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ENVIRONMENTAL CHANGE AND VEGETATION SUCCESSION ALONG AN EPHEMERAL RIVER: THE KUISEB IN THE NAMIB DESERT

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ABSTRACT Forests line the course of the Kuiseb River, an ephemeral river in the Namib Desert, and several areas of these forests are characterized by high concentrations of tree death (Mizuno, 2005; Mizuno & Yamagata, 2005). We sought to clarify the relationship between recent environmental changes and such tree deaths in the region. In November 2007, we examined the roots of a seedling of *Acacia erioloba* that was germinated by rainfall beginning in January 2006. The *Acacia erioloba* had grown to a height of 10cm and its roots to over 230cm, within two years. In the sapling (seedling) stage, *Acacia erioloba* extends its main roots deeply until it reaches a moist, fine-grained soil layer (sandy silt) and can absorb water through lateral roots. When it reaches the stage at which the water supply from the moist, fine-grained soil layer is insufficient for its growing size, the tree extends innumerable lateral roots within a 50cm depth from the land surface, where they absorb water that has been transported to a shallow depth by fog and other sources. *Acacia erioloba* dies when its lateral roots are unable to absorb water. Until the mid-1970s, successive floods repeatedly deposited fine-grained materials (e.g., sandy silt) that create water-bearing sediments for the growth of *Acacia erioloba*, and the trees died only rarely. However, from 1980 to 1985 these materials became increasingly scarce due to the decreasing occurrence of flooding, and consequently many trees died. It is reasonable to infer that the trees died because fine sediments were no longer being regularly deposited, and because of the drawdown of the groundwater level, both of which are making it difficult for the shallow roots of the trees to absorb the water necessary to survive.

Key Words: Environmental change; Vegetation succession; Tree death; Flooding; Sand dune.

INTRODUCTION

The Namib Desert is located along the western coast of Namibia and is affected by the cold Benguela Current. Although forests are present along the Kuiseb River in the Namib Desert, many trees are almost dead in certain areas (Mizuno, 2005; Mizuno & Yamagata, 2005). During the early 1980s, a dramatic decrease in flooding in the Kuiseb River resulted in a rapid decline in the groundwater table, leading to a large die-off of mature *Faidherbia albida* (Ward & Breen, 1983; Jacobson et al., 1995). Although no studies have been conducted to examine the relationships between groundwater dynamics and vegetation communities, numerous anecdotal observations shed light on this issue (Jacobson et al., 1995). The aim of this research is to clarify the relationship between recent environmental changes and tree death.

STUDY AREA AND METHODS

I. Study Area

Research was performed near Gobabeb along the Kuiseb River in the Namib Desert from 2002 to 2007 (Figs. 1 & 2). In Gobabeb, although the annual rainfall is only 27mm, fog-water precipitation is 31mm (Lancaster et al., 1984). Extending inland for tens of kilometers on many mornings, the fog is densest at an elevation of 300–600m. The fog is at its densest and fog-water precipitation is at its greatest about 40km inland from the coast because the altitude of the Namib Desert gradually increases eastward from the coast. Fog arises, on average, 37 days per year (1976–1981) in Gobabeb and constitutes the most important water supply for animals and plants in the Namib Desert (Lancaster et al., 1984). The daily mean temperature per month is highest (24.8°C) in March and lowest (17.6°C) in August, and annual mean temperature is 21.1°C (Lancaster et al., 1984). More than 90% of the annual rainfall occurs in the rainy season, from January to April. The absolute humidity is high in this period (Fig. 3). The coastal area is cool; the highest monthly mean temperature, 17.7°C, is in February and the lowest, 12.9°C, is in October. The annual mean temperature is only 15.5°C owing to the cold Benguela Current.

Although forest is distributed along the course of the Kuiseb River, several areas are characterized by extensive tree death (Figs. 4, 5 & 6). These locations have the topography of a river bank (Figs. 7 & 8).

II. Methods

This study examined a land strip extending 50km along the Kuiseb River. The area was characterized by extensive tree death, and its vegetation, topography, and soil were examined. Quadrats were established for Sites 1 through 4 (Fig. 1). The quadrat of Site 1 was established to include the slope of the sand dune, a river bank formed by the redeposition of dune sand, and the slope (high-water bed) below the river bank.

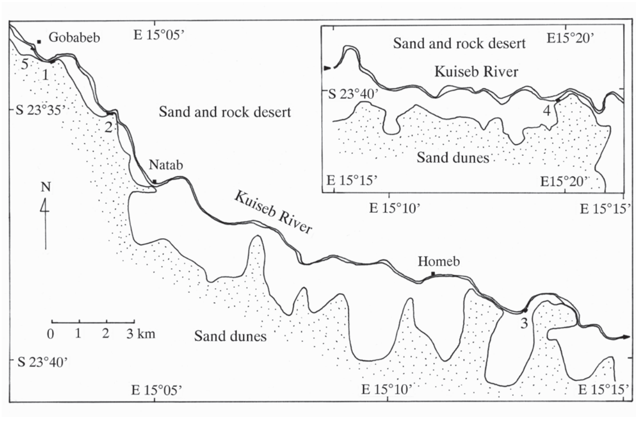


Fig. 1. Study sites. Sites 1–4: Sites with many dead trees; Site 5: Control site.

The trees were divided into four status groups: healthy growing, unhealthy growing, dying, and dead. Assuming that the highest leaf rate of trees is 100%, a leaf rate of 60–100% was regarded as "healthy," 20–60% as "unhealthy," 0% to 20% as "dying." To take seasonal differences into account, these characteristics were assessed in both summer (November-December) and winter (August).

The distribution of vegetation at Site 1 was mapped using a measure, compass, GPS, and an infrared distance meter (Fig. 4). Soil profile and soil water were measured in pits that were 1–2m deep. Wood fragments and litter were dated by ^{14}C (radiocarbon) (AMS) dating methods. In the case of modern samples from 1950, the dates were obtained by comparison between the ^{14}C concentration of samples and global data (Mizuno, 2005). Soil water was measured in soil moisture by volume using a Hydro-sense soil moisture meter (Campbell Scientific Ltd.).

The movement of the sand dune end was measured from December 2002 to November 2007 at point K (Fig. 4).

The distribution of saplings (seedlings) was mapped at Quadrat S (Fig. 4) of Site 1 in August 2007.

Fig. 2. Kuiseb River between sand dune and rock desert near Gobabeb.

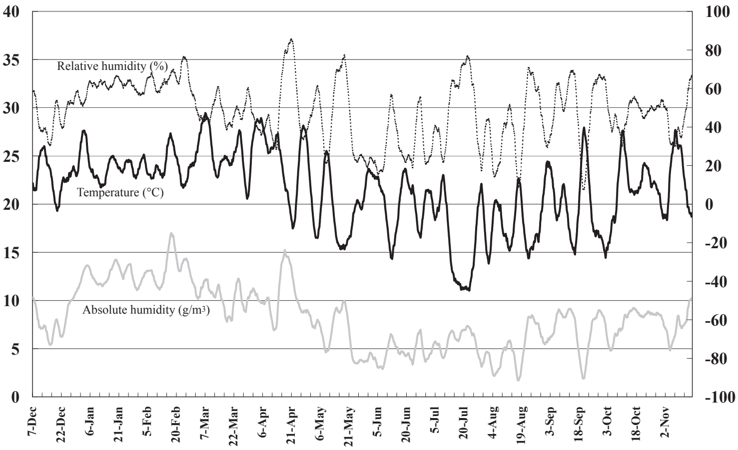


Fig. 3. Temperature (left scale of graph), relative humidity (right scale), and absolute humidity (left scale) at Gobabeb from December 7, 2005 to November 18, 2006.

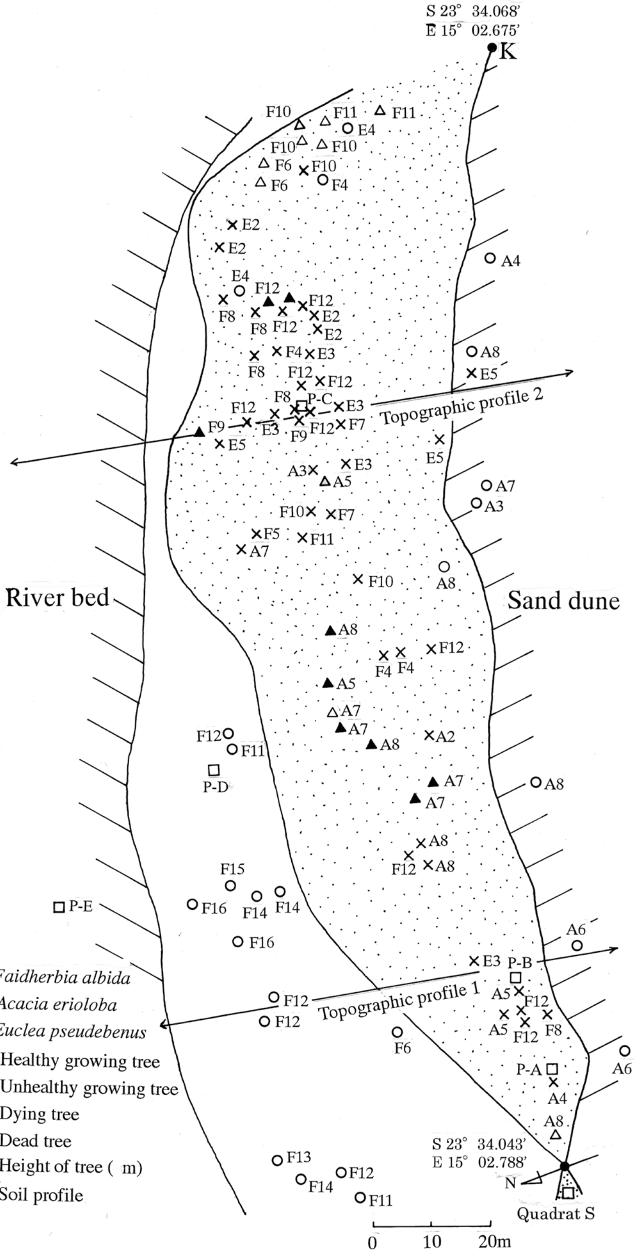


Fig. 4. Topography and distribution of trees at Site 1.

The dotted area indicates the river bank composed of dune sand. K is the reference point used to measure movement of the sand dune. Trees were divided into four status groups: healthy growing tree; unhealthy growing tree; dying tree; and dead tree. Assuming that the highest leaf rate of trees is 100%, a leaf rate of 60–100% was regarded as "healthy," 20–60% as "unhealthy," 0–20% as "dying," Taking seasonal differences into consideration, assessments were made in summer (November–December) and winter (August).

Fig. 5. Dead trees on the river bank betwee the sand dune and river bed at Site 1.

Fig. 6. Dead trees at Site 1.

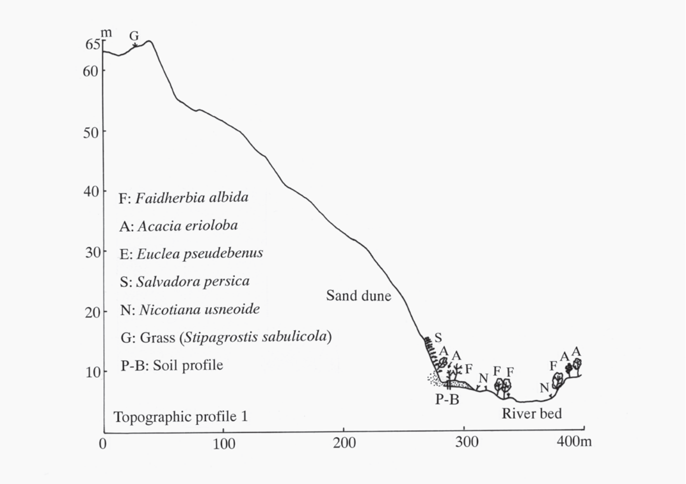


Fig. 7. Topographic profile 1 at Site 1 (Fig. 4).

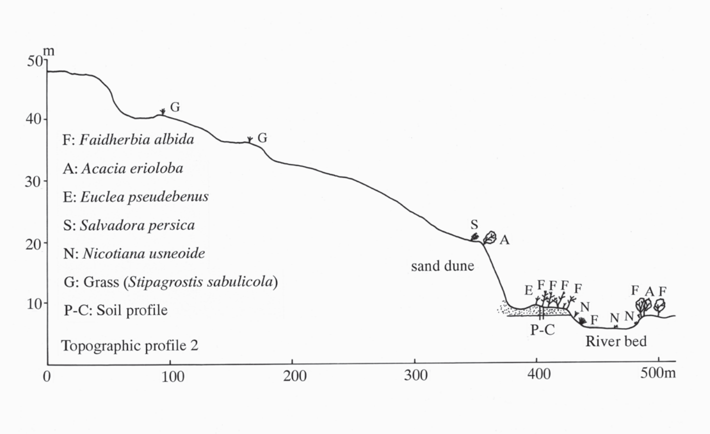


Fig. 8. Topographic profile 2 at Site 1 (Fig. 4).

RESULTS AND DISCUSSION

I. Seedlings Establishment and Survival

The precipitation was particularly abundant in 2006 at Gobabeb (Fig. 9). Rainfall was recorded at 12.8mm in January, 20.9mm in February, 14.5mm in March, 43.0mm in April, 1.1mm in May, 6.9mm in October, and 0mm in other months in 2006. The annual precipitation in 2006 was therefore 99.2mm, of which 91.2mm fell during the rainy season from January to April. Many shoots developed in areas that had previously been free of saplings by the unusually abundant rainfall of 2006.

The growing process of saplings was observed in Quadrat S (10m × 10m) on the bank along the river (Figs. 4 & 10). On *Faidherbia albida*, where 219 saplings were recorded on August 10, 2006, 153 had died by August 20, 2007 (Figs. 11 & 12; Table 1). Twenty-one saplings germinated after August 2006, 11 of which survived. Because it began to rain in January of 2006, it is considered that these saplings only began to germinate after January 2006. As a result, 77 saplings of *Faidherbia albida* survived and 163 died.

Of *Acacia erioloba*, 107 saplings existed on August 10, 2006, 40 of which had died by August 20, 2007.

The survival rate (the ratio of living seedlings on August 20, 2007 to all seedlings in 2006 and 2007) was thus 32% for *Faidherbia albida* and 74% for *Acacia erioloba* (Table 1).

This observation clearly implies that, although *Faidherbia albida* germinate more readily than *Acacia erioloba*, the former are less likely to survive than the latter. Because of the intensity of the struggle for survival, the sapling death rate was high in areas where the sapling density was also high (Fig. 10).

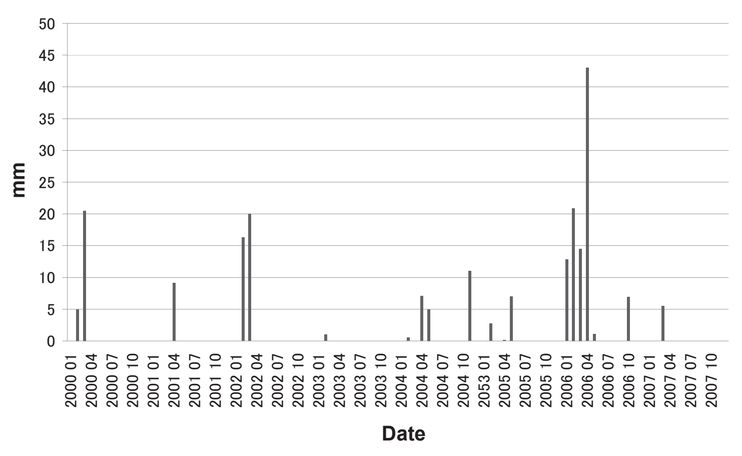


Fig. 9. Precipitation of Gobabeb from January 2000 to October 2007.
The data are from the Gobabeb Training and Research Centre.

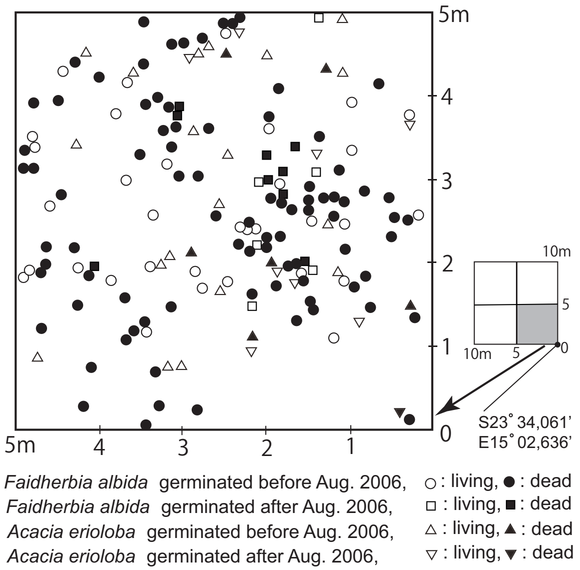


Fig. 10. The distribution of saplings at Quadrat S (Fig. 4) in August 2007.

Fig. 11. The distribution of saplings on August 10, 2006.

Fig. 12. The distribution of saplings (seedlings) on August 20, 2007.

Table 1. The existence of sapling at Quadrat S (10m × 10m) (Fig. 4).

		Aug. 10, 2006		Aug. 20, 2007	Survival rate*
Faidherbia albida	Living	219	66 (+11)	77	32%
	Dead		153 (+10)	163	
Acacia erioloba	Living	107	71 (+43)	114	74%
	Dead		36 (+4)	40	

*Survival rate = Living seedling on August 20, 2007 / All seedling in 2006 and 2007.
( ): Seedling germinated after August 2006.

Fig. 13. Soil profile at Quadrat S in Site 1 (Fig. 4) and roots of *Acacia erioloba* sapling.

Fig. 14. Roots of *Acacia erioloba* sapling. The *Acacia erioloba* has grown to a height of 10cm and its roots to 230cm within two years, from January 2006 to November 2007.

II. Growth of *Acacia erioloba* Saplings and Soil Condition

The roots of an *Acacia erioloba* sapling that had been germinated by rainfall from January 2006 onward were examined in November 2007. The height of the sapling was 10cm at that time. The roots were investigated by making a pit at the base of the plant. The tip of the roots was below the bottom of the pit, 230cm below the ground (Figs. 13 & 14). Based on this measurement, it was determined that the *Acacia erioloba* had grown to a height of 10cm and its root to a length of over 230cm within the two-year period from January 2006 to November 2007 (Fig. 15). According to Moser (2006), the average root length of *Acacia erioloba* seedlings 63 days after their emergence was 97.5cm at Gobabeb, and the daily root growth rate was approximately 1.5cm (Table 2).

The roots examined were primarily the main roots. The lateral roots were largely absent (Fig. 15). The soil profile at the pit indicated that, although the soil between the land surface and the deeper level was predominantly sandy, layers of fine-grained soil such as sandy silt were present at depths of 93–114 cm and 118–124cm. The lateral roots were seen to grow readily in the sandy silt soil layer (Fig. 15). It is reasonable to assume that this fine-grained soil layer was composed of fluvial materials brought from the upper reaches of the river. This layer has a higher water content than the sandy soil of the coarse-grained layers (Figs. 15 & 16).

Lamina was found in the soil layer at depths of 20–55cm, and cross-lamina was found in soil at depths of 70–76cm and 80–93cm (Fig. 15). This lamina structure reflects the water flow characteristic of flooding. Because the color of this sandy soil was grayer than that of the sand dune nearby, the soil was likely created from a mixture of sand from the dune and gray fluvial materials

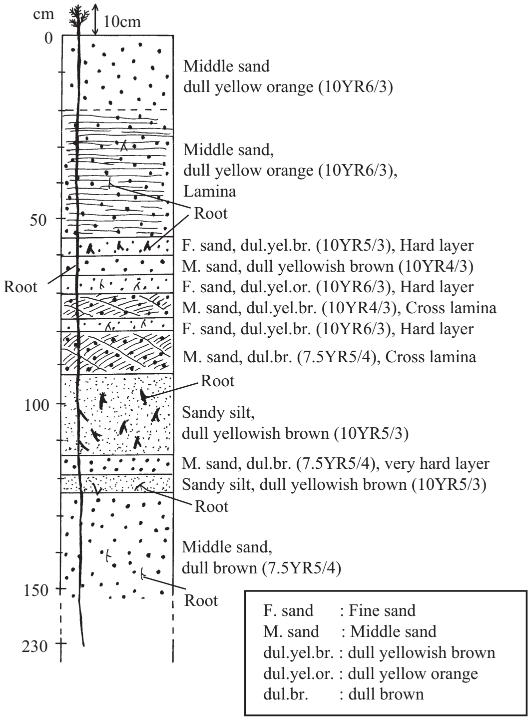


Fig. 15. Soil profile (Fig. 13) at Quadrat S in Site 1 (Fig. 4) and the roots of *Acacia erioloba* (Fig. 14).

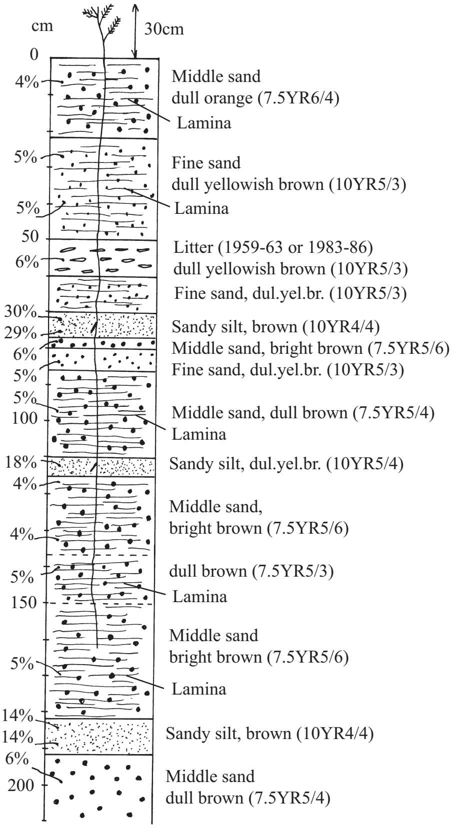
Table 2. Root length (mean ± SE) and daily root growth rate (mean ± SE) of *Faidherbia albida* and *Acacia erioloba* seedlings 31 and 63 days after emergence, Gobabeb, Kuiseb River, 2004 (n = number of seedlings) (Moser, 2006).

Specie	31 d root length (cm)	63 d root length (cm)	31 d growth rate	63 d growth rate
Faidherbia albida	28.7±2.4 (n=17)	79.8±6.5 (n=17)	0.9±0.1 (n=17)	1.3±0.1 * (n=17)
Acacia erioloba	38.7±3.6 (n=15)	97.5±7.8 (n=19)	1.2±0.1 (n=15)	1.5±0.1 ns (n=19)

* indicates significance level of $p < 0.05$.
ns means “not significant.”

from the upper reaches of the river. Although the sand from the dune consists mostly of orange quartz with oxidized surficial iron, the soil of the river bank at this location consists mostly of quartz and mica and is dull yellowish brown to dull yellowish orange. The mica is also transported from the upper reaches of the river by flooding.

The soil profile for another point on the riverbank was examined in August 2008 (Fig. 16). The three sandy silt layers (at 70–77cm, 110–115cm, and 182–192cm in depth) had higher water contents (14–30%) than the sandy soil lay-



dul.yel.br.: dull yellowish brown

Fig. 16. Another soil profile at Quadrat S in Site 1 (Fig. 4).
4%: Water content by volume, 7.5YR6/4: Soil color, 1959–1963: ^{14}C dates for litter.

ers (4–6%). Lateral roots had clearly grown here only in sandy silt soil (Fig. 16). A buried litter layer was found at a depth of 50–60cm. The date of the deposition of litter was estimated at between 1959–1963 or 1983–1986 by ^{14}C concentration. The latter date coincides with the date of extensive tree death in this area (Mizuno, 2005). In 1980–1985, very little flooding occurred (Fig. 24), and the litter was presumably deposited there without being washed.

In both soil profiles, fine-grained soil of sandy silt was not found at depths less than 70cm (Figs. 15 & 16). This means that fine-grained materials transferred from the upper reaches of the river decreased because of the recent infrequency of flooding.

Floods erode the sand dunes and re-deposit the sand elsewhere, while also bringing comparably fine-grained fluvial materials from the upper reaches of river. From this process, the soils are formed. It is reasonable to assume that *Acacia erioloba* germinates by the water supply of rainfall and flood, and that its saplings extends their main roots down to absorb the water and their lateral roots in the fine-grained soil layer.

III. Mature *Acacia erioloba* and Water Condition

We found an 8m tall *Acacia erioloba* that had extended innumerable lateral roots (thicker than 10cm in diameter in some cases) at a depth of 50cm from the land surface and efficiently absorbed water near the land surface (Figs. 17 & 18). Although the annual rainfall in Gobabeb is only 27mm, precipitation derived from fog provides an additional 31mm (Lancaster et al. 1984). The fog arose on an average of 37 days per year from 1976–1981 in Gobabeb (Lancaster et al. 1984). Fog moisturizes the land surface and is presumably an important source of water for trees (Fig. 19).

Acacia erioloba extends its main root deep into the fine-grained soil layer

Fig. 17. Roots of 8m-tall *Acacia erioloba*.
The mature *Acacia erioloba* extends a great number of lateral roots radially within a 50cm depth from the land surface.

Fig. 18. Roots of *Acacia erioloba* lying on its side. *Acacia erioloba* extends a great number of lateral roots in the shallow depth, and absorbs water through them.

Fig. 19. Fog in the morning at Gobabeb.

and absorbs the water with lateral roots that are grown in that layer during the sapling stage. When the water supply from the main roots becomes insufficient for the plant's large body, and/or the extension of lateral roots into spaces created through natural processes becomes possible, the tree is likely to extend a number of lateral roots into the shallow depth and absorb available moisture.

IV. Tree Deaths in Forests along the Kuiseb River

Forests are distributed along the course of the Kuiseb River, several parts of which are characterized by extensive concentrations of tree death. These locations have the topography of a river bank (Figs. 4, 5, 7 & 8) on which sand from dunes has accumulated to a thickness of 1m by flood (Mizuno, 2005).

In the soil profile of site 1, thick sand deposits were recorded on the banks where many dead trees were also present. Lamina structures reflecting the water

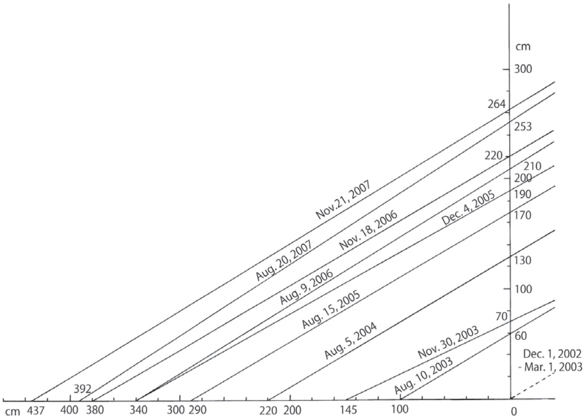


Fig. 20. Movement of sand dune from December 1, 2002 to November 21, 2007.
The advancement is represented as sequential cross-sections from right to left (south to north).

flow of flooding were found in the soil layers, implying that this sand deposition was not from wind-blown sand, but from the erosion of sand dunes by flooding.

The sand dune has advanced northward. To monitor sand dune advancements, a reference location was set at point K, as shown in Figure 4, where a pole was planted at the end of the sand dune on November 29, 2002. The rate of advancement was found to be 40–145cm/year on the basis of the measurements taken between December 2002 and November 2007 (Fig. 20). The slope of sand dune was steeper in August (average: 31.3°) than in November (average: 29.0°), as the floods during the rainy season from January to April (Fig. 9) trim the tips of the dunes.

V. Recent Environmental Change and Tree Death

At Site 1, soil profiles from the bank formed by the redeposit of dune sand (P-A, P-B, and P-C; Fig. 4), the high-water bed below the bank (P-D, Fig. 4), and the river bed (P-E, Fig. 4) were compared (Fig. 21).

The upper layers of the soil profiles that included almost no litter (P-A, P-B, P-C) suggest that the bank has been recently formed by the redeposit of dune sand (Fig. 21). The date of tree death (P-B) was estimated at either 1959–1962 or 1983–1987 by ^{14}C concentration (Mizuno, 2005). In the soil profile P-B, it is reasonable to assume that the sand was deposited over the wood fragments by floods in the 1960s to 1970s, based on its estimated date (1959–1963) and on the fact that the trees appear to have died between 1983 and 1987 (Mizuno, 2005). In the soil profile P-C, dull brown (7.5YR5/4) sand deposits to a thickness of 150cm overlie dull yellowish-brown (10YR5/4) sandy silt. A wood fragment at the bottom of the sand layer had an estimated date of 1955–1958 by ^{14}C concentration (Mizuno, 2005), and the date of tree death was estimated at 1962–1964 or 1976–1979 by ^{14}C concentration (Mizuno, 2005). In the soil profile P-C, it appears that sand was deposited over the wood fragments by floods in the 1960s to 1970s and that the trees died between 1976 and 1979.

In the three soil profiles at the points of tree deaths (P-A, P-B, P-C), coarse sand is deposited more than 70cm from the land surface, and no fine-grained soil exists in the layers shallower than that. It is reasonable to assume that

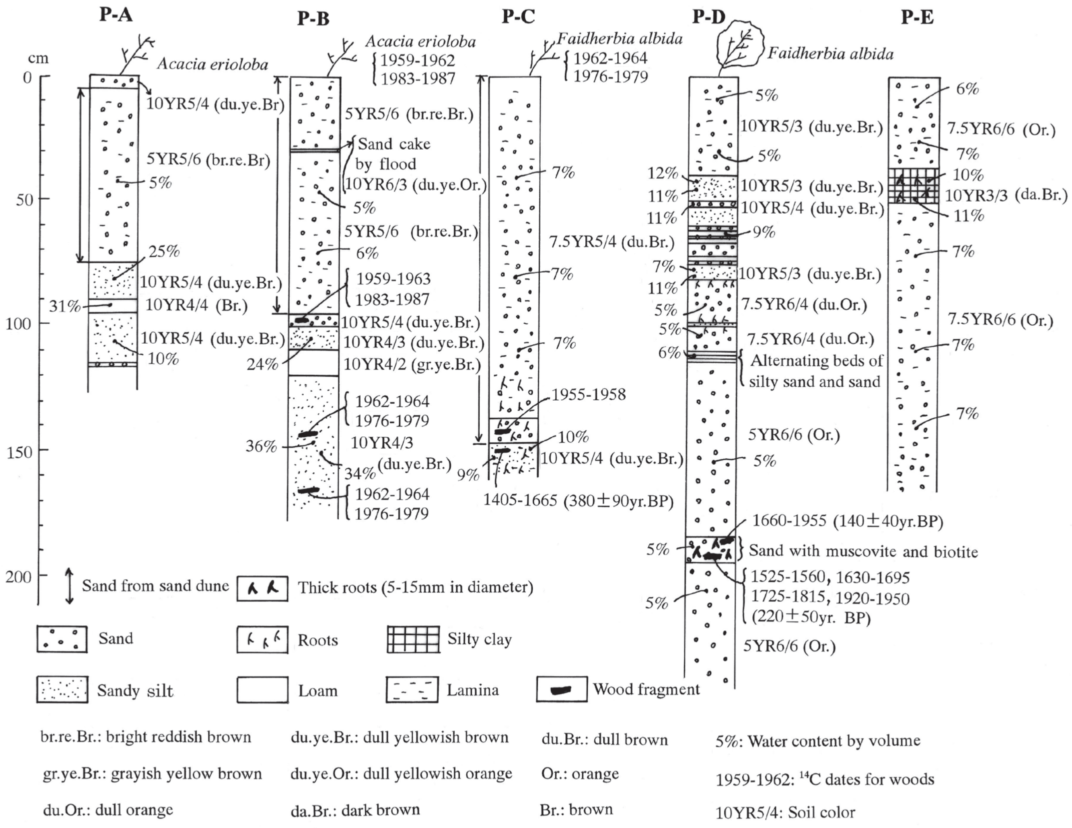


Fig. 21. Soil profiles at Site 1 (Fig. 4). P-A, P-B, P-C: Soil profiles in areas covered by dead trees. P-D: Soil profile in an area covered by healthy, growing trees. P-E: Soil profile in the river bed (Mizuno, 2005).

Fig. 22. Kuiseb River.
Kuiseb River usually has no surface flow.

Fig. 23. Kuiseb River flood.
(January 18, 2004: by Andrea Schmitz).

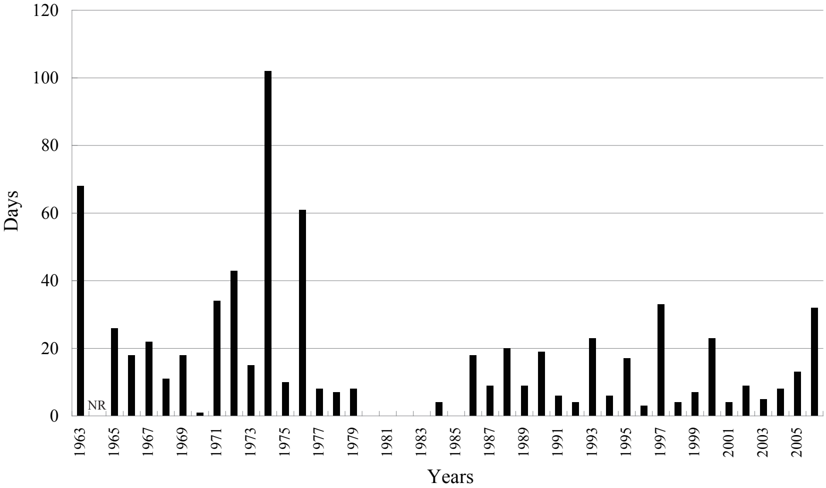


Fig. 24. Summary of Kuiseb River floods at Gobabeb, 1963–2006.
1963–1985: Seely et al., 1981; Ward and Brunn, 1985. 1985–2006: from data of the Gobabeb Training and Research Centre.

trees died because they could not absorb water contained at the fine-grained soil layer through their shallow roots. In the soil profile of P-D at the point of no tree deaths, a fine-grained soil layer (sandy silt) between 40 and 80cm depth from the ground can bear water.

VI. Flood Fluctuations and Tree Death

In Gobabeb, the number of days of flood (in which all running water is considered flood) (Figs. 22 & 23) for the Kuiseb River was 33.0 days per year from 1963 to 1976, and 10.0 days per year from 1977 to 2006. This represents a decrease to only one third of the 1963–1976 value (Fig. 24). The period 1976–1987, estimated by ^{14}C methods as the date range of extensive tree deaths, coincides with the period when the number of flood days was very low. Until 1976, each successive flood regularly transported and deposited fine-grained materials (e.g., sandy silt) that could bear water from the upper reaches of the river, and the trees did not die. For 9 years, from 1977 to 1985, the number of flood days decreased to 27 in total (3.0 days/year). For six years, from 1980 to 1985, very little flooding occurred, and many trees died, presumably due to deficiency in deposition of the fine materials at shallow depth, as well as lowering of the groundwater level.

CONCLUSIONS

The reason behind extensive tree deaths along the Kuiseb River has been investigated since 2001. Tree deaths were concentrated on river banks where sands from dunes had been thickly redeposited by flooding. *Acacia erioloba* was abundant in these areas. Although *Faidherbia albida* germinated more commonly than *Acacia erioloba* on the river banks, the former was less likely to survive than the latter.

In an effort to explain the deaths of so many mature *Acacia erioloba*, the environmental conditions were analyzed. *Acacia erioloba* extends its main roots deep into the moist, fine-grained soil layer immediately after germinating and absorbs water through lateral roots there. When these seedlings become mature trees, they are likely to extend a great number of lateral roots in the shallow depth and absorb water seeping into the shallow layer of land. Fog often arises in the morning around Gobabeb, and the shallow roots absorb water brought by the fog.

Flooding occurred frequently until the early 1970s but has become less common since then. The groundwater level also dropped due to the decrease in flooding. Although successive floods used to bring and deposit fine-grained materials from the upper reaches of the river, such materials are becoming scarcer. It is reasonable to conclude that the cause of extensive tree death was a lack of water caused by this lack of deposition of fine materials and the attendant drop in the groundwater level, both of which made it difficult for the shallow tree roots to absorb water at its shallow depth.

The findings and considerations so far in this paper have implications for human activities in this area. The livelihood of the Topnaar people is highly dependent on the fragile forests along the Kuiseb River. Forests provide shade, firewood, and building materials to the people, and food to livestock. If flooding continues to decrease, it is likely that trees deaths will increase, which will negatively affect the livelihood of the local people.

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