Soil Characteristics of Rehabilitating and Unmined Coastal Dunes at Richards Bay, KwaZulu-Natal, South Africa

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Abstract

The postmining rehabilitation of coastal sand dunes north of Richards Bay (28°43′S, 32°12′E), South Africa, is resulting in the development of a series of known-aged stands of vegetation dominated by *Acacia karroo* (sweet thorn). Other broad-leaved species are establishing themselves in rehabilitating areas more than 12 years of age. Soils from rehabilitating stands 3–5, 9–12, 13–15, and 16–18 years of age, from two disturbed, unmined stands 30 and 58 years of age, and from a mature unmined stand were examined to assess age-related trends in selected soil properties. Individually, these stands represent a series of different developmental stages of a coastal dune successional sere. Soil organic material, percentage organic carbon and concentrations of sodium, potassium, magnesium, calcium, and nitrogen increased with an increase in habitat regeneration age. Concentrations of most of these elements were lower than those recorded on the 58-year-old unmined and mature unmined stands. Multivariate analyses suggest, however, that the similarity of these values for rehabilitating stands to those for the unmined stands increased with an increase in regeneration age. The growth response of *Raphanus sativus* (radish) plants, based on mass attained under experimental growing conditions in soil collected from these stands, suggests an increase in soil fertility with an increase in regeneration age.

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Introduction

The post-mining rehabilitation of dunes along the coast of KwaZulu-Natal some 16 km to the north of Richards Bay since 1977 has resulted in the development of a narrow strip of indigenous vegetation all along the mining path. Although the structure of these coastal dunes has been well described (Tinley 1985), the development of soil properties in the wake of the mining path or other disturbances has not been thoroughly investigated. But studies have been undertaken by Lubke et al. (1992) on rehabilitation at Richards Bay and by Scott et al. (1993) on the development of soil properties of rehabilitating stands in the Richards Bay area. Because soil is considered to be one of the primary agents in determining vegetation development, the importance of soil characteristics in ecological studies cannot be over-emphasized (Barbour et al. 1987). Studies have suggested that the availability of carbon, nitrogen, water, and phosphorous, to name but a few, may influence successional dynamics (Lloyd & Pigott 1967; Walker et al. 1981; Tilman 1986) and that these in turn may influence community structure (Tilman 1986). Studies of both primary (Lawrence et al. 1967) and secondary succession (Tilman 1983, 1986) have shown nitrogen especially to be a major limiting nutrient. Because nitrogen is known to increase with successional age (Tilman 1987), the quantity of nitrogen in the soil at any stage of the rehabilitation process may indicate the successional status of the soil. Also, a possible gradient in soil pH may be associated with succession because a decrease in pH due to leaching and the accumulation of weak organic acids is expected as vegetation development proceeds (Crawley 1986). It is therefore conceivable that quantitative, directional changes in soil properties over time following disturbance may indicate how these properties develop during the rehabilitation process.

This study is therefore aimed at examining soil properties of four coastal dunes undergoing between 3 and 18 years of rehabilitation following mining and at comparing these with soil properties of two adjacent unmined but disturbed forests of 30 and 58 years old, respectively, as well as with a mature forest of unknown age but at least 100 years old. Because humus, the main constituent of soil organic material (Williams 1987), consists primarily of decomposing plant material that continuously accumulates on the soil surface from which it is broken down and recycled into the top layer of soil, any changes in soil attributes taking place during succession should first be evident in the upper 10 cm. Thus, we sampled the upper 10 cm of the soil in four rehabilitating areas, two unmined but disturbed forests, and a mature forest at Richards Bay, and compared their soil properties.

Materials and Methods

Study Area

The study area where dune mining and rehabilitation is ongoing is situated about 16 km northeast of the coastal town Richards Bay (28°43′s, 32°12′E) and has been described by van Aarde et al. (1996*a*). It comprises a series of rehabilitating stands, varying in age from a few months to 18 years at the time of the study, adjacent to a 100–250–m–wide seaward belt of unmined coastal dune vegetation. Four of these rehabilitating stands undergoing between 3 and 18 years of regeneration were used in this study. Patches of sand dunes stripped of vegetation in preparation for mining as well as dunes being reshaped and prepared for rehabilitation also occur in the study area. Stands of unmined coastal dunes to the north of the mining operation comprise patches of forest which, based on the inspection of aerial photographs, had been cleared of all vegetation some 30–35 years prior to the present study. Some of these patches have been afforested with *Pinus elliottii* (flash pine) and *Eucalyptus grandis* (eucalyptus), while others, for unknown reasons, were recolonized by indigenous vegetation, mainly broad-leaved trees such as *Canthium inerme* (common turkey-berry), *Celtis africana* (white stinkwood), *Draceana aletriformis* (large-leaved dragon tree, dominant in the shrub layer), *Clausena anisata* (horsewood), *Peddiea africana* (poison olive), *Deinbollia oblongifolia* (dune soap berry), *Scutia myrtina* (cat-thorn), and *Teclea gerrardii* (Zulu cherry-orange). One of these 30–35 year old patches was also included in this study as a 30 year old disturbed, unmined forest.

Adjacent to the southern end of the rehabilitating path lies a patch of indigenous forest known as Ntongande which, according to aerial photographs, was stripped of all vegetation during 1937. Thus, at the time of the study this stand was 58 years old and was also included as a study site, referred to as the 58-year-old, disturbed unmined stand, Ntongande. To the north of the mining path lies a patch of dune forest, of unknown age but at least 100 years old, considered to be representative of a mature forest (Weisser & Marques 1979) and known as Zulti North (Fig. 1). This patch of dune forest was also included in the study and considered to be the mature study site.

The method of rehabilitation of mined dunes has been described by Camp (1990) and Lubke et al. (1992). The mechanical reshaping of dunes is followed by the spreading of a 10–15–cm layer of topsoil collected ahead of mining and after forest clearance to facilitate sand mining for rutile, zircon, and ileminite. Because the same procedure has been used to rehabilitate mined dunes in the area for the past 18 years, these mined dunes now comprise a sequence of known-aged stands of developing vegetation with young communities dominated by low-growing *Acacia karroo* (sweet thorn) shrubs and a ground cover primarily consisting of the grass *Dactyloctenium geminatum*. Rehabilitating stands older than 12 years can be described as woodlands dominated by *A. karroo*, with broad-leaved trees characteristic of the surrounding indigenous unmined forests establishing themselves. The oldest rehabilitating stands (18 years at the time of the study) are characterized by open patches forming in the woodland canopy as a result of *A. karroo* falling over. These patches are being colonized by broad-leaved species typical of mature forests, including *Sideroxylon inerme* (white milkwood), *Celtis africana*, *Mimusops caffra* (coastal milk redwood), *Vepris lanceolata* (white ironwood), and *Trichilia emetica* (Natal mahogany). On these older stands, the groundcover is dominated by the herb *Asystasia gangetica*, with the grass *Brachiaria chusqueoides* also well established (Camp 1990). A management policy of minimum interference is adhered to once the rehabilitation process has been initiated and involves the mechanical control of alien invasive plants (van Aarde et al. 1996*a*). The colonization of all rehabilitating stands by animals takes place of its own accord.

The soils of the area are typically alkaline and sandy, with low silt and clay content, and consist mainly of fine- and medium-grained sands (Scott et al. 1993). Soil development is considered to be slow in both the natural dune systems and the restored *Acacia* woodland (Avis 1992). The typical soil profile of vegetated coastal dunes comprises a variable layer between 2 mm and 10 cm of organic material or litter on an orthic A horizon underlain by regic sand (Tinley 1985; Scott et al. 1993). Little variation is observed in these coastal soil forms; coastal sand dunes are generally considered to be naturally deficient in both water and nutrient concentrations (Tinley 1985; Scott et al. 1993), except in the topsoil humus of vegetated dunes (Tinley 1985). It is therefore the soil attributes in the topsoil layer that are the subject of interest in this study. Because this study is purely descriptive, only structural characteristics of the top 10 cm of the soil profile will be considered.

Sampling Procedure

Soil samples (2500–3000 g per sampling point) were collected at a soil depth of 10 cm on three sampling occasions between February and October 1995 from four rehabilitating stands between 3 and 18 years of recovery

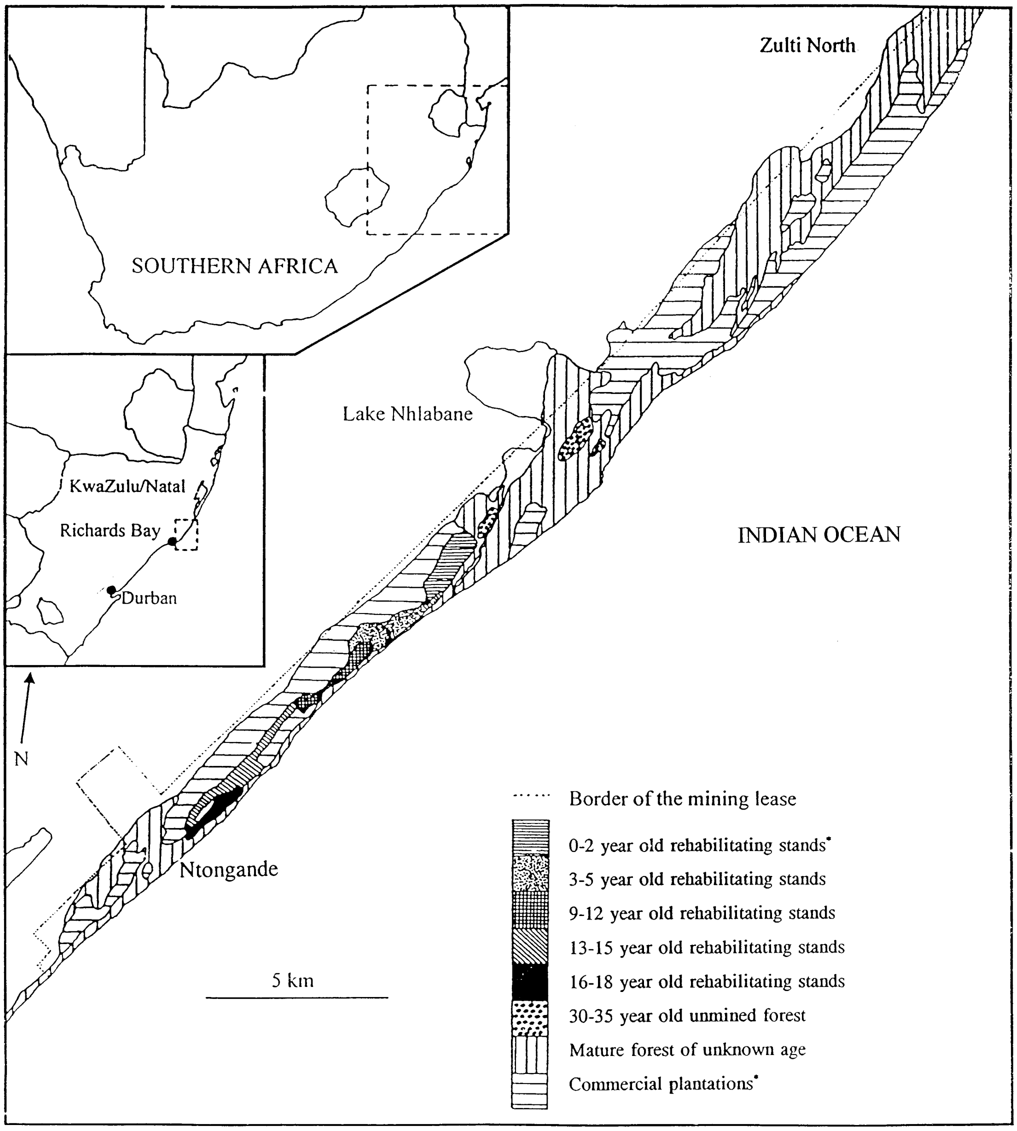

Figure 1. Map of the study area northeast of the coastal town Richards Bay (28°43′S, 32°12′E). Asterisk denotes areas not sampled. Modified from van Aarde et al. (1996*b*).

following mining, from a 30-year-old disturbed unmined stand, from a 58-year-old unmined stand (Ntongande), and from a stand of mature forest (Zulti North). Soils collected on the first two sampling occasions in February and May 1995 were used to determine soil macro characteristics (soil humus or soil organic material), whereas soils collected on the third sampling occasion in October 1995 were used to assess soil chemical characteristics (organic carbon, nitrogen, phosphorus, potassium, sodium, calcium, and magnesium). All sampling was conducted on the sea-facing slopes of the second dune from the coastline. Samples were collected on five randomly selected fixed-width transects (6 × 35 m) located during each of the sampling occasions on each of the stands. Each sample comprised six subsamples taken at different localities on each of the transects by means of a square corer (10 × 10 × 10 cm). These soil samples were stored in paper bags at room temperature (25°C) for three months until analyzed.

Soil Macro Characteristics

All samples were oven-dried overnight at 60°C prior to analyses. Percentage total organic content (%TotOrg) representing the decomposing plant material for each of the samples is expected as a percentage of the difference in a soil aliquot's weight prior to and after the burning thereof in a crucible over a bunsen burner for 30 minutes (Williams 1987). Percentage organic content representing the decomposing plant material less than 2 mm in particle size (%Org < 2 mm) and greater than 2 mm in particle size (%Org > 2 mm) was determined similarly after aliquots were passed through a 2-mm sieve. To determine pH of the soil, a 10-g sample was mixed with distilled water in a 1:2 ratio of soil (dry weight) to water and the pH of the water recorded with a pH metre.

Chemical Analyses

The determination of carbon (C), calcium (Ca), organic nitrogen (N), potassium (K), magnesium (Mg), sodium (Na), and phosphorus (P) concentrations in each of the samples followed the procedures suggested by Moore and Chapman (1986) and The Non-affiliated Soil Analysis Working Committee (1990). Calcium and Mg content was determined by atomic absorption spectroscopy, whereas K and Na were determined by flame emission spectroscopy. Organic carbon was determined by the Walkley-Black method. Nitrogen was determined by the Kjeldahl method of digestion by sulphuric acid. Nitrite is seldom present in detectable amounts (The Non-Affiliated Soil Analysis Working Committee 1990) and therefore was not included in the analysis.

Soil Fertility

Soil fertility was assessed by determining the growth response of *Raphanus sativus* (radish) seeds planted in aliquots of soil from each sample taken from the upper 10 cm in the four rehabilitating stands, the 30-year disturbed stand, and the mature forest (100 years) and grown in an outdoor planthouse. One hundred aliquots of 300 g each of soil from each stand were placed in 250-ml styrofoam cups, and a randomly selected seed was planted in each of these at 1-cm soil depth, resulting in 100 replicates per stand. Each pot received the same amount of distilled water daily (80–100 ml) as needed to prevent drying and was exposed to the same temperature (~28°C) and sunlight. Radishes were allowed to grow for 27 days, after which they were harvested, cleaned by washing, oven-dried at ~60°C for two days, and weighed. Total plant weight, tuber weight (part of plant between first root hair and base of stem), and leaf weight (part of plant above base of stem) were recorded separately.

Statistical Analysis

Samples collected during the first and second sampling occasions were used in the analyses of soil macro characteristics (organic material) and were considered separately to determine whether differences existed between the sampling occasions using a Student's *t* test (Sokal & Rohlf 1981). Soil macro variables that did not differ between sampling occasions were grouped together and subjected to a one-way analysis of variance (ANOVA; Sokal & Rohlf 1981) to assess interstand differences. Data not characterized by homogeneous variances (Bartlett's test; Sokal & Rohlf 1981) were log- and fourth-root transformed; in all cases Tukey multiple range test at $p < 0.05$ was used to determine which stands differed from one another. For those variances that were heterogeneous even after transformations, a minimum significance difference test (MSD; Sokal & Rohlf 1981) was performed to elucidate differences between stands. Significance was taken at the 95% level.

Only samples collected during the third sampling occasion were used to assess soil chemical variables, and these were subjected to nonparametric Kruskal-Wallis tests (Kruskal & Wallis 1952) to determine significant differences between stands. Mann-Whitney *U*-tests (Sokal & Rohlf 1981) were used to elucidate which stands differed from each other.

Multiple dimensional scaling (MDS; Ludwig & Reynolds 1988) using Bray-Curtis similarity indices (Bray & Curtis 1957) was used to ordinate all sites based on soil chemical variables (organic C, N, Na, K, P, Ca, Mg) in a two-dimensional component space. Data from the third sampling occasion were used. Analysis of similarity (ANOSIM; Clarke & Green 1988) was used to test whether within-stand similarities were higher than between-stand similarities, based on soil chemical variables. Significance was taken at the 95% level.

Results

Organic Material

Sampling occasion had no influence on %Org < 2 mm, %Org > 2 mm, and %TotOrg on any of the stands (Table 1). Stand age also did not influence %Org > 2 mm ($F_{(5,52)}$ 5 1.42), but %Org < 2 mm did differ between stands ($F_{(5,52)} = 10.88$; $p < 0.01$), with the value for the youngest (3–5 years) rehabilitating stand (lowest organic content) differing significantly from that for the oldest (16–18 years) rehabilitating stand (higher organic content). The 30-year-old stand and the youngest, second-youngest (9–12 years), and second-oldest (13–15 years) rehabilitating stands did not differ significantly from one another (Tukey multiple range test). Significant differences existed for this variable between the mature unmined stand (ZN) and the youngest and second-youngest rehabilitating stands (Fig. 2).

Significant differences furthermore existed between stands for %TotOrg ($F_{(5,52)} = 8.75$; $p < 0.01$), with values for the youngest and oldest rehabilitating stands, the 30-year-old unmined stand and the youngest and second-oldest rehabilitating stands, Zulti North and the rehabilitating stands less than 15 years old differing from each other (Tukey multiple range test). The unmined stands did not differ significantly from the oldest rehabilitating stand (Tukey multiple range test). Overall, or-

Table 1. Percentage soil organic content (mean ± SD) recorded during February 1995 and May 1995.

Stand Age in Years	*February*	*May*	t *Value*	df	p
	Organic content < 2 mm				
3–5	0.69 ± 0.11	0.72 ± 0.19	−0.35	8	0.74
9–12	0.91 ± 0.20	1.03 ± 0.50	−0.47	8	0.65
13–15	1.16 ± 0.97	0.89 ± 0.31	0.59	8	0.57
16–18	1.86 ± 0.96	1.25 ± 0.42	1.29	8	0.23
30	1.57 ± 0.71	2.55 ± 2.37	−0.79	7	0.46
>100	2.57 ± 1.21	2.31 ± 0.51	0.45	7	0.67
	Organic content > 2 mm				
3–5	0.12 ± 0.05	0.08 ± 0.06	0.59	8	0.57
9–12	0.39 ± 0.48	0.30 ± 0.53	0.28	8	0.79
13–15	0.25 ± 0.31	0.14 ± 0.12	0.73	8	0.48
16–18	0.16 ± 0.12	0.23 ± 0.16	−0.76	8	0.47
30	0.22 ± 0.08	0.25 ± 0.26	−0.21	8	0.84
>100	0.30 ± 0.27	0.30 ± 0.26	0.00	8	0.99
	Total organic content				
3–5	0.80 ± 0.10	0.81 ± 0.23	−0.13	8	0.90
9–12	1.30 ± 0.55	1.33 ± 0.83	−0.06	8	0.96
13–15	1.41 ± 1.27	1.04 ± 0.43	0.63	8	0.55
16–18	2.02 ± 0.95	1.48 ± 0.55	1.09	8	0.31
30	1.80 ± 0.68	2.80 ± 2.35	−0.82	7	0.44
>100	2.87 ± 1.40	2.61 ± 0.69	0.37	7	0.72

ganic content increased with an increase in regeneration age of stands exposed to mining.

Soil Chemical Variables

All chemical variables assessed during this study differed significantly between stands (Kruskal-Wallis test, $p < 0.01$; Table 2). Nitrogen concentration increased gradually with regeneration age, but values on mined stands were significantly lower than those on unmined stands, except for the 30-year-old unmined stand, which also differed significantly from other unmined stands (Table 2).

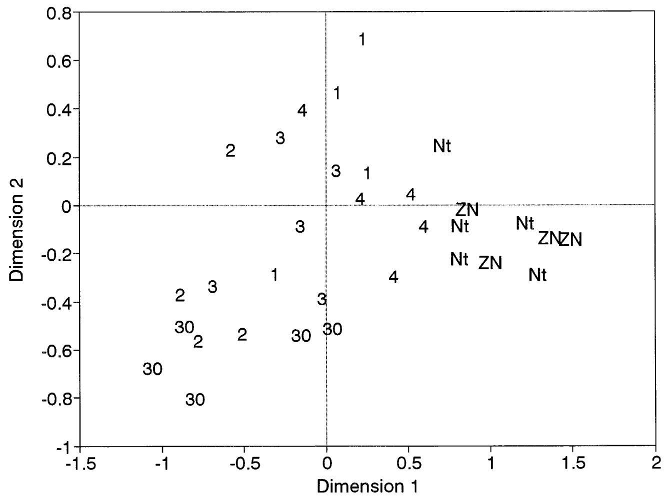

Figure 2. The ordination of rehabilitating and unmined stands for soil chemical variables using multiple dimensional scaling. 1, 3–5 year old rehabilitating stands; 2, 9–12–year–old rehabilitating stands; 3, 13–15–year–old rehabilitating stands; 4, 16–18–year–old rehabilitating stands; 30, 30-year-old unmined forest; Nt, 58-year-old (Ntongande) forest; ZN, Zulti North.

Although the percentage of C for the youngest rehabilitating stand was higher than that for the second youngest stand (Table 2), thereafter C increased with an increase in regeneration age of mined stands. Mann-Whitney *U*-tests showed significant differences between all rehabilitating stands and unmined stands, although rehabilitating stands 1 and 2 and stands 1 and 3 did not differ significantly from one another (Table 2). The mean values for stand 3 and the 30-year-old stand and for stand 1 and the 30-year-old stand also did not differ significantly from each other (Table 2). The mean values for the 58-year-old and mature unmined stands were significantly higher than the highest value recorded for rehabilitating mined stands (Table 2).

Phosphorus concentrations (mg/kg) of samples differed between stands (Table 2), with significant differences between mined rehabilitating stands, except for

Table 2. Mean ± SD of soil chemical variables of rehabilitating and unmined stands of different ages.

	n	*pH*	*P (mg/kg)*	*Ca (mg/kg)*	*Mg (mg/kg)*	*K (mg/kg)*	*Na (mg/kg)*	*N (mg/kg)*	*C (%)*
Stand 1 (3–5 years old)	5	7.75 ± 0.52[a]	22.35 ± 6.15[b]	1001 ± 327[ab]	64.65 ± 10.95[bc]	39.68 ± 9.69[ab]	20.30 ± 3.26[ab]	440 ± 218[a]	0.54 ± 0.33[ab]
Stand 2 (9–12 years old)	5	6.36 ± 1.05[ab]	9.93 ± 3.30[ac]	370 ± 139[c]	47.96 ± 9.17[b]	27.62 ± 10.67[a]	15.10 ± 3.96[b]	489 ± 133[a]	0.46 ± 0.13[b]
Stand 3 (13–15 years old)	5	7.08 ± 0.57[a]	16.39 ± 2.05[b]	690 ± 243[b]	57.90 ± 7.26[b]	32.38 ± 5.65[ab]	17.10 ± 4.69[bc]	569 ± 184[a]	0.69 ± 0.16[a]
Stand 4 (16–18 years old)	5	7.12 ± 0.52[a]	11.43 ± 1.79[ac]	1103 ± 215[a]	83.42 ± 8.71[ac]	29.28 ± 4.18[a]	24.04 ± 3.39[ac]	833 ± 343[ab]	1.10 ± 0.26
Disturbed stand (30 years old)	5	5.76 ± 0.13[b]	3.25 ± 0.85	302 ± 201[c]	93.66 ± 23.60[ac]	42.62 ± 9.56[b]	16.88 ± 2.22[b]	643 ± 216[a]	0.75 ± 0.18[a]
Ntongande (58 years old)	5	7.26 ± 0.40[a]	13.20 ± 5.38[abc]	1650 ± 322[d]	188.10 ± 43.46[d]	170.4 ± 203.5	41.66 ± 18.71[a]	1409 ± 459[bc]	1.82 ± 0.22[c]
Zulti North (mature)	4	7.50 ± 0.53[a]	11.35 ± 4.80[ac]	1934 ± 418[d]	176.90 ± 34.51[d]	52.98 ± 17.36[b]	33.96 ± 9.63[a]	1899 ± 479[c]	2.01 ± 0.52[c]
Kruskal-Wallis test (H(6,N) = 34) $p < 0.01$		16.94	22.39	28.62	28.96	21.94	23.14	19.62	26.92

For each stand, means within a column followed by the same letter are not significantly different ($p < 0.05$; Mann-Whitney *U*-tests). n = sample size.

stands 1 and 3 and stands 2 and 4. The lowest concentration of P was recorded on the 30-year-old stand, which differed significantly from all rehabilitating stands and the other unmined stands (Table 2). The highest concentration of P was recorded in the youngest rehabilitating stand.

Calcium concentrations (mg/kg) differed significantly between stands, with the youngest rehabilitating stand having a significantly higher concentration of this element than the second-youngest rehabilitating stand (Table 2) but a lower concentration than the oldest rehabilitating stand, from which it did not differ significantly. Calcium concentrations were lowest in the 30-year-old stand, which differed significantly from all stands except the second-youngest stand. Higher concentrations of this element than that recorded in any of the rehabilitating stands occurred in the 58-year-old Ntongande, with the highest concentrations in Zulti North (Table 2).

Magnesium concentrations (mg/kg) were higher in the youngest rehabilitating stand than in the second-youngest stand, with values increasing towards that recorded in the oldest rehabilitating stand but not attaining that recorded for the unmined stands (Table 2).

The highest concentration of K (mg/kg) was recorded for samples from the 58-year-old unmined stand (Ntongande), with this value significantly different from the mature, unmined Zulti North (Table 2). Values for both these unmined stands differed significantly from those for mined stands, except for Zulti North and the rehabilitating stands 3–5 and 13–15 years old, which did not differ significantly (Table 2).

Sodium concentrations (mg/kg) were also higher on the youngest rehabilitating stand than on the second-youngest stand, with concentrations increasing from the second-youngest stand to the oldest rehabilitating stand. The highest concentrations were recorded on the unmined stands (Table 2), but values for the 30-year-old stand were lower than those for the oldest mined stand and comparable to values for mined stands 9–12 and 13–15 years of age. Sodium concentrations on the oldest rehabilitating stand were lower than those on the unmined, mature stands but did not differ significantly from them (Table 2).

pH values measured across all stands varied with two points but were similar for stands 3–5, 13–15, and 16–18 years old as well as for Ntongande (58 years) and Zulti North (mature) (Table 2). The pH was, however, significantly lower for samples from the 30-year-old disturbed, unmined stand than those recorded from the other stands, except the 9–12 year old stand (Table 2).

Multiple dimensional scaling resulted in a separation of some stands, with the oldest rehabilitating stand (stand 4) grouped closest to the unmined stands (Ntongande and Zulti North), but not completely separated from the younger rehabilitating stands (Fig. 2). But significant differences still existed between the oldest rehabilitating stand and the unmined forests, as shown by ANOSIM (Table 3). The younger rehabilitating stands (stands 2 and 3) were more similar to each other and to the 30-year-old unmined stand than to the other stands (Fig. 2). This was also confirmed by ANOSIM, which showed the oldest rehabilitating stand to be significantly different from stands 2 and 3 and the 30-year-old stand (Table 3).

Soil Fertility

Mean individual weight of radish plants increased with an increase in regeneration age of mined stands, and values for the 30-year-old stand were higher than those for any of the soils sampled on the rehabilitating stands (Table 4). The highest mean weights, however, were recorded for plants grown in sand from the mature, unmined stand at Zulti North.

Discussion

The rehabilitation of mined sand dunes in the study area is resulting in the development of a known age se-

Table 3. Results of pairwise comparisons (ANOSIM) between stands using all soil chemical variables.

	Rehabilitating Stands (Years)				*Unmined Stands*		
	Stand 1 (3–5)	*Stand 2 (9–12)*	*Stand 3 (13–15)*	*Stand 4 (16–18)*	*Disturbed (30 Years)*	*Ntongande (58 Years)*	*Zulti North (Mature)*
Stand 1		0.60	0.10	0.17	0.58*	0.82*	0.90*
Stand 2			0.28	0.94*	0.04	1.00*	1.00*
Stand 3				0.33*	0.39*	0.98*	1.00*
Stand 4					0.70*	0.48*	0.64*
Disturbed						0.95*	0.96*
Ntongande							−0.10
Zulti North							

*Denotes significance at the 95% level.

Table 4. Mean ± SD of dry weight (mg) of radish plants grown on soils collected from different stands.

Stand	*Age in Years (No. of Plants)*	*Mean ± SD Weight (mg)* Total	Leaf	Tuber
1	3–5 (88)	0.05 ± 0.01	0.04 ± 0.01	0.01 ± 0.00
2	9–12 (94)	0.06 ± 0.02	0.05 ± 0.02	0.01 ± 0.01
3	13–15 (85)	0.06 ± 0.02	0.05 ± 0.01	0.01 ± 0.01
4	16–18 (93)	0.07 ± 0.03	0.05 ± 0.02	0.02 ± 0.01
Disturbed	30 (92)	0.10 ± 0.03	0.08 ± 0.03	0.02 ± 0.01
Zulti North	Mature (99)	0.14 ± 0.04	0.10 ± 0.03	0.03 ± 0.01

ries which, with the unmined stands of known age, represent a coastal dune successional sere (Lubke et al. 1992; Mentis & Ellery 1994; van Aarde et al. 1996*b*). This also provides a gradient along which the development of the soil profile, together with the accumulation of elements and the enrichment of soils, can be studied. Earlier studies of both topsoil and subsoil from pre-mining indigenous coastal forests at Richards Bay as well as post-mining rehabilitating areas (Lubke et al. 1992) showed that concentrations of base elements such as phosphorus, sodium, and calcium in topsoil and subsoil from pre-mining areas and post-mining tailings in the study area were similar to those in the soil of rehabilitating areas. Our study shows an increase in concentrations of elements in the soil with regeneration age of stands exposed to mining, while values for a 30-year-old disturbed unmined stand tended to be lower than those recorded for mined and other unmined stands. Phosphorus did not follow this age-related trend, however, but rather fluctuated in concentration. Phosphorus primarily accumulates in soils as a result of microbial activity and, although organic phosphorus may be absorbed by plants directly, it becomes available through mineralization to organic phosphorus (Dalal 1977). Phosphorus moves slowly through soils (Blair 1976), and variable quantities in soils may result from variable microbial activity (Clark & Rosswall 1981) as well as mineralization.

All elements but nitrogen occurred at higher concentrations in the soil of the youngest rehabilitating stand than in the soil from the second-youngest stand. This is not surprising because the topsoil in the youngest rehabilitating stand comprises much of the topsoil collected prior to mining and spread over the dunes to induce rehabilitation. The trend in nitrogen concentration may be ascribed to its depletion by fast-growing annuals and grasses. Despite the age-related increase in nitrogen concentrations, absolute values on mined stands were much lower than those on unmined stands and those recorded in other biomes (Tilman 1987; Stock et al. 1995). Even though the unmined stands had much higher levels of nitrogen than the rehabilitating stands, the levels of nitrogen in the unmined stands are not considered high. Low levels of nitrogen in these stands are therefore not surprising, particularly when considering that dynamic models predict that it can take 100 years for nitrogen concentrations to change from low to high on nutrient-poor soil (Tilman 1985).

Our study indicates that nitrogen, carbon, calcium, magnesium, and potassium concentrations are changing directionally with regeneration age, suggesting that the availability of these elements in rehabilitating stands are increasing with time. This suggested age-related increase in soil fertility is supported by the radish growth trial, which indicated an increase in plant biomass with soil age.

The relatively high growth rate of *Acacia karroo* which dominates all the mined rehabilitating stands could conceivably affect nutrient turnover (Vitousek & Walker 1989; Stock & Allsopp 1992). Like other *Acacia* species, *A. karroo* has the ability to fix nitrogen (Barnes & Fagg 1995) and thus may enrich surface soils. Stock et al. (1995) noted that phosphorus was not enhanced in *Acacia*-invaded ecosystems, which is consistent with our study. But Stock et al. (1995) did not record an age-related accumulation of nitrogen for areas invaded by the exotic *Acacia cyclops* (rooikrans) and *Acacia saligna* (Port Jackson willow).

The low levels of nitrogen on rehabilitating stands suggest that nitrogen mineralization rates may be low, which may make *A. karroo* more dependent on nitrogen fixation. Plants that cannot fix nitrogen may therefore be unable to colonize these nitrogen-poor sand dunes as effectively as *A. karroo*. This is in agreement with Tilman's (1982) suggestion that the greater ability of early successional species to acquire nitrogen and grow in nitrogen-poor soils is due to their superior ability to compete for soil nitrogen. The relatively low concentrations of most elements on the 30-year-old unmined stand were associated with a lower pH. This may be due to exotic pine trees growing on this stand, because invasive pines are known to alter the spatial distribution of nutrients within an ecosystem (Musil & Midgley 1990).

The regeneration of these dunes is associated with an increase in litterfall and accumulation. This will conceivably alter nutrient and organic matter input into the soil (Witkowski & Mitchell 1987), as we recorded. Scott et al. (1993) failed to detect any clear trends in the accumulation of organic matter content with stand age, probably due to limited sample size and their study being conducted on the B horizon, which is below the topsoil layer. Changes in soil properties are much slower in the B horizon and therefore take longer to detect.

Decomposition and nutrient cycling processes may be enhanced in the older rehabilitating stands, which would be consistent with suggestions of feedback processes between plant species and soil nutrient dynamics (Vitousek & Walker 1989; Wedin & Tilman 1990). To allow predictions of this nature, however, nutrient turnover rates need to be addressed, which would involve determining decomposition and nitrogen mineralization rates to identify patterns of soil nutrient release.

Our findings are consistent with those of previous studies of nutrient enrichment of surface soils during succession. Because a unidirectional quantitative change of soil characteristics is occurring on the rehabilitating stands over time, our study supports the notion that soil properties are developing on this sere of coastal dune forest. Thus, with time following disturbance and without further disturbance, soil properties of rehabilitating areas may approach those of surrounding unmined forests in the Richards Bay area. Our study further suggests that *A. karroo* in particular, with its ability to grow at low nitrogen levels, may be an important component driving the vegetation development in the rehabilitating stands at Richards Bay, influencing changes in soil characteristics in tandem with those tree species that are becoming established in openings within 18-year-old *A. karroo* woodland (van Dyk 1997). We therefore echo Tilman's (1986) suggestion that the ability of plants to grow at low nitrogen levels may be an important determinant of the sequence of succession on nitrogen-poor soils. We further note that the concentrations of elements other than potassium on the 58-year-old stand were very similar to those recorded on the mature stand, suggesting that full recovery of these elements may occur within a relatively short time.

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