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Recovery of topsoil physicochemical properties in revegetated sites in the sand-burial ecosystems of the Tengger Desert, northern China

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Abstract

Recovery in soil properties and processes after sand burial in the Tengger Desert, northern China, was documented at five different-aged revegetated sites (1956, 1964, 1973, 1982, and 1991) and at a reference site with native vegetation, which had never been damaged by sand burial and was enclosed for grazing. The proportions of silt and clay, depth of topsoil and biological soil crusts, and concentrations of soil organic C, K, total N and total P increased with years since revegetation. Most characteristics of topsoil (0–5 cm) characteristics had recovered to 60% of those measured at the reference site by 50 years after sand-binding vegetation had been established. Exceptions were electrical conductivity and contents of sand, silt, $CaCO_3$ and organic C, which recovered to 20–40% of the values at the reference site. The difference in annual recovery rates of soil properties between the two most recently revegetated sites (0–14 years) was greater than the difference between the two oldest revegetated sites (43–50 years). Best-fit asymptote models showed that the estimated times for the soil properties in the 50-year-old site to reach the same levels as in the reference site (i.e. an undisturbed, native steppified desert ecosystem) would be between 23 and 245 years, but for some properties even maximum recovery after >50 years still fell significantly short of the level at the reference site. These results suggest that soil recovery is a slow process in an extremely arid desert environment, and therefore the conservation of soil habitat is a crucial issue for land managers.

Keywords: Revegetation; Soil nutrients; Sand burial; Desert ecosystems; Chronosequence; Restoration

1. Introduction

Sand burial is a major cause of environmental damage in the Chinese arid environments associated with wind erosion, and it may result in the conversion of steppe to sandy desert. In recent centuries, large areas of desert steppe in the south fringe of the Tengger Desert in northern China have been covered by mobile sand dunes due to the southward extension of the dunes (Li et al., 2004a). Such changes have been particularly fast in the Shapotou–Hongwei region of the Ningxia Hui Autonomous District. In northern China, revegetation is one of the most effective approaches to protect steppe from sand burial (Zhang and Zhao, 1989; Gao et al., 2002). In order to protect a 40-km segment of the Lanzhou–Baotou railway line in the Shapotou–Hongwei region, a 16-km-long vegetation protection system was

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established in 1956, with a width of 500 m to each side of the railway (Shapotou Desert Research Station, 1991; Li et al., 2003). Initially, a sand barrier was established using woven willow branches or bamboos to reduce wind erosion. Behind the sand barrier, straw checkerboards have been built of wheat or rice straw, usually 1 m^2 in area, which remain intact for 4–5 years, helping the planted xerophytic shrubs to adapt to an environment with wind erosion. Straw checkerboards at a height of 0.15–0.2 m above the ground increase the roughness of the sand surface 400–600 times, and reduce wind velocity by 20–40% at a height of 0.5 m above the surface, and by 10% at 2 m (Zou et al., 1981; Fullen and Mitchell, 1994). The quantity of sand transported over a straw checkerboard is only 1% of that blown over an uncovered mobile sand dune (Zhu et al., 1992). Xerophytic shrub seedlings such as *Artemisia ordosica* Krasch, *Caragana korshinskii* Kom., *C. microphylla* Lam., *Calligonum mongolicum* Turc'z, *Atraphaxis bracteata* A. Los, *A. pungens* Jaub. et Spach., *Elaeagnus angustifolia* L., *Salix gordejevii* Y. L. Chang, and *Hedysarum scoparaium* Fisch. were planted within the checkerboard and they grew without irrigation (Li et al., 2003). The stabilized area was further expanded in 1964, 1973, 1982, and 1991, using the same revegetation methods, namely planted 2-year-old seedlings of xerophytic shrubs with the same density (16 individuals per 100 m^2; Shapotou Desert Research Station, 1991). These rehabilitation methods have changed mobile dunes to stable productive ecosystems. Fifty years after the establishment of sand-binding vegetation cover, more than ten additional species have colonized the area, and vertebrates have increased from two to more than 30 species (Li et al., 2004b). It is a challenge for us to learn how to evaluate the patterns and processes of ecological restoration by revegetation, particularly the recovery rate of soil characteristics. However, almost no information about this issue is available for Chinese desert regions.

A chronosequence of recovery sites covering a period of 50 years and adjacent enclosed native vegetation sites in the Shapotou–Hongwei region of the Tengger Desert allowed us to study the pattern of soil restoration because monitoring the same area or region through time is normally considered the most reliable way of measuring change (Powlson et al., 1998). The rate of topsoil formation is important for assessing soil recovery after disturbances (Selbold et al., 1999), including soil loss due to soil erosion (Lal, 1994; Lepper and Scott, 2005) and landslip (Sparling et al., 2003). A number of soil parameters associated with the formation of topsoil, such as biochemical properties, chemical (organic C, total C, total N, pH) and physical (soil depth, bulk density, particle size distribution) characteristics (Singh et al., 2001; Duan et al., 2004) and soil depth (Trustrum and De Rose, 1988) were used to determine the rate and extent of soil recovery. The objectives of this study are (1) to measure various soil properties at different sites with different ages, (2) to estimate the rates of recovery of soil chemical and physical characteristics in a 50-year chronosequence of revegetation sites in comparison with native vegetation sites, and (3) to evaluate the potential capacity of restoration in such an extreme habitat. This study will contribute to our understanding of ecological restoration by the establishment of vegetation in extremely arid desert systems.

2. Study sites and methods

2.1. Study site

This study was conducted in the Shapotou–Hongwei region, located at the southeastern fringe of the Tengger Desert (37°32′–37°26′ N, 105°02′–104°30′ E; Fig. 1), with an altitude range of 1300–1350 masl. The study area exhibits a typical ecotone between steppe and sandy deserts (Li et al., 1998). According to local meteorological records for years between 1956 and 2005, mean annual temperature is 10.0 °C, mean January temperature is −6.9 °C and mean July temperature is 24.3 °C. There are 2730 sunshine hours per year in average, and the duration of the plant growing season is 150–180 days. Mean annual precipitation is 180.2 mm and about 80% of this falls between May and September. Annual potential evaporation is about 2900 mm. Groundwater may exist at a great depth (e.g. 80 m) and is not available to support large areas of natural vegetation cover. Hence, precipitation is usually the only source of water for plant growth. The main soils are Orthic Sierozem and aeolian sandy soil (FAO/UNESCO, 1974; Chen et al., 1998). The zonal vegetation belongs to the transitional type between desert and steppe. The predominant plants are semishrubs, shrubs, forbs, and grasses, and include *Remuria soongorica* Maxim, *Salsola passerina* Bunge, *Oxytropis aciphylla* Ledeb., *Caragana korshinskii* Kom., *Ceratoides lateens* Reveal et Holmgren, *Stipa breviflora* Griseb., *Carex stenophylloides* Krecz, and *Cleistogenes songorica* Ohwj. There are two types of azonal vegetation: the psammophilous series and the hygrophilous series. The former develops in the dune area, and consists of psammophytes such as *Agriophyllum squarrosum* Moq, *Psammochloa cillosa* Bor, *Artemisia sphaerocephala* Krasch, *A. ordosica*

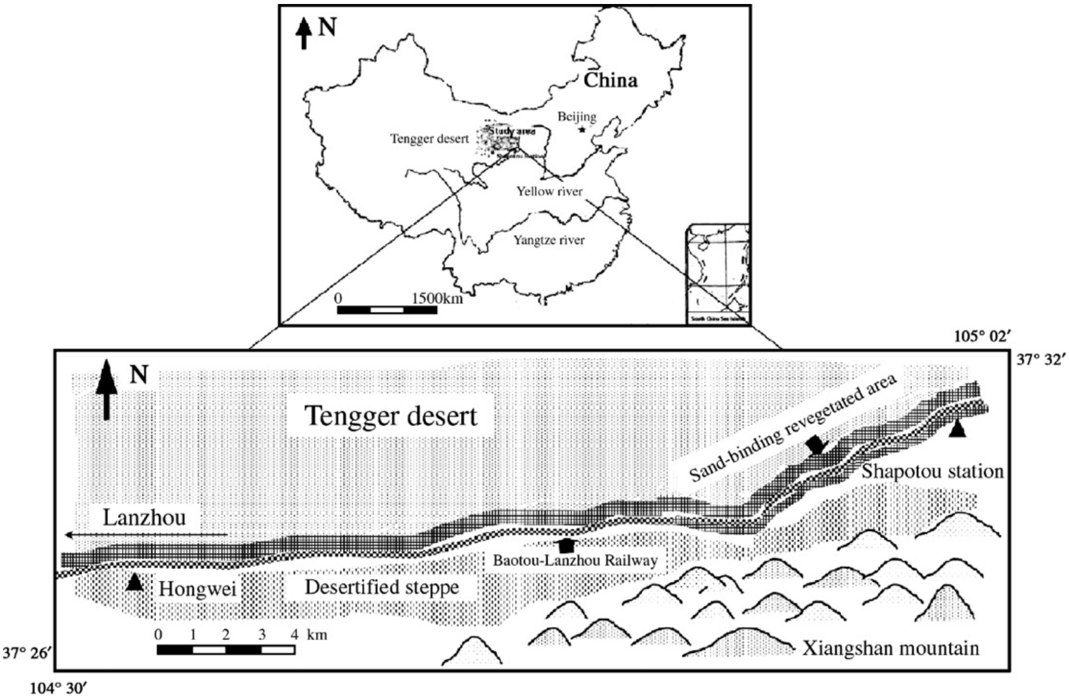

Fig. 1. Diagram showing the study area along the Baotou–Lanzhou railway at the Shapotou region of the Tengger Desert, China.

Krasch, and *Hedysarum scoparium* Fisch. They scatter on the dunes or aggregate in the interdune depressions with extremely variant cover ratios ranging from less than 1% to 30% (Shapotou Desert Research Station, 1991). Biological soil crusts (cyanobacteria crusts) began to colonize on the dune surface once the sand dunes had been stabilized by the establishment of straw checkerboards and revegetation; then they were converted to lichen and moss crusts (Li et al., 2003). This process enhanced the development of topsoil on the dune surfaces in the Tengger Desert (Li et al., 2004a).

We investigated five sites revegetated in 1956, 1964, 1973, 1982, and 1991, respectively, and a reference site with undegraded native vegetation (Fig. 2). Vegetation traits, including establishment of sand-binding vegetation, dominant plant species, shrub cover, and herbaceous cover for these sites are given in detail in Table 1.

2.2. Methods

Because the sites with different ages were stabilized using very similar approaches, including planting shrub seedlings of the same species with the same density in similar straw checkerboards (see Table 1), they can represent the different successional stages of sand-binding vegetation. Therefore, we chose the commonly applied method, space for time substitution, which assumes that the simultaneous sampling of different

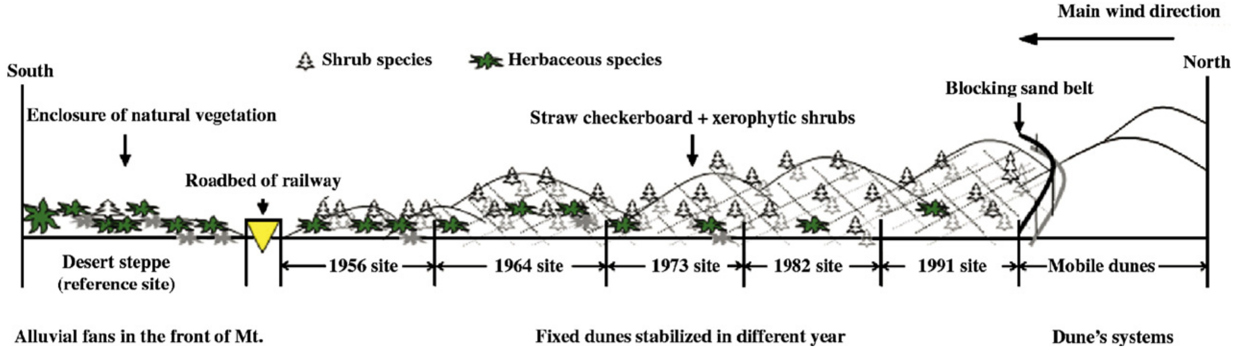

Fig. 2. Schematic description of the study site in the Shapotou–Hongwei region of the Tengger Desert, northwestern China.

sites of different ages is equivalent to resampling the same site through time. Thus, soil water contents were measured for each different-aged site in 2005. For comparison, soil water contents of both mobile dunes and the reference site were also measured. Soil samples were collected manually with a core sampler, and dried in the laboratory at 105 °C for 24 h. Measurements of the soil sample weight before and after drying gives the soil water content in gravimetrical terms (Nanjing Institute of Soil Research, 1980). Soil samples with 10 replications were taken randomly from the interdunes of each site two weeks after the rainfall in September 2005; then soil depth, including the thickness of the biological soil crust, was measured at each sampling place.

Measurement of soil parameters involved soil sampling (10 replications) at depths of 0–5 cm in interdunes at each site during the growing season of 2005. Air-dried soil samples were sieved through a 2-mm mesh screen and used for further analysis. Particle size was analyzed by the pipette method (Agriculture Chemistry Specialty Council, Soil Science Society of China, 1983); soil bulk density was determined by inserting a metallic cutting ring of known internal volume (5 cm in depth and diameter) in the soil and thereafter dry weight of a unit volume of soil was estimated (Liu, 1996). Maximum water-holding capacity (WHC) was also estimated by using the same cutting ring with intact soil. The soil cutting ring was closed at one end with a fine mesh and open at the other

Table 1
The description of five different aged sites of revegetation, and control site (mobile dunes) and the reference site of restoration, located in the southeastern fringe of the Tengger Desert, Northern China

Age of site investigated in 2005 (year of revegetation)	Approaches to sand stabilization and revegetation	Remaining shrub species of revegetation in 2005	Native/invasion dominant plant species	Shrub cover (herbaceous cover) (%)
Mobile dunes (0)	No	No	*Hedysarum scoparium*, *Agriophyllum squarrosum*	1 (<1)
14 (1991)	Straw-checkerboard of 1 m^2 and planted 10 xerophytic shrubs with allocation density of 16 individuals per 100 m^2	*Amorpha fruticosa*, *Artemisia ordosica*, *A. sphaerocephal*, *Caragana korshinskii*, *C. microphyll*, *Calligonum arboresscens*, *Hedysarum scoparium*	*Hedysarum scoparium*, *Agriophyllum squarrosum*, *Bassia dasyphylla*, *Echinos gmelinii*, *Eragrostis poaeoides*	22 (12)
23 (1982)	Similar to 14-years old site	*Artemisia ordosica*, *Caragana korshinskii*, *C. microphyll*, *Hedysarum scoparium*	*Artemisia ordosica*, *Hedysarum scoparium*, *Bassia dasyphylla*, *Eragrostis poaeoides*, *Corispermum patelliforme*	20 (21)
34 (1973)	Similar to 14-years old site	*Artemisia ordosica*, *Caragana korshinskii*, *Hedysarum scoparium*	*Artemisia ordosica*, *Hedysarum scoparium*, *Bassia dasyphylla*, *Eragrostis poaeoides*, *Corispermum patelliforme*, *Sonchus arvensis*, *Scorzonera mongolica*	12 (20)
43 (1964)	Similar to 14-years old site	*Artemisia ordosica*, *Caragana korshinskii*, *Hedysarum scoparium*	*Artemisia ordosica*, *Bassia dasyphylla*, *Eragrostis poaeoides*, *Sonchus arvensis*, *Scorzonera mongolica*, *Euphorbia humifusa*	9 (19)
50 (1956)	Similar to 14-years old site	*Artemisia ordosica*, *Caragana korshinskii*, *Hedysarum scoparium*	*Artemisia ordosica*, *Scorzonera mongolica*, *Sonchus arvensis*, *Chloris virgata*, *Aristida adscensionis*, *Setaris viridis*, *Bassia dasyphylla*, *Chenopodium aristatum*	9 (40)
Reference site	Enclosure for grazing	No	*Artemisia ordosica*, *Caragana korshinskii*, *Lespedeza davurica*, *Ceratoides lateens*, *Oxytropis aciphylla*, *Stipa breviflora*, *Carex stenophylloides*, *Cleistogenes sogorica*, *Allium mongolicum*, *Oxytropis myriophylla*, *Enneapogom brachystachyus*, *Aparagus gobicus*	20(45)

end, and was saturated with water for 6 h. Then the surplus water was sucked off using a sand-bed, and the remaining water in the soil represented the maximum WHC (Öhilinger, 1996). Soil pH was determined in a soil–water mixture with a ratio of 1:5. Soil organic carbon (SOC) was determined by the dichromate oxidation method of Walkley–Black (Nelson and Sommers, 1982).

Total N was measured using a Kjeltec System 1026 distilling unit (Tecator AB, Höganäs, Sweden). Soil phosphorus (P) and potassium (K) were measured using standard methods of the Chinese Ecosystem Research Network (CERN) (Liu, 1996). Electrical conductivity (EC) was measured using a portable conductivity meter (Cole-Parmer Instrument Company, IL, USA). Soil soluble salts were analyzed using methods described by the Nanjing Institute of Soil Research (1980). The cation exchange capacity (CEC) was determined after leaching of <2 mm air-dried soil with 1 M CH_3COONH_4 at pH 7.0; Exchangeable cations (K^+ and Na^+) were determined by flame spectrophotometry (Blakemore et al., 1987). Table 2 shows the results of the above measurements.

2.3. Statistical analysis and data presentation

Statistical analysis of variance (ANOVA) and that of least significant difference (LSD) were carried out using the SPSS software package. Values of LSD were obtained at the 5% level of significance (Table 2). A parameter of soil properties is regarded as significantly different between two sites if the difference of the mean values from the sites is smaller than LSD.

Recovery rates of the key parameters of soil characteristics were modeled using linear relationships or best-fit asymptote models. The optimal shape of the simulating curve depended on regression analysis and correlation test for different models (Li et al., 2000). In other words, we used an asymptote model instead of a liner relationship if the former was more fitted to the observed recovery pattern of soil characteristics. Recovery time was obtained by estimating the number of years required to undergo 90% of change to reach the level of the asymptote, because many characteristics did not fully recover to the values for the non-eroded soils (Sparling et al., 2003). The calculation procedure was completed using the Origin 7.0 software package (Northampton, MA, USA).

3. Results

3.1. Topsoil physical properties

Soil physical analysis revealed marked trends in the depth of topsoil, that of biological soil crusts, and soil texture according to site ages (Table 2). Soil depth, including surface thickness of crusts, increased from

Table 2
Topsoil characteristics (mean±standard error) of revegetated sites, mobile dune site and reference site in the southeastern fringe of the Tengger Desert, northern China

Soil properties	Age of site (year)						Reference site	$LSD_{0.05}$
	0	14	23	34	43	50		
Sand (%)	99.67±0.26	78.87±1.51	71.54±1.18	70.48±1.20	68.28±1.71	66.39±1.77	13.54±2.04	2.10
Silt (%)	0.01±0.07	15.6±1.35	23.59±1.92	24.18±1.82	24.79±1.58	22.59±2.02	72.00±1.77	2.30
Clay (%)	0.22±0.28	4.54±2.20	4.87±0.97	5.34±0.87	6.93±1.12	11.01±0.83	14.45±0.98	1.65
Depth of soil and crusts (cm)	0	0.72±0.02	1.40±0.04	1.70±0.02	2.20±0.16	2.50±0.03	4.87±0.84	0.46
WHC (%)	9.32±1.38	11.27±2.12	13.38±2.26	15.44±1.35	16.87±1.62	16.22±1.71	24.16±2.17	2.60
Topsoil water content (%)	1.55±0.18	1.92±0.34	2.09±0.53	2.1±0.21	2.2±0.38	2.56±0.16	3.31±0.27	0.48
Bulk density (%)	1.53±0.02	1.52±0.02	1.50±0.02	1.50±0.02	1.47±0.03	1.44±0.02	1.13±0.08	0.05
pH	7.42±0.26	7.82±0.05	7.9±0.13	7.91±0.09	7.93±0.05	7.99±0.07	8.28±0.17	0.19
Organic C (g kg^{-1})	0.37±0.13	1.65±0.34	4.32±0.31	5.56±0.41	7.59±0.29	7.74±0.20	20.54±1.05	0.68
Total N ((g kg^{-1})	0.17±0.02	0.22±0.05	0.52±0.08	0.66±0.09	0.74±0.10	1.02±0.21	2.07±0.25	0.20
C:N ratio	2.17±0.83	7.50±2.94	8.31±1.51	8.42±1.12	10.49±1.47	7.94±2.05	10.08±1.61	2.50
Total P ((g kg^{-1})	0.40±0.06	0.44±0.05	0.71±0.03	0.72±0.02	0.75±0.02	0.77±0.02	1.38±0.04	0.11
Total K ((g kg^{-1})	0.11±0.04	0.99±0.13	1.17±0.09	1.23±0.10	1.25±0.09	1.32±0.05	1.78±0.06	0.14
EC (m s^{-1})	0.09±0.05	0.14±0.02	0.15±0.07	0.17±0.03	0.17±0.05	0.19±0.05	1.28±0.96	0.12
Total salt (g kg^{-1})	0.40±0.08	0.60±0.06	0.80±0.23	0.80±0.09	1.10±0.13	1.10±0.14	1.30±0.34	0.25
$CaCO_3$ content ((g kg^{-1})	0.30±0.04	1.20±0.07	1.90±0.07	1.98±0.04	2.30±0.12	2.39±0.02	10.18±0.93	0.50
CEC (cmol kg^{-1})	3.68±0.35	3.84±0.27	3.84±0.25	3.74±0.23	3.71±0.23	3.69±0.17	3.60±0.11	0.34
Exchangeable cations K^+ (cmol kg^{-1})	0.37±0.03	0.36±0.02	0.35±0.03	0.41±0.05	0.36±0.05	0.42±0.05	0.42±0.05	0.06
Exchangeable cation Na^+ (cmol kg^{-1})	0.09±0.03	0.17±0.02	0.18±0.05	0.15±0.03	0.16±0.04	0.17±0.02	0.15±0.03	0.05

0.72 cm at the 14-year-old site to 2.50 cm at the 50-year-old site, and reached 51.3% of the soil depth (4.87 cm) at the reference site. The above age sequence is associated with a sharp decline in sand content and rise in silt and clay contents. The differences in soil physical characteristics between the two most recently revegetated

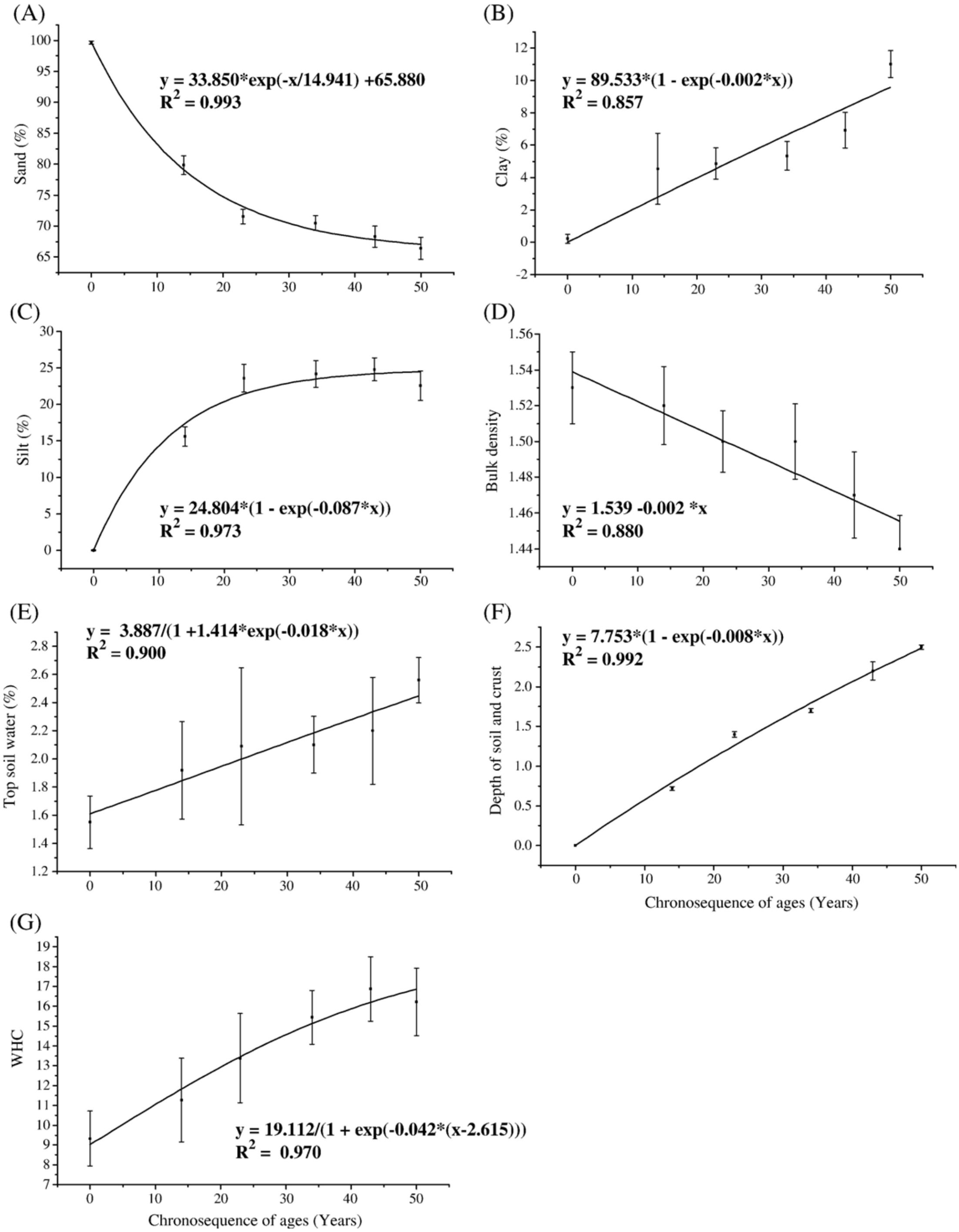

Fig. 3. Recovery curves of seven key physical soil properties from a chronosequence of revegetated sites in a sand-burial habitat at the fringe of the Tengger Desert, China, including simulation curves of (A) sand; (B) clay; (C) silt; (D) bulk density; (E) top soil water content; (F) depth of soil and crust; and (G) water-holding capacity (WHC).

sites are greater than those between the two oldest revegetated sites. The content of clay at the 50-year-old site reached 76.2% of that at the reference site; changes in clay content were more rapid at the older sites (>40 years) than in the younger sites. Changes in bulk density were relatively slower than the other measured soil physical properties during the 50 years after revegetation; however, bulk density at the 50-year-old site was significantly different from that found at the reference site ($p<0.01$). Maximum topsoil water-holding capacity (WHC) was the lowest and the rate of rainfall infiltration was 100% in mobile dunes before revegetation even in the case of high rainfall intensity. The establishment of sand-binding vegetation enhanced WHC (Table 2). Maximum WHC increased from 11.3% at the 14-year-old site to 16.2% at the 50-year-old site. Maximum WHC at the 50-year-old site was 67.1% of that at the reference site. In agreement with WHC, topsoil water content increased with this successional gradient defined by 0- to 50-year-old revegetated sites and the reference site undegraded native vegetation. Soil water content at the 50-year-old site was 77% of that at the reference site.

3.2. Soil chemical properties

Soil organic C, total N, total P, and K were very low in dune systems before revegetation (Table 2). The concentrations of these parameters at the 50-year-old site were lower than those at the reference site (natural desert steppe) by 37.7–74.2%. However, they tended to increase with an increasing site age. Incremental rates of these parameters were distinctly higher in the younger sites than in the older sites. The C:N ratio increased from 7.5 at the 14-year-old site to 7.9 at the 50-year-old site. This ratio was significantly lower in mobile dunes before revegetation, whereas the ratio at the 50-year-old site was 78.8% of the reference site. In general, incremental rates of C:N were higher at the younger sites than at the older sites during 50-year period. Soil pH was lower at the younger sites than at the older sites. The rise in soil pH with the site age was slower than the above parameters. However, soil pH in the reference site was significantly higher than that in mobile dunes and younger sites, such as the 14-year-old and 23-year-old sites. The EC increased with the site age. Sand burial reduced EC in comparison with the reference site. The accumulation of total salt and $CaCO_3$ in topsoil increased with the site age. At the 50-year-old site, the values of both parameters were 84.6% of total salt and 23.5% of $CaCO_3$ in comparison with the reference site.

As with most of the above soil parameters, CEC and the measured exchangeable cations (K^+ and Na^+) tended to increase with the site age. Note also from Table 2 that the concentrations of CEC and exchangeable cations were higher in the reference site than in the oldest (50 years) revegetated site. ANOVA suggested that the variations in CEC and exchangeable cations were not significantly different for sites during a 50-year period of soil/vegetation development in dry dunes.

3.3. Recovery rate of topsoil characteristics

Fig. 3 and Table 3 indicate that sand-particle content and bulk density decrease with recovery chronosequence. The proportion of sand in the soil texture takes

Table 3
Intercepts, rate parameters and asymptote levels of curves fitted to the recovery of soil physical, chemical characteristics of a chronosequence

Soil characteristics	Intercept	Rate parameter	Asymptote	90% of asymptote level	Years to reach 90% of asymptote level	Percentage recovery from reference sampling date
Sand (%)	99.73	0.067	65.88	72.47	87.02	21
Clay (%)	0	0.002	89.53	80.58	77.88	100
Silt (%)	0	0.086	24.80	22.32	26.66	34
Top soil water (%)	1.61	0.018	3.89	3.50	119.32	100
WHC (%)	9.03	0.042	19.11	17.20	54.34	79
Depth of soil and crust (cm)	0	0.008	7.75	6.98	127.98	100
Bulk density	1.53	0.002	1.54	0.15	244.89	100
pH	0.26	0.097	7.96	7.16	49.53	96
$CaCO_3$ (g kg^{-1})	0	0.048	2.61	2.35	47.95	26
Total N (g kg^{-1})	0.04	0.050	1.77	1.59	89.53	85
Organic C (g kg^{-1})	0.29	0.113	8.21	7.40	43.95	40
C/N	1.13	0.189	8.91	8.02	17.31	88
Total K (g kg^{-1})	0.07	0.170	1.29	1.16	22.70	73
Total P (g kg^{-1})	0.16	0.061	0.83	0.74	39.86	60
EC (m s^{-1})	0.11	0.576	0.26	0.23	123.54	20
Salt (g kg^{-1})	0.06	0.041	1.51	1.36	69.19	100

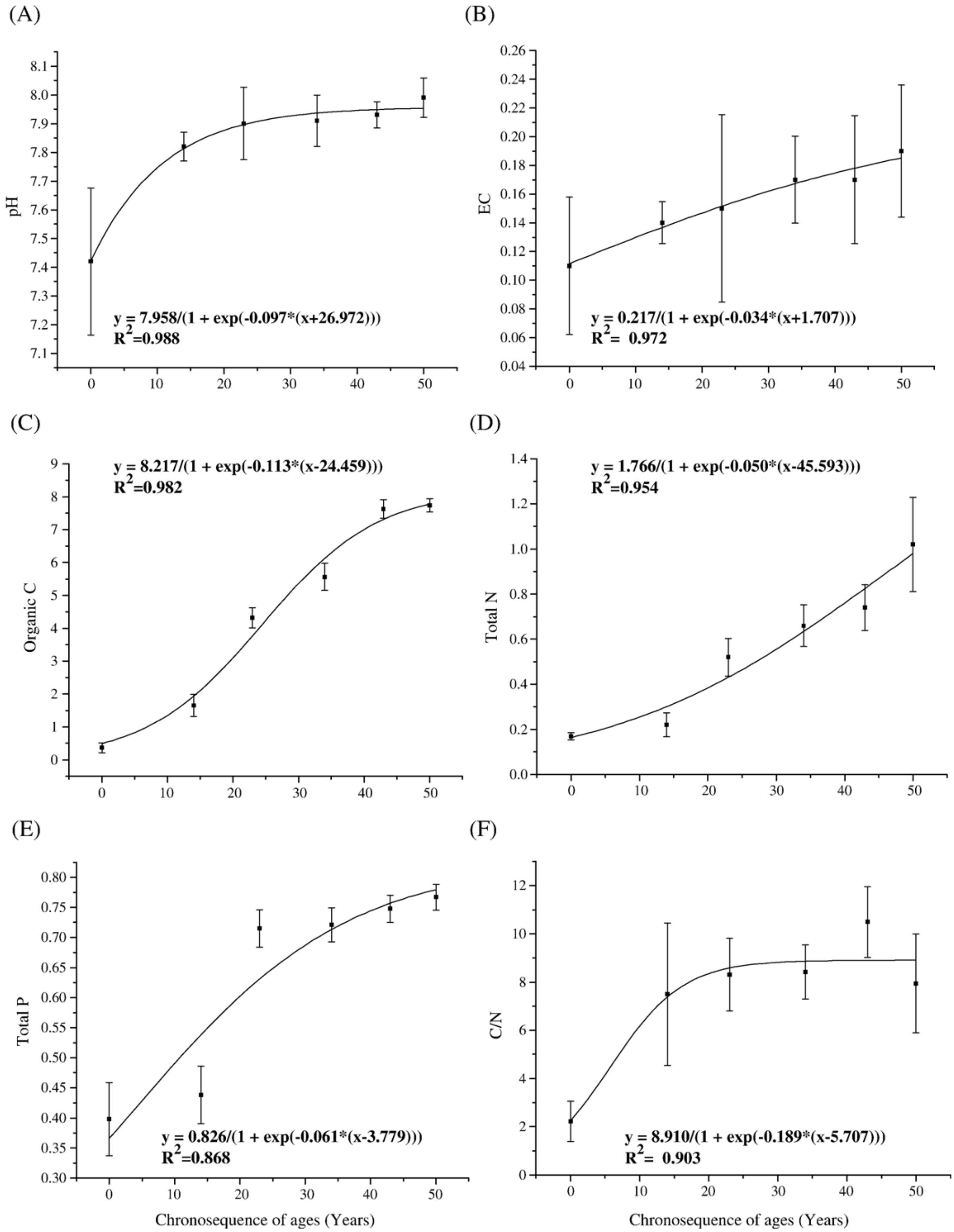

Fig. 4. Recovery curves of six key chemical properties from a chronosequence of revegetation sites, including (A) pH; (B) electrical conductivity (EC); (C) organic C; (D) total N; (E) total P; (F) C/N.

87 years to reach 90% of the asymptote level which is 21% of the value on the reference site. The proportions of clay and silt increases with site age, and takes 78 years and 22 years to reach 90% of the asymptote level, which is 100% and 34% of the values at the reference site, respectively. Bulk density is slow to recover and may take over 245 years to reach the value of the reference site. Topsoil water content needs

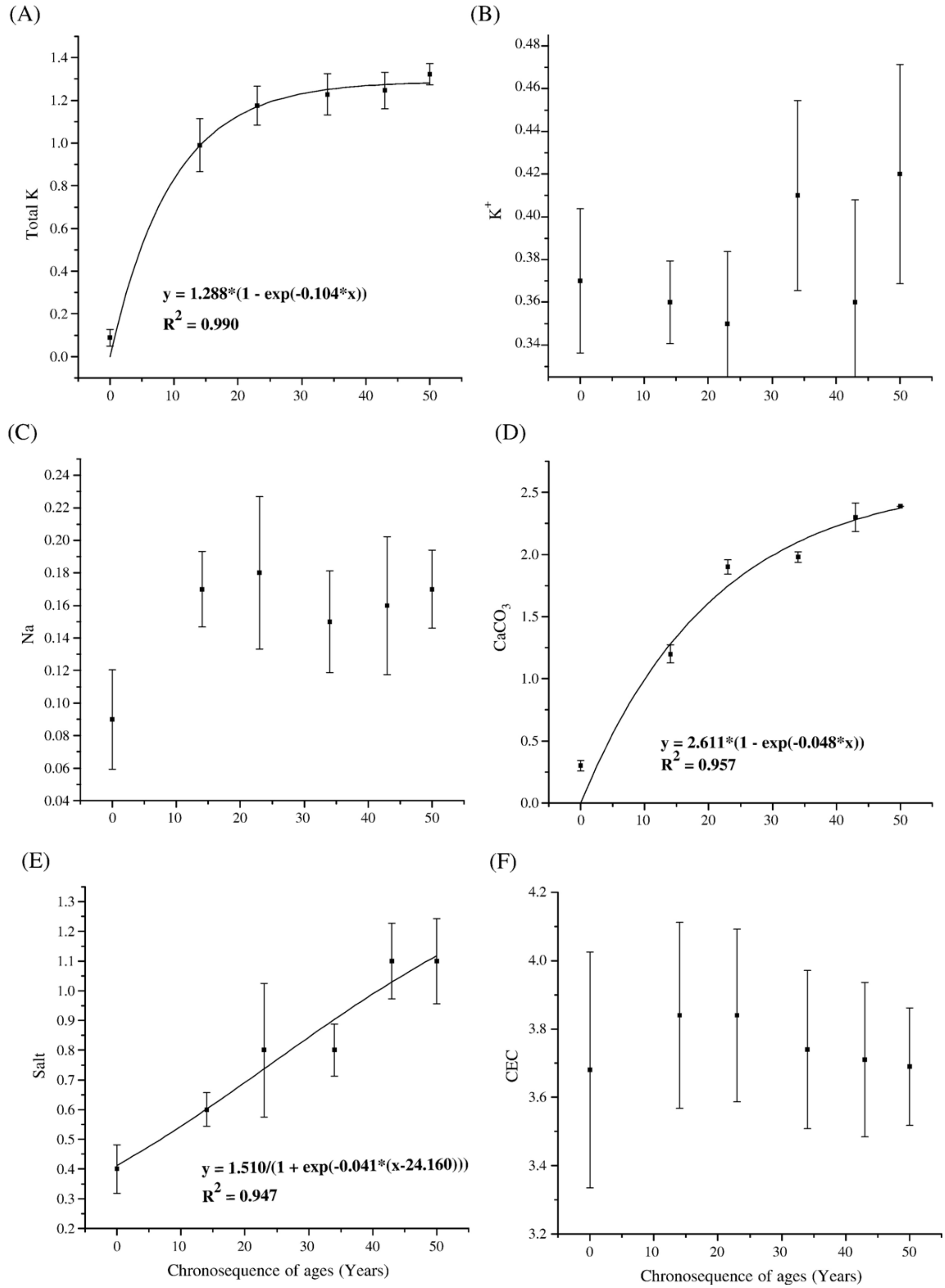

Fig. 5. Recovery curves of (A) total K; (B) K^+; (C) Na; (D) $CaCO_3^{2-}$; (E) salt; and (F) cation exchange capacity (CEC) from a chronosequence of revegetation sites.

120 years to reach the value at the reference site, and soil depth and thickness of biological soil crust need 128 years. WHC takes 55 years to reach 90% of the asymptote or 79% of the value at the reference site.

For soil chemical properties, such as soil pH, it takes 50 years to reach 90% of the asymptote level or 96% of the value at the reference site (Fig. 4). The accumulation of $CaCO_3$ in topsoil takes 58 years to reach 27% of the value at the reference site. Total N reaches 85% of that at the reference site during 90 years, whereas organic C recovers 40% during 44 years. The recovery of the C:N ratio is relatively faster in comparison with other soil parameters, and takes 17 years to reach 90% of the asymptote; the maximum recovery is 88% of the value at the reference site. Recovery to 90% of the asymptote for total K and P needs 23 years and 40 years, respectively. In this case, the maximum recovery of K and P is 73% and 60%. The recovery of EC takes place most slowly, taking 124 years to reach 90% of the asymptote or 20% of the value at the reference site, whereas total salt content recovers rapidly, taking about 70 years to reach the value at the reference site (Table 3). In addition, CEC, exchangeable K^+ and Na^+ do not show clear relationships with recovery chronosequence, and the asymptote model cannot be fitted to the data (Fig. 5).

4. Discussion

Sand dunes of the Tengger Desert move toward the southern desert steppe (Fig. 2) at a rate of 5 m/year (Shapotou Desert Research Station, 1991). The surface of the original grassland of the desert steppe is being covered gradually by mobile sand (Li et al., 2004a). This process makes the surface soil texture coarser than that of the desert steppe. However, the process of sand stabilization by establishing a "sand barrier" of straw checkerboard and revegetation facilitated the entrapment of dust-fall and the accumulation of fine particles in the topsoil (Fearnehough et al., 1998; Li et al., 2006). A fine soil texture facilitates the formation of soil aggregates and increases soil porosity in desert ecosystems. In this way, it improves topsoil's water-holding capacity, which in turn enhances the water content of the topsoil, and ultimately the overall productivity of the soil. In addition, fine-textured soil supports the growth of herbaceous species better than coarse-textured soil; the latter, in general, creates a habitat for some psammophytes, especially xerophytic shrubs (Brown, 1997). Increasing clay and silt contents in soil texture with time after revegetation is also positively correlated with the improvement of most soil parameters, such as an increase in soil organic matter, organic C and total N (Parton et al., 1988; Burke et al., 1990; Brown, 1997). Therefore, the recovery of clay and silt content in the topsoil is an important index for monitoring soil changes along a chronosequence. Meanwhile, soil depth is a direct index representing this change (Trustrum and De Rose, 1988). Most of the soil parameters measured are strongly related to the site age (Table 2), suggesting that a revegetative approach is effective in enhancing topsoil recovery after sand burial in extremely arid regions.

Recovery of topsoil characteristics through establishing sand-binding vegetation in a sand-burial environment in the Tengger Desert was estimated to take between 23 and 245 years (Table 3), with chemical characteristics generally recovering more rapidly than physical characteristics. Recovery (to 90% of the asymptote level) was most rapid for the C:N ratio (17 years). This recovery feature has also been confirmed by other researchers (Sparling et al., 2003). Amongst soil characteristics, recoveries of clay content, topsoil water content, depth of soil and crust, and total salt content need between 70 and 245 years to reach the level of the native desert steppe (reference site). The revegetated area of dune systems in the Tengger Desert entrapped dust-fall (<50 μm) at a rate of 1581.4 g hm^{-2}/year due to dust storms which occur on 136 days/year in average (Fan et al., 2002). The desert environment provides a sufficient amount of fine particles for accumulation on the stabilized surface in the study region. The development of a biological soil crust facilitates soil formation on the stabilized dune surface. The crust forms once the sand dune has been stabilized using a sand barrier of straw checkerboard and sand-binding vegetation. Increases in clay content and soil depth in turn enhance topsoil water-holding capacity and increase water content in the topsoil layer. Faster recovery of total salt content in the topsoil can be attributed to greater evaporation on the stabilized dune surface than on the mobile dune surface (Shapotou Desert Research Station, 1991). Recovery of total K can be explained by the fact that the Tengger Desert is rich in K (Chen et al., 1998).

During a 50-year period, we found that recovery for most soil characteristics was more rapid in the early stages than in the later stages, as also noted in some reports on the recovery process of landslip sites in moist tropical forest ecosystems (e.g., Singh et al., 2001), and in the dry hill county of New Zealand after landslip erosion (Sparling et al., 2003). After 50 years the maximum recovery of some topsoil properties such as EC, organic C, $CaCO_3$ content, WHC, silt and sand content is less than 50% of values in the native desert steppe (Table 2). This means that the recovery of desert steppe ecosystems is slower than the recovery reported in other ecosystems (Trustrum and De Rose, 1988; Lambert et al., 1993; Singh et al., 2001; Sparling et al., 2003).

The asymptote model and linear model cannot be fitted to the data on the recovery of CEC, exchangeable K^+ and Na^+. This may be explained that these parameters are more sensitive to both measurement (with high variance, Fig. 5) and influence of complex soil processes in comparison with other parameters of soil. This suggests that these parameters are not suitable for monitoring topsoil recovery in the Tengger Desert. In addition, some researchers have suggested soil microbial biomass as a possible early indicator of long-term trends (Powlson et al., 1987; Sparling, 1992). Total C and N have the advantage of being easier to measure than biochemical measures such as microbial C and mineralizable N (Sparling et al., 2003).

5. Conclusions

In the Tengger Desert, sand dunes stabilized by the sand barrier of straw checkerboard and revegetation enhanced the recovery of topsoil on dune systems. However, this is a slow process in the extremely arid desert environment. Recovery of topsoil after sand burial through a revegetation approach needs between 23 and 245 years. The recovery rate is more rapid in the early successional stages than in the later stages, with chemical properties generally recovering more rapidly than physical properties. After 50 years since sand-binding vegetation had been established, most of topsoil properties recovered to 60% of the level at the reference site. For some properties, even maximum recovery after >50 years did not reach the level found at the reference site. These findings mean that soil conservation is a vital issue in extremely arid desert regions.

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