover, the results will be restricted by the date of the oldest dataset.

The main challenge in applying wood as source of information on longevity and growth of non-temperate trees is the lack of seasonality. In general, growth is continuous and no annual growth rings are formed. However, growth can be periodic, for instance in response to the shift between rainy and dry periods, and growth rings have been described in several tropical species (Fichtler, Clark & Worbes, 2003; Worbes & Junk, 1989). The presence of such anatomical features related to discontinuity in growth can be either regular or irregular and therefore not necessarily useful for age-determination. For acacias anatomical features delimiting growth periods have been recognized, but their regularity and consequently their potential for dendrochronology depend on the location and growth conditions of individuals studied (Eshete & Stahl, 1999; Gourlay, 1995b; Martin & Moss, 1997; Wyant & Reid, 1992).

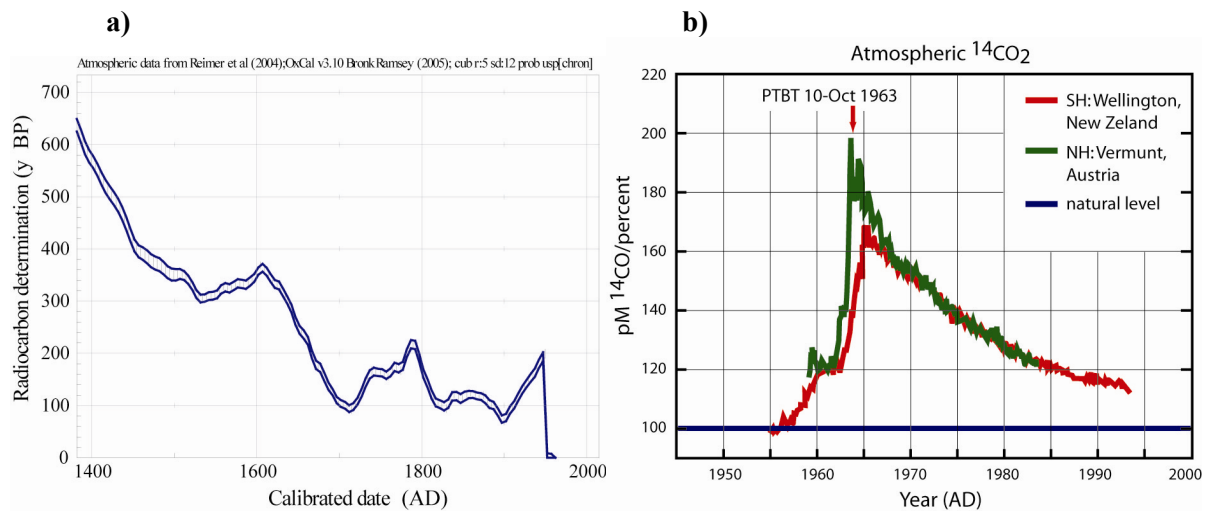


Figure 7: Calibration curves. a) Conventional radiocarbon ages (y BP) are calibrated to get calendar dates (AD). The “wiggles” from 1650 to 1950 make it impossible to get a precise calibrated date based on only a single sample formed within this period. b) The high post bomb atmospheric ¹⁴C can give very precise ages for samples formed in the period from 1955 into the 1990s; based on measurement of atmospheric ¹⁴C in the relevant hemisphere (graphics from Wikimedia commons; based on data from Levin et al. (1994) and Manning (1994)).

In paper IV, the focus was on if and how properties of *A. tortilis* wood could reveal its age, and the rate and conditions of its growth. For this a combination of methods, including radiocarbon dating, growth equations and wood anatomical features have been applied. A short introduction to these methods and approaches is given below, while paper IV should be consulted for information about their exact application.

The radioactive isotope ¹⁴C in living tissues mirrors the ¹⁴C in the atmosphere, and is a marker of time in wood. When the tissue dies, its contact with the atmosphere is severed; as time passes, ¹⁴C in a sample will decay at a known rate (half-life). The age of the sample can therefore be estimated by measuring remnant ¹⁴C and establishing its proportion of the total carbon content in the sample. The principle for radiocarbon dating is straightforward as long as the atmospheric level of ¹⁴C is stable. However, the atmospheric level of ¹⁴C has varied over time and consequently so has the ¹⁴C content in living organic material. The variation is partly because the natural formation of radioactive carbon in the atmosphere by cosmic rays varies, and in recent centuries (1650-1950) also because the release of inactive carbon (e.g. in CO₂) from fossil fuels has diluted atmospheric levels (Tans, Dejong & Mook, 1979). Due to such variations there is no one to one relation between conventional radiocarbon age and calendar dates, and calibration curves are therefore needed (Fig. 7a). These curves are established from the level of ¹⁴C in wood of known age, as estimated from direct counts of

annual rings or from a fit with dendro-chronological standard curves (Blackwell, Buck & Reimer, 2006).

While the combustion of fossil fuels was a major cause of the reduced level of ^{14}C in the atmosphere before 1950, this so-called Suess-effect was cancelled out from 1955 onwards by the Cold War nuclear bomb testing that caused a great increase in the atmospheric level of ^{14}C (Hua et al., 1999; Levin & Hesshaimer, 2000; Levin et al., 1985; Nydal & Lovseth, 1983). These high atmospheric levels of ^{14}C are referred to as *post-bomb/bomb* ^{14}C . It was not until the test ban treaty was signed in 1963 that a decrease in the atmospheric levels began. The elevated ^{14}C levels give precise dates for samples formed from 1955 until the 1990s (Levin & Hesshaimer, 2000; see Fig. 7b).

Because a pilot study including 6 conventional radiometric dates and 3 AMS-dates suggested that trees may have dated to the so-called “wiggly” period between 1650 and 1950, it was necessary to date several samples and to use post-bomb dates for reliable estimates of recent growth rates. The possible combinations of dates were the basis for different age scenarios which were assessed by fitting them to a sigmoid growth equation (Zeide, 1993). A non-linear diameter-age relationship was clearly exemplified by one of the dated samples where the recent growth rate based on post-bomb ^{14}C would indicate an age of more than 1000 years, while the calibrated AMS-dates excluded this possibility. The Gompertz equation was selected because it is described by only 3 parameters (limited number of observations was available) and because it models tree growth well (Zeide, 1993). As concluded in paper IV the current approach would increase its reliability if number of observations (i.e. dates) was

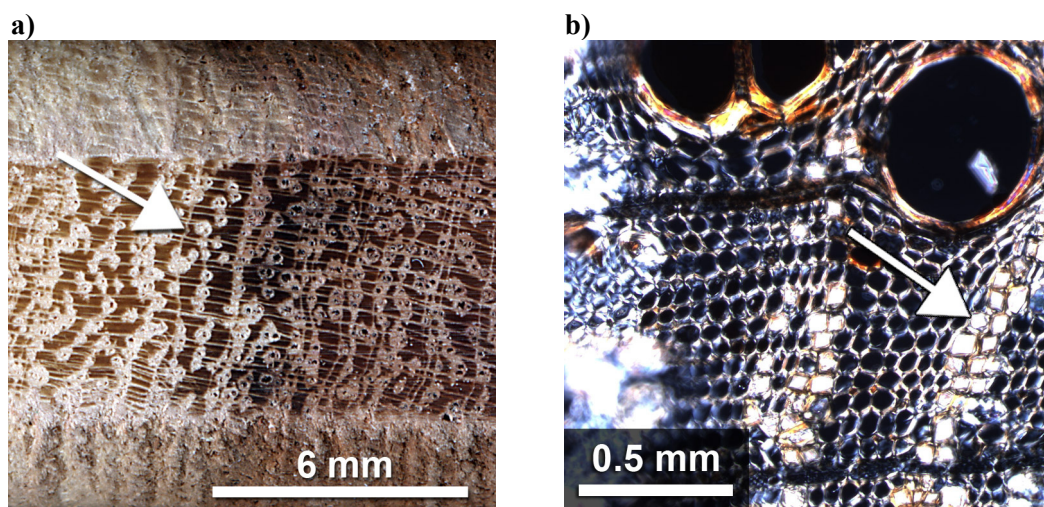


Figure 8: Marginal parenchymatic bands in *Acacia tortilis* wood. The white arrows point out the marginal parenchymatic bands in a) a polished tree core and b) a microtome cross-section, where the calcium-oxalate crystals in the bands are visible in differential interference contrast.

increased, but it clearly shows that the age of the acacias studied should be counted in centuries rather than decades.

Studies of the wood anatomy of *Acacia tortilis* for age determination, with special emphasis on the narrow marginal parenchymatic bands, have been undertaken, mainly by Gourlay (Gourlay, 1995a, b; Gourlay & Grime, 1994; Gourlay & Kanowski, 1991). These bands are characterised by an increased concentration of calcium oxalate crystals that are located in chambered cells. Crystals are rhomboidal in shape, with a greatest dimension in the order of 16 up to 30 μm (Fig. 7b). Such crystals are found in many plants, and within most of their organs and tissues, and have three main functions: calcium regulation, plant protection and detoxification of aluminium/heavy metals, and perhaps others which so far have been supported by only limited evidence (Franceschi & Horner, 1980; Franceschi & Nakata, 2005). When crystal concentration is high in leaves it acts as foraging protection (Franceschi & Nakata, 2005; Ward, Spiegel & Saltz, 1997), while in bark it might act as protection against bark beetles and other pests (Franceschi et al., 2005). The large concentration of crystals in acacia wood not only affects its density, but also contributes to a fuller combustion (oxygen released from the oxalate) and acts as a flame retardant (released CO_2) that gives a glowing combustion, explaining why it is a highly valued source of domestic fuel (Prior & Cutler, 1992).

Long-term dynamics of wadi trees in the ED

Lately, several studies have been performed to fill the gap in our knowledge about the long-term dynamics of trees in arid and semi-arid environments. A major focus has been on savanna-trees as part of the patch-dynamics problem complex (Higgins, Bond & Trollope, 2000; Jeltsch, Weber & Grimm, 2000; Moustakas, 2006; Moustakas et al., 2006; Sankaran, Ratnam & Hanan, 2004; Wiegand, Saitz & Ward, 2006), while a series of studies has focused on the *Acacia raddiana* populations in the Negev, Israel (Lahav-Ginott, Kadmon & Gersani, 2001; Munzbergova & Ward, 2002; Or & Ward, 2003; Rohner & Ward, 1999; Shrestha et al., 2003; Wiegand, Jeltsch & Ward, 2000, 2004; Wiegand et al., 2000a; Wiegand et al., 2000b). Results presented in this study stand apart because its focus has been on a hyper-arid area where climatic extremes prevail, at the same time as the sites studied have been selected along a gradient reflecting the large variations in local topo-hydrological conditions. To quantify these conditions the SRTM elevation dataset was applied (cf. above). To my knowledge it is the first time such studies as presented in papers II and IV have been undertaken in the hyper-



Figure 9: Root sprouting in *A. tortilis*, observed in W. Dabur.

arid deserts of north-Africa. Below the main results are presented and some general and comparative aspects discussed:

No seedlings and in general few saplings were observed in the field. The stricter estimate of recruitment (paper II) ranged between 1 % and 38 % at sites during the period studied, however, because of browse suppression (observed for all individuals) and resprouting (observed for 97 % of individuals) it is possible that even this estimate is too high.

In paper II sprouting is shown to be a very important strategy for increasing population persistence, and in the light of these results the root sprouting observed in both *A. tortilis* and *Balanites aegyptiaca* should be the subject of further investigation (Fig. 9). Wiegand, Jeltsch & Ward (2000) concluded that vegetative reproduction is absent in *A. raddiana* in the Negev, based on the observation that seedling distribution relative to the distribution of adult trees did not depart significantly from randomness. If a similar spatial analysis were performed focusing on the vegetative reproduction of trees in the ED, the distribution of saplings should be studied in relation to the distribution of both surviving and dead adult trees. A main challenge for such an analysis would be the general rarity of saplings that makes it difficult to detect significant departures from randomness (Fortin & Dale, 2005).

A pest influencing the acacia population viability is the bruchid beetle which as larvae develops within acacia seeds and destroys the cotyledons, and thereby reduces seed viability (Or & Ward, 2003). The bruchid beetles' effect on the seed bank was not investigated in the course of this study, but in the field exit holes were observed on seed pods. In the Negev the effect of bruchid larvae on the viability of seeds is so detrimental that it is unlikely that a seed can survive into a second year (Rohner & Ward, 1999; Wiegand, Jeltsch & Ward, 2000). If

this is the case in the ED as well, then it is evident that adult trees have to be continuously present if recruitment from seeds is to be secured (but see below) and that vegetative reproduction is of even greater importance for the long-term viability of populations.

Recruitment varies among the sites studied here, and this is in line with the spatial and temporal heterogeneity of recruitment found in the Negev (Wiegand, Jeltsch & Ward, 2004). None of the indicators of water conditions tested could explain this variation, although it should be mentioned that altitude was close to significant. This might suggest that local, fine-grained variations in soil moisture conditions, in particular for the occurrence of safe sites for the germination of seeds, are important.

Overall, 41 % of the mature population has disappeared between 1965 and 2003, corresponding to an annual mortality rate of 1.1 %. At individual sites mature mortality ranges from 9 to 68 %. Of the indicators of water conditions tested, some had a significant influence on the survival of trees and were interpreted as related to the temporary presence of surface water; i.e. ‘catchment size’ and ‘distance to coast’ on a regional scale and ‘distance from ephemeral stream’ and the interaction of the latter and “tree density” on a local scale. The indication that density might play a role in survival can be further investigated by analysing bivariate point patterns (Kenkel, 1988; Wiegand & Moloney, 2004). While point patterns cannot detect the cause of death, the type of spatial process producing the observed pattern can indirectly suggest a likely cause (Fortin & Dale, 2005).

In addition to the bruchid beetle, we observed other infections in acacia trees. These have not been studied, but an attempt has been made to identify the pest organism from photos. Holes in the wood were frequently observed, and these are most likely from beetles which breed in dead woody tissue and do not harm the trees much. Smaller round holes have probably been made by ambrosia beetles, in the Scolytinae or Platypodinae, while oval holes are likely to have been made by a cerambycid or buprestid (pers. comm. L. Kirkendall, BIO, UiB). In addition we also observed a wax scale, of the genus *Ceroplastes*, perhaps *C. confluens*, *C. paucispinus*, *C. sinoiae* or *C. stenocephalus* (pers. comm. G. Hodges, Florida State Collection of Arthropods). This taxon lives on the sap, and can lead to the drying out or eventual death of branches, or in heavy attacks to the death of whole individuals (Stimmel, 1998). Local informants in Sudan say that branches infected by a pest should be coppiced to avoid drying out the trees (pers. comm. K. Krzywinski, BIO, UiB). The effect of wax scale infections on the acacia population should be followed up by further studies that include the possible effect of past and present management techniques to mitigate tree mortality.

On the basis of the available evidence, however, it seems that charcoal production is and has been the main threat to the population during the period studied (paper II). Charcoal production using living trees has been reported by travellers in the past, and there are indications that living trees are also exploited in its production today. The mortality estimated here, is therefore higher than the natural mortality. Standing dead trees should be an indication of natural mortality. In the Negev in Israel standing dead trees are observed frequently, corresponding to an annual mortality of 1.7 % (Ward & Rohner, 1997). In ED on the other hand, standing dead trees are extremely rare or nearly absent in the whole area. In the Negev dead trees seem to be a good estimate of natural mortality because the Bedouins have been more or less absent from their homeland since they escaped during the 1948 war and later have been prevented from returning (Ginguld, Perevolotsky & Ungar, 1997). Tree mortality in the Negev seems to be caused mainly by water stress (BenDavid-Novak & Schick, 1997; Shrestha et al., 2003).

Whether or not mortality in the Negev is significantly higher than that in the ED is unknown, but it is reasonable to ask how natural mortality can be lower in the ED when it is higher and drought-induced under better water conditions in the Negev. Data from the Negev, where rainfall is both higher and more regular than in the ED (Evenari, 1985), suggest that Negev trees are less deeply rooted and more dependent upon surface water than previously believed (BenDavid-Novak & Schick, 1997; Shrestha et al., 2003). Acacia trees at a “mesic” site were also less able to retain water through dry summers than those at xeric sites (Shrestha et al., 2003). This suggests that these trees are responding to local conditions. For *Faidherbia alba* it has been shown that individuals growing under a variable rainfall regime had a well-developed taproot, while under a regular rainfall regime it was the side roots that were most developed (Vandenbeldt, 1991). This raises questions about the rooting structure of trees in arid areas, an issue also raised in paper IV: 1. Is it possible that trees in the hyper-arid ED in general have deeper roots and less dependence on surface water than in the Negev where rainfall is higher and more regular? 2. Are trees in the ED better adapted to extreme aridity as a consequence of higher water stress (cf. Molinier et al., 2006)? Still, variations in rooting structure from site to site, and perhaps even within sites should also be considered in further studies, for the results from paper IV suggest that landscape heterogeneity might be much greater than often assumed for a seemingly homogenous and harsh desert environment.

From the image analysis (paper I) it seems possible that all larger trees registered in 2003 were already present, and in fact large, also in 1965. This indicates that these trees are long-

lived and slow growing. Slow growth is confirmed by the results of the post-bomb radiocarbon dates (paper IV), ranging between 0.2 and 2.4 mm/yr. Assuming that long-term growth rate lies in the same range and is comparable to recent growth rates, it seems likely that trees which have been dated are from 200 to 650 years old. Considering the extreme climatic conditions under which they grow, ages in this range seem to fit well with estimates from other arid regions (see paper IV). With an extended dataset it should be possible to look into temporal patterns in establishment and to investigate whether recruitment events are concurrent with characteristic regional climatic events (Verschuren, Laird & Cumming, 2000). Such a dataset could also be used to look further into population demography and the question about the importance of large versus small recruitment events (Midgley & Bond, 2001; Wiegand, Jeltsch & Ward, 2004). Because of the temporal and spatial variation in growth rates (see below) the size of individuals is probably not a good indicator of population demography.

While it is uncertain exactly how old trees are, it is clear that the dated individuals cannot be much older than the maximum age found by the scenario approach (650 years) since none of the oldest samples gave a unique calibrated date (cf. Fig. 7a). It is also clear that although parenchymatic bands are present in the wood, they are not regular time-markers and do not facilitate age determination.

There was great variation in growth rate, both temporally and spatially (paper IV). Growth conditions are apparently best in W. Jimal, and tree size cannot, therefore, be used as an indicator of difference in age among sites. Also within sites there seems to be variations in growth conditions. We found no or only poor correlations between band patterns in trees from the same site. As concluded, this can also indicate that browsing or pollarding, operating at an individual level, influences the formation of parenchymatic bands and the growth of trees and that it is not just water conditions that are locally heterogeneous (cf. above).

On the basis of recruitment and mortality estimates, it is evident that the primary vegetation resource for the pastoral nomads in the ED is in alarming decline. The reduction in tree population size must be seen in relation to rare recruitment, slow growth and great longevity. It should be taken into account that future climate change may result in even rarer recruitment events (Giannini, Saravanan & Chang, 2003; Held et al., 2005; McCarthy, 2001; Wiegand, Jeltsch & Ward, 2004). These facts indicate that the ED acacia population may not be resilient and consequently that it will take a very long time for deforested landscapes to recover.

The management of wadi trees in a regional perspective

Trees, the primary vegetation resource for the pastoral nomads in the ED, are in alarming decline, probably due mainly to over-exploitation. At the same time trees are a fundamental pillar in the nomadic lifestyle, as can be seen by the fact that every single tree is either browsed or pollarded (papers I and II). According to nomads in Egypt one tree provides fodder for two goats per year in the form of leaves, young shoots, pods and seeds. A set of management strategies and crucial and potentially complex rules of ownership have been developed by the nomads in order to protect, secure and optimize their utilisation of trees (Briggs, Badri & Mekki, 1999; Hobbs, 1989; Krzywinski & Pierce, 2001). This traditional pastoral management has developed in accordance with the prevailing environmental conditions over millennia (cf. Study area and Fig. 3). Similar management strategies are common in arid regions (and others) where trees are a major dependable resource (Birks, 1988; Hobbs, 1989; Mortimore & Turner, 2005).

The tree - domestic animal – human interface not only secures a resource for the nomads, but also has several positive effects on the microhabitat, the ecosystem and even the tree. The tree as a physical structure influences the microclimatic conditions under its canopy, and animals are not only attracted by the browse a tree supplies but also by its shade, resulting in a higher input of animal droppings and thereby nutrients in the crown zone. This has positive effects on understory productivity (Belsky, 1994). Reid & Ellis (1995) also found that the higher nutrient content and better water retention capacity of soils where livestock had been gathered (corrals) enhanced the survival and growth of first year seedlings.

Stable fodder is obtained from trees by browsing or by shepherds shaking leaves to the ground (cf. Study area). Shaking branches with the shepherd's crook probably also prevents certain types of pest attacks; during a seminar in the St. Katherine Protectorate it was seen that fenced trees were in a much poorer state owing to pests than were surrounding unprotected trees which were managed in a traditional way. According to local informants shaking branches for fodder reduces the risk of infections and pollarding the risk of death.

It is also recognized that the digestion of seeds by ungulates can reduce a bruchid infestation or its effect, as well as improve germination and the dispersal of seeds (Barnes, 2001; Midgley & Bond, 2001; Miller, 1994; Or & Ward, 2003; Rohner & Ward, 1999). As for the Negev, it has been suggested to reintroduce domestic animals, e.g. camels, as a measure to facilitate tree regeneration (Wiegand, Jeltsch & Ward, 2004). It was also advised to take away the animals after recruitment events to prevent browsing-induced killing of seedlings and

saplings (Wiegand, Jeltsch & Ward, 2004). The establishment of recruits is one of the main obstacles to the renewal of populations (Kenneni & van der Maarel, 1990; Midgley & Bond, 2001; Rohner & Ward, 1999; Wiegand, Jeltsch & Ward, 2004; Wilson & Witkowski, 1998). Removing animals might therefore be necessary if they are not properly herded in keeping with longstanding traditions, i.e. are driven rapidly from place to place to prevent over-utilisation of available resources. Movement, the underlying principle in the nomadic lifestyle, prevents reduction of the resource base.

Pollarding as a strategy is primarily done to optimize the use of fodder resources and to remove dry branches. As a result branches left on the ground constitute a stable fuel resource. Moreover, pollarding reduces the transpiration rate and, according to the Beja in Sudan, is also used actively to prevent the drying out of withering trees (Krzywinski & Pierce, 2001). It is also considered as very advantageous because it improves the vitality and vigour of the trees (Springuel & Mekki, 1994). It is probably also advantageous in relation to infections caused by wax scales (cf. above).

Dry branches from pollarding or wood from dead individuals are used to produce charcoal in a sustainable manner. Small scale production for domestic use must be distinguished from larger scale commercial production which also exploits living trees and seems to be the main cause of tree mortality in the ED. In Wadi Allaqi, however, charcoal production is a major economic income generating activity for the nomads, who claim that only dead trees or dry branches are exploited (Briggs, Badri & Mekki, 1999; Springuel & Mekki, 1994). Seen in relation to the possible positive effect of root sprouting for sustaining populations, it is of concern that even roots are dug out to increase the profit of charcoal production. While it is probably well known locally and only used as an excuse for cutting down trees, it should be emphasised that trees having exposed roots and/or no leaves are not necessarily dead (cf. paper II).

The primary driving force for commercial charcoal production is monetary income. There is a big market and demand for energy in general and for charcoal in particular (Hillring, 2006). It is a well established fact that one of the chief causes of desertification is the tendency to view the environment as a medium for rapid material or economic gain (Geist & Lambin, 2004). This, however, raises the question of who the producer is and whether the motivation is for surplus income or for securing basic needs (Floyer, 1893; Hobbs, 1989; Krzywinski & Pierce, 2001; Springuel & Mekki, 1994). In the northern ED people from the Ma'aza tribe admitted that the heyday of tree cutting (1940s) was a result of "drought induced despair" (Hobbs,

1989), in other words of poverty. But poverty is not necessarily connected to drought, in particular not among nomads whose lifestyle is an adaptation to dry periods. Poverty today is mainly a political issue, at the global as well as at national and local levels, in particular as regards development and marginalization of minority and indigenous populations. When day-to-day survival becomes a major challenge for the Ababda, traditional management strategies might be disregarded, but generally they have a strong moral commitment to conserving their resources (Briggs, Badri & Mekki, 1999; Grainger, 2003; Hobbs, 1989; Krzywinski & Pierce, 2001). On the other hand, locals who have settled, or in other ways have lost their connection and any previous commitment to the land, have another attitude towards the resources. *“Well-established old patriarchs with children to follow them preserve the trees most carefully, never cutting the branches, but serving themselves only with such leaves as are shaken off by the shepherd’s long crook. But a family who have usurped another’s valley, or who are perhaps merely shepherds of sheep of some rich Nile-dweller, will cut down every branch and finally burn the trunks into charcoal”* (Floyer, 1893). If this is so, it is to be expected that improving the nomads’ conditions can reduce destructive charcoal production and facilitate their continued existence as pastoralists. This is needed for a continued management of the desert cultural landscape, but also for retaining the indigenous cultural identity, heritage and knowledge. In Europe it has become a great challenge to preserve past cultural landscapes that bear witness to our common cultural heritage, because we have realised almost too late what was being lost. In Egypt there are still good opportunities to be grasped, in particular in its southern part, e.g. in the Bisharin Gebel Elba area.

While Gebel Elba has been a protected area since 1985, Wadi Jimal was only protected in 2003. Ironically, it is only since the establishment of the Wadi El Gemal – Hamata Protected Area that tourism has really started to influence the inland desert. Hopefully the good experience with involving local tribes in other Egyptian parks (Grainger, 2003) will be furthered and improved. In particular the opportunity for the nomads to improve their own situation through tourist activities is important. Tourism must be prevented from selling the desert life experience in a way that exploits it exclusively for the economic gain of outsiders. An eco-lodge has already been established in Wadi Jimal and a major attraction there is the nomadic lifestyle and the traditional knowledge it preserves. Strangely enough the lodge employs Bisharin camel guides although Wadi Jimal is Ababda land. In the longer term serious effort should be made to fully integrate the Ababda in the park management, thus acknowledging that this is their homeland. The question of rights to land is problematic, and already in 2003, when tourism had just started, a conflict arose in the W. Dabur area where

developers had built a tourist camp without considering the traditional rights of the local Ababda sub-tribe.

As the above observations show, prohibiting the traditional utilisation of resources is not a solution to prevent ecosystem change, and the problem of charcoal production extends far beyond the question of whether nomads manage resources properly or not. Conserving ecosystems or landscapes under human influence, i.e. cultural landscapes, by prohibiting human intervention is increasingly acknowledged to be a mistake (Krzywinski & Pierce, 2001). If the desert cultural landscape is to remain for future generations nomads must be empowered and their lifestyle encouraged rather than marginalized. This depends on policy makers recognising not only that traditional strategies are sustainable in the long-term, but also that the nomadic lifestyle and cultural heritage are important in themselves. The nomads have developed and lived in accordance with a lifestyle that is in keeping with the resilience of the environment (Coughenour et al., 1985; Davis, 2005; Ellis & Swift, 1988; Krzywinski & Pierce, 2001). Interestingly, it is exactly this that lies at the heart of the arid land degradation debate – that the land-use intensification in dryland ecosystems increases these ecosystems' vulnerability to dry episodes (Geist & Lambin, 2004).

Conclusions

This study was motivated by the need for further knowledge about the long-term dynamics of arboreal vegetation in arid lands, which is required if the effects of desertification are to be controlled and mitigated. Lack of data with appropriate spatial and temporal resolution has been a hindrance for long-term studies of scattered tree populations, and this was dealt with in two different approaches: the use of first generation, high resolution US reconnaissance CORONA imagery in combination with field data, and the use of pre- and post-bomb ^{14}C content and anatomy of *Acacia tortilis* wood.

It has been demonstrated in this study that CORONA images offer a spatial and temporal dimension for ecological information which other data sources cannot furnish at a comparable cost, coverage, resolution or accessibility. In the 1965 KH-4A images a high percentage of trees mapped in 2003 was detected (70 % of trees with canopy area $> 6 \text{ m}^2$), and those undetected seem to have been present already in 1965 but concealed by landscape elements that reduce image contrast. The historical ecological information content is considerable and imagery is well suited for change analyses. For such analyses it should be noted that pollarding trees and the resultant reduction in canopy area may lead to misinterpretation.

A challenge for historical imagery and its use in change analysis is, however, the lack of contemporaneous reference data that prevents a proper accuracy assessment of the derived product. To deal with this a method was developed during this research which supplies essential information about the reliability of the results, thus assuring that appropriate management measures can be taken.

Vegetation changes are ongoing in the ED, and the results obtained here also fill in gaps in our knowledge on vegetation changes in hyper-arid areas in general. The overall trend in tree population size is negative; at some sites this trend is alarming because the reduction in mature trees is substantial (>50 %) at the same time as recruitment is nearly absent. At a few sites there is a positive trend and better recruitment. Frequent observations of sprouting in saplings indicate that this is an important mechanism to increase their persistence. It is establishment itself that seems to be the main challenge in the recruitment process. There are indications that hydrological variables and surface water in particular can explain some of the observed pattern in mortality, but our results also indicate that direct human intervention, i.e. charcoal production, is the main cause of tree mortality in the ED.

CORONA imagery indicated that 97 % of the population mapped in 2003 was already present in 1965 and that trees grow slowly and are older than previously assumed. This is confirmed by results based on the ^{14}C content of *A. tortilis* wood. Annual radial increment growth varied between 0.2 and 2.4 mm, and variations are both spatial and temporal. The ages of the trees examined seem to be from 200 to 650 years. The post-bomb ^{14}C content in *A. tortilis* wood gives valuable information about tree growth and is required to assess the age scenario approach applied here. This approach should be extended with more samples from each core examined in order to make age estimates more reliable.

The possibilities for dendrochronological studies based on *A. tortilis* from the ED are poor, but marginal parenchymatic bands can give insight into fine scale variation in growth conditions and the past management of trees.

The longevity, low recruitment and high mortality of the trees studied suggest that the recovery time for deforested locations will be long and that management measures will have to be taken as soon as possible to prevent complete deforestation. In this process traditional local management practices have to be acknowledged and mobilised.

Future perspectives

This study has raised several questions that should be addressed in future research projects. For a set of these questions it would be fruitful to apply spatial statistics to get further information about underlying processes; e.g. is vegetative reproduction an important mechanism in population viability; and are there any indications that the death of trees is influenced by droughts or pests? It would also be rewarding to study whether the variation in tree density on the landscape scale, within and among wadis, can be explained by topohydrological parameters. If tree patterns can be understood on the landscape scale, it will be possible to approach questions such as the long-term effects of past deforestation, e.g. in antiquity, on recruitment. For such studies the high resolution QuickBird images available for extensive parts of the ED will certainly be an asset. In combination with CORONA images, necessary studies of vegetation changes are feasible also in other hyper-arid regions.

Studies of the effect of pests on mortality (scale wax) and seed bank viability (bruchid beetle) in the ED should also be undertaken, and be seen in relation to traditional management techniques. Moreover, there are important questions related to the rooting structure of trees. While those are methodologically challenging, an experimental approach in which saplings are grown under various water regimes could give insight into the development of horizontal-versus tap- roots. Such an experiment in combination with cambial injury as time markers should also make it possible to study the effect of water on parenchymatic band formation and thereby improve our understanding of the temporal growth variations in desert trees. This will facilitate age determination which should then be followed up by augmenting the set of dated samples.

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