Natural recovery of steppe vegetation on vehicle tracks in central Mongolia

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Steppe desertification due to vehicle travel is a severe environmental issue in Mongolia. We studied natural vegetation recovery on abandoned vehicle tracks in the central Mongolia steppe through vegetation surveys and stable isotopic techniques. The following issues were addressed: (i) invasion of pioneering plant species, (ii) alteration of soil surface features, and (iii) contribution of revegetated plants to soil organic matter (SOM). The pioneering plant species that firstly invaded the abandoned tracks are those that could germinate, root and survive in the compacted track surface. *Salsola collina* is one of these candidate plants. Due to revegetation, soil surface hardness was reduced. With the improvement of surface microenvironmental conditions, other plants began to colonize and establish; concomitantly species richness and species diversity increased. Carbon isotope ratios of SOM at the top surface layer indicated that C_4-derived carbon contributed more to SOM in the early phase of recovery and decreased with further recovery.

1. Introduction

Desertification is usually defined as land degradation in arid, semiarid and dry subhumid areas caused by combined effects of various natural and anthropogenic factors (UNEP 1992; Le Houérou 1996). Over 90% of territory in Mongolia belongs to arid, semiarid and dry subhumid regions, and is ecologically fragile and susceptible to economic overexploitation (Batjargal 1997; MNEM 1997a). Over three fourth of the terrestrial ecosystems in the country (*ca.* 1.2×10^6 sq. km) is subjected to various degrees of desertification, which is critically affecting sustainable development of the Mongolian economy (Batjargal 1997; MNEM 1999). Although the primary cause for desertification is overgrazing, however,

other human-related factors such as deforestation, improper agronomic management, fuel wood gathering, excessive water use, mining, and vehicle tracks are also important contributors (Batjargal 1997).

With rapid economic and social transformation in Mangolia starting from the early 1990s, the number of vehicles increased tremendously from 43792 in 1990 to 81693 in 2000 with an annual increase of about 9% (NSOM 2000). This rapid growth in the number of vehicles far exceeded the growth of the capacity for road construction. As of 2001, the total road length in Mongolia was 11100 km, out of which only 11.9% was asphalt-paved, 12.5% gravel-paved, and the remaining 75.6% earthy (UNESCAP 2001). The unpaved earthy tracks are created on-site by compaction

caused by many vehicles driving on the same spoor. As of 1997, vehicle tracks have led to *ca.* 8000–10000 km² of desertified land across the country, and were the primary cause for steppe degradation in some places (MNEM 1997b). Vehicle tracks are, therefore, one of the serious environmental issues in Mongolia. When a vehicle track is abandoned, revegetation (recovery) may occur via self-rehabilitation mechanisms (Whisenant 1999). In this paper, by investigating vegetation and soil surface changes on abandoned vehicle tracks in a central Mongolian steppe, we attempt to address: (i) which plants are the first to invade the abandoned tracks, (ii) how soil surface conditions change with the recovery, and (iii) to what extent native plants contribute to soil organic matter during the recovery process.

2. Materials and methods

The research site was located in Kherlenbayan-Ulaan (KBU), Hentiy province, Mongolia (47°12.838'N, 108°44.240'E, 1235 m asl) (figure 1). People in this area have maintained the traditional nomadic life style for centuries. The climate is continental in the temperate zone. The season from November to late April is long, cold and dry. The spring from May to June is windy and dry. The summer from June to September is warm and relatively wet. The growing season is about six months from late April to late October (Li *et al* 2005). According to the report of the KBU Weather Station (averages from 1993–2002), the mean annual air temperature of the region is 1.2°C. Mean daily temperatures for January and July are –22.9 and 21.4° C,
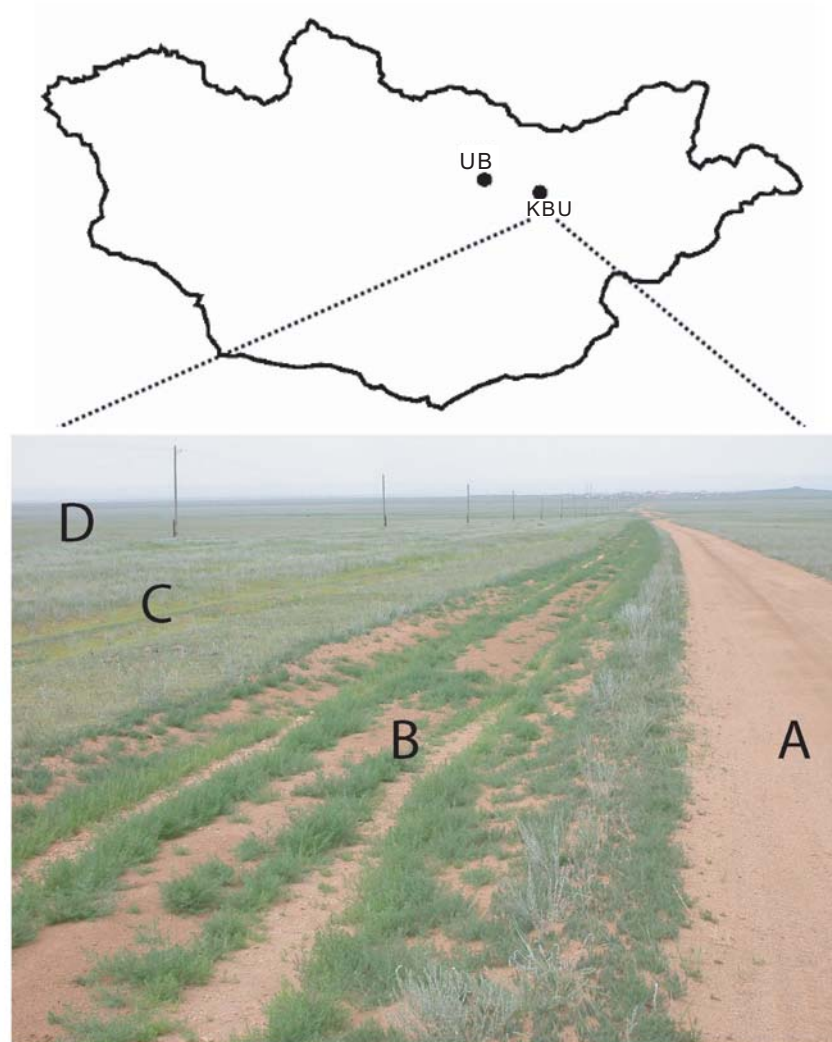
Figure 1.   Location of the study site: Kherlenbayan-Ulaan (KBU), about 250 km away from Ulaanbaatar (UB), the capital of Mongolia. A, B, C, and D represent the current vehicle track (track A), the track abandoned for three to five years (track B), the track abandoned for ten to fifteen years (track C), and the native steppe (D) respectively.

respectively. Mean annual precipitation is 196 mm, of which 88% falls between June and September. The soil is a typical chestnut soil (Kastanozem), characterized by low organic matter content, low levels of nitrogen, thin in depth, and sandy in texture (Asano 2004). There are scattered stones on the surface and in the soil. Lime (sometimes gypsum) often accumulates in the subsoil. The short-grass steppe is the major vegetation type in the region, and is dominated by cool-season C_3 species, including mainly *Stipa krylovii* (feather-grass), *Carex duriuscula* (needle-leaf sedge), *Artemisia frigida* (fringed sagebrush), *Allium mongolicum* (Mongolian onion), *Leymus chinensis* (Chinese wild-ryegrass), and *Caragana microphylla* (littleleaf peashrub), and a few C_4 plants such as *Cleistogenes squarrosa* (bridlegrass) and *Salsola collina* (Russian thistle, tumbleweed).

There were many unpaved earthy multi-lane vehicle tracks at the KBU steppe. These tracks were created by changing lanes, passing, and driving randomly. When surface conditions became unsuitable for driving, the tracks was then abandoned. The abandoned tracks may be naturally recovered through revegetation (secondary succession) (Whisenant 1999). At the KBU steppe, we selected two abandoned tracks (track B and track C), which were in parallel and adjacent to the current track (track A) (figure 1), to investigate vegetation recovery. Each investigated track extended over 500 m and was 2–3 m in width. According to the drivers who often drove through these tracks over the past 20 years and the herdsmen who live in KBU, track B was abandoned three to five years ago, and track C was abandoned around ten to fifteen years ago. Both track B and track C were not used by vehicles recently. A section of the steppe close to track C (D in figure 1) was selected as a reference treatment (called native steppe here after).

In July 2003, vegetation investigation, including species composition and frequency, was conducted on ten random quadrats of 50 × 50 cm at each site with the exception of track A, where there was no surface vegetation. Total vegetation cover and cover for each species at each quadrat was visually estimated. Species diversity is a descriptive measure of plant community structure. We calculated species diversity using the Shannon-Wiener diversity index (D_{SW}) (Zar 1999):

$$D_{SW} = -\sum_{i=1}^{S} p_i \ln p_i, \tag{1}$$

where p_i is the proportion of species i in the community, and S is the number of species in the sample. The species richness in this study denotes the total number of species present at each investigated site (Magurran 1988).

At each site, soil samples (excluding live plant materials and un-decomposed litter) at six depths (0–1.9, 2–4.9, 5–9.9, 10–19.9, 20–29.9, and 30–50 cm) were collected with a soil corer (0.06 m in diameter). The soil at each depth was collected from three cores (holes, about 0.5 to 1.0 m apart), mixed and passed through a 2 mm sieve on the spot. To avoid spatial heterogeneity, the soil profile samples at the sites excluding track A had three replicates from three locations (20 m apart). The soil profile sample at track A had no replication, but was collected from 5 soil cores (10 m apart), and respectively mixed for each depth. In addition, sunny healthy leaf samples from dominant plant species at the native steppe were collected for isotope analysis. Soil samples were oven-dried at 105°C for three days in the lab while the leaf samples were air-dried in the field and then oven-dried in the lab at 65°C for three days. Coarse grinding was done for the soil samples with a mortar and pestle. Leaf samples were frozen using liquid nitrogen and then ground with mortar and pestle. Both the soil and plant samples were sifted with 40 mesh (425 μm) sieve, and then sealed in glass vials. In order to remove inorganic carbonate carbon, soil samples were treated with 1 N HCl at 25°C for one to three days and then rinsed with distilled water (Midwood and Boutton 1998). Sub-samples (about two mg for leaf samples, and 2 to 15 mg for soil samples depending on depths) from these samples were placed in tin capsules (Universal tin container, Thermoquest Italia SPA, Rodano, Milan, Italy) for determination of stable carbon isotopic composition ($\delta^{13}C$), carbon (C) content, and nitrogen (N) content using an isotope ratio mass spectrometer (Finnigan MAT delta S, Bremen, Germany) coupled with an elemental analyser (Carlo Erba EA1108 elemental analyzer, Fisons Instruments, Danvers, MA, USA) at the Center for Ecological Research, Kyoto University, Japan. Precision of individual measurement on the spectrometer was ± 0.15‰ for $\delta^{13}C$. Stable isotopic compositions of the samples are expressed as part per thousand (per mil, ‰) using the delta (δ) notation:

$$\delta_{sample} = \left[\frac{R_{sample}}{R_{standard}} - 1 \right] \times 1000, \tag{2}$$

where R_{sample} and $R_{standard}$ represent the heavy-to-light isotope ratios of the sample of interest ($^{13}C/^{12}C$), and the international standard (Pee Dee Belimnite, PDB), respectively. The N and C content of the samples is expressed as a percent on weight basis.

In addition, we measured soil surface hardness (upper 4 cm) in June of 2004 at aforementioned four sites using a hardness meter (DIK–5553, Daiki Rika Kogyo Co., Ltd., Tokyo, Japan). At each site, 30 points were measured and then averaged.

Using the statistical software Data Desk (Data Description Inc., Ithaca, NY, USA), the paired *t*-test or multiple *F*-test were performed to compare the difference between the means of the sites, and a one-way ANOVA was

used to reveal the effect of depth on carbon content, nitrogen content and stable carbon isotope composition of the soil organic matter at the sites.

3. Results

3.1 *Species composition and diversity*

The native steppe had higher species richness than track B and track C (table 1). Species diversity as indicated by the Shannon-Wiener diversity index increased with recovery from the abandoned tracks (table 1). The total vegetation cover was sparse at track B, but had a tendency to increase with recovery (table 1). Irrespective of site identity, few species were found commonly, and others appeared rarely (table 2). Track B and track C had similar species richness following partial recovery, but their dominant species compositions were different (table 2). Track B was dominated by *Salsola collina*. In contrast, track C was dominated by *Carex duriuscula* and *Artemisia frigida*. The dominant

Table 1. Species richness, Shannon-Wiener diversity index (D_{SW}) and total vegetation cover

Site	Species richness	DSW	Cover (mean $\pm$ SD%)*
Track A	0	–	0
Track B	7	0.66	30 ± 5^a
Track C	8	0.77	55 ± 10^b
Native steppe	13	0.96	65 ± 8^c

The superscript lowercase letters indicate that there was a significant difference between the sites at the *P*-level of 0.05 ($n = 10$).

species in the native steppe were *Stipa krylovii, Carex duriuscula, Cleistogenes squarrosa* and *Artemisia frigida*.

3.2 *Stable carbon isotopic evidence for vegetation recovery*

Carbon (C) in soil organic matter (SOM) primarily comes from roots, litter and dead parts of overlying vegetation, and thus reflects vegetation change as the soils form over time. The stable C isotope ratio of SOM ($\delta^{13}C_{SOM}$) can be used to unravel the C sources of various plant functional types (C_3 and C_4 plants in this study) with contrasting photosynthetic pathways (Dzurec *et al* 1985; Schwartz *et al* 1986; McPherson *et al* 1993; Boutton *et al* 1998) historically. Specifically, the $\delta^{13}C_{SOM}$ values of shallow soil depths provide information of recent C input from C_3 and C_4 plants (Boutton *et al* 1998). During photosynthesis, C_3 plants discriminate against the heavy isotope ^{13}C of atmospheric CO_2 much more than C_4 plants. Therefore, organic tissue of C_3 plants is relatively depleted in ^{13}C compared to C_4 plants (Farquhar and Lloyd 1993). The $\delta^{13}C$ values of dominant C_3 plants and C_4 plants at the native steppe averaged -26.2 ± 0.2 SE ‰ (15 species), and -13.4 ± 0.9 SE ‰ (2 species), respectively. There was a 13‰ difference in $\delta^{13}C$ between C_3 and C_4 plants.

The $\delta^{13}C_{SOM}$ values in entire soil profiles at the sites were significantly lower than the $\delta^{13}C$ values of current C_4 plants, and higher than the $\delta^{13}C$ values of current C_3 plants ($P < 0.001$). There was an obvious depth effect of $\delta^{13}C_{SOM}$ for all the sites ($P < 0.001$) (figure 2). The $\delta^{13}C_{SOM}$ values were lowest near the soil surface, increased with depth within the upper 0–10 cm layer, but decreased with depth from 10 cm down to 40 cm. The mean $\delta^{13}C_{SOM}$ value within the

**Table 2.** Frequency (%) of plant species from ten 0.25 m² quadrats.

Plant species	Track B	Track C	Native steppe	Functional type
Stipa krylovii	–	–	90	C_3
Carex duriuscula	–	90	90	C_3
Leymus chinensis	30	40	40	C_3
Cleistogenes squarrosa	10	60	90	C_4
Artemisia frigida	60	100	100	C_3
Artemisia adamsii	10	–	20	C_3
Caragana microphylla	–	–	10	C_3
Melissitus ruthenicus	10	10	10	C_3
Stellaria dichotoma	–	10	–	C_3
Allium mongolicum	–	–	10	C_3
Heteropappus altaicus	–	–	40	C_3
Dracocephalum moldavica	10	–	–	C_3
Potentilla sp.	–	30	10	C_3
Erodium stephanianum	–	–	10	C_3
Salsola collina	100	10	10	C_4
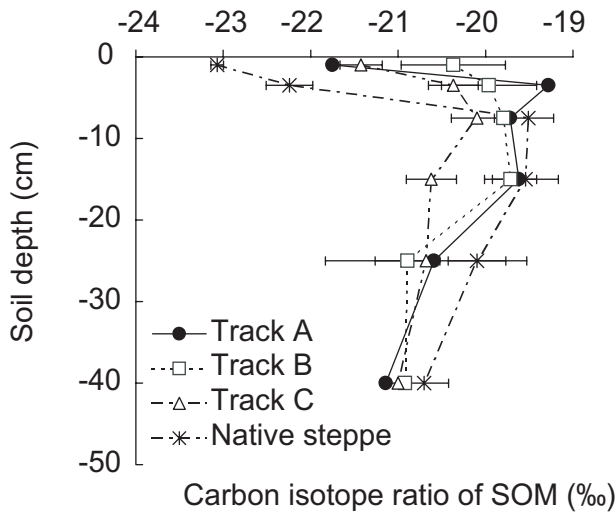
Figure 2. Mean $\delta^{13}C$ values for soil organic matter (SOM) plotted against depth in the sites. ($n = 3$ for track B, track C and the native steppe, and $n = 1$ for track A). Bars indicate standard errors.

Figure 3. Proportion of C_4-derived carbon in the soil organic matter within the upper 2-cm depth with respect to natural recovery on the abandoned tracks. The same lowercase letters beside the bars are not significantly different at the P-level of 0.05 ($n = 3$).

0–2 cm depth of the native steppe soil was –23.1‰, increased to –19.5‰ at the 10 cm depth, and decreased to –20.7 ‰ at the 40 cm depth. More enrichment in ^{13}C for SOM at the deeper depth might be due to the fact that C sources were more ^{13}C-enriched at the time when SOM accumulated since the atmospheric CO_2 was gradually ^{13}C-depleted over the last 200 years (Freidli *et al* 1986; Conway *et al* 1994). This enrichment might be also associated with a possible fractionation effect during SOM decomposition and litter decay by microbes (Stout *et al* 1981; Nadelhoffer and Fry 1988), and the addition of relatively ^{13}C-enriched root tissue to deeper soils (Boutton 1996). Site-to-site difference in $\delta^{13}C_{SOM}$ was larger in the upper 10 cm depth and converged at the depth of 40 cm, approaching a relative constant value of about –21‰. This implies that the isotopic influence due to vegetation recovery is primarily evident in the near-surface soils. The mean $\delta^{13}C_{SOM}$ values within the 0–2 cm soil depth were –21.8‰ at track A, –20.4‰ at track B, and –21.4‰ at track C, respectively. Soil organic C at track A was relatively depleted in ^{13}C as compared to those at track B and track C. This is likely to be due to the influence from the remnant C signature prior to disturbance or to lateral C movement from track shoulders where the native steppe was distributed and topographically higher than track lanes. Relative to the native steppe, SOM of the 0–2 cm depth was significantly enriched in ^{13}C by approximately 3‰ for track B and 2‰ for track C respectively ($P < 0.05$). This suggests that during the recovery, C contribution to SOM might depend on overlying C_3 and C_4 plant shift. Therefore, the $\delta^{13}C_{SOM}$ data might provide evidence on the temporal change of functional plant types during the recovery on tracks.
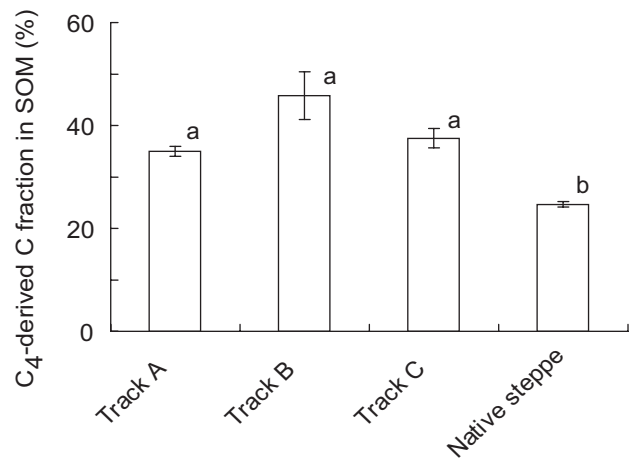
Assuming that the $\delta^{13}C$ of SOM near the top of the soil profile exclusively depends on inputs of organic matter from recent overlying C_3 and C_4 plants, a simple two end-number model (the mass balance approach) can be used to identify the proportion of C sources from each plant type (Boutton *et al* 1998):

$$\delta^{13}C_{SOM} = f\delta^{13}C_{C4} + (1-f)\delta^{13}C_{C3}, \tag{3}$$

where $\delta^{13}C_{SOM}$ is the $\delta^{13}C$ value of SOM within the 0–2 cm, $\delta^{13}C_{C4}$ (= –26.2‰) and $\delta^{13}C_{C3}$ (–13.4‰) are the average $\delta^{13}C$ values of C_3 and C_4 plants respectively. f and $(1 - f)$ are the proportion of C_4- and C_3-derived C in SOM respectively. The relative proportion of C_3 and C_4 plants varied with recovery inferred from the C isotope data of SOM. The f was greatest at track B (46%), indicating that a substantial proportion of organic C was C_4 in origin. The f value was lowest at the nearby native steppe (25%), suggesting that C inputs were C_3-dominated. The f values were intermediate at track A (35%) and at track C (38%). C_4-derived C contributed more to SOM at the top 2 cm layer of the soil at the abandoned tracks than at the native steppe, and this contribution decreased with recovery (figure 3). Relative to the native steppe, the higher proportion of C_4-derived C at the current track may indicate lateral intrusion of C_4 plant C from the track shoulder into the track lanes.

3.3 *Soil surface hardness*

The immediate consequence of vehicle travel was destruction of surface vegetation cover, removal of surface soil,
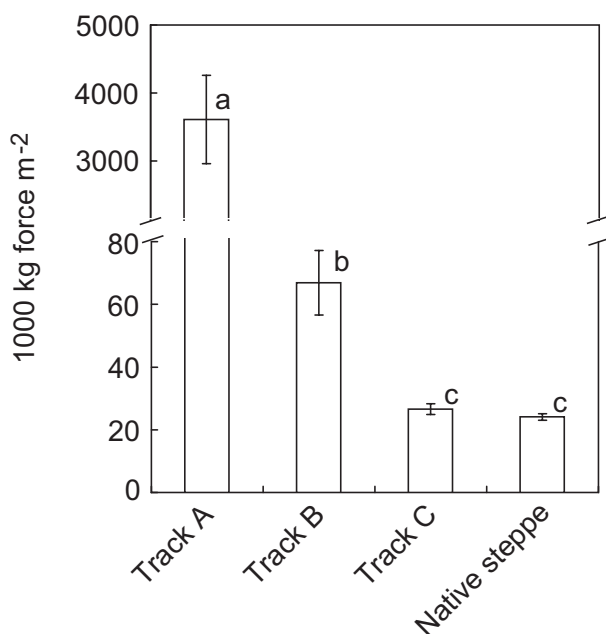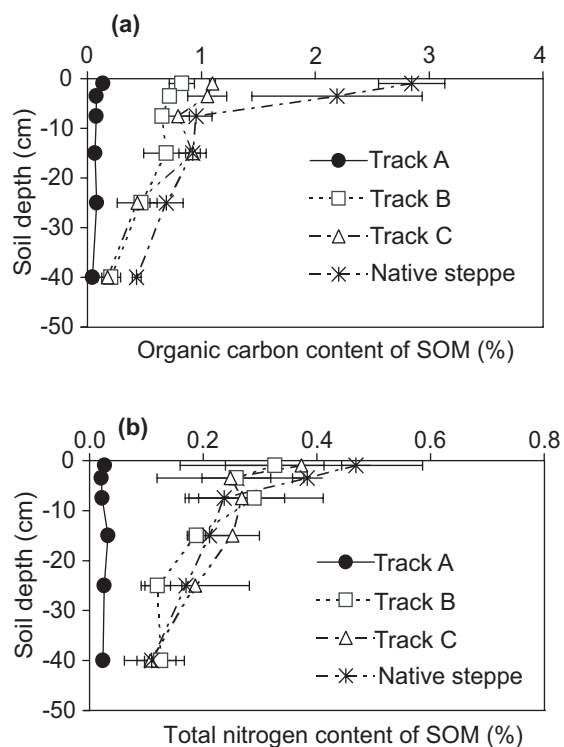
Figure 4. Variation of soil hardness with revegetation on the abandoned tracks in the steppe of Mongolia. The bars indicate standard errors. The same lowercase letters beside the bars are not significantly different at the *P*-level of 0.05 (*n* = 30).

Figure 5. Soil organic carbon content **(a)** and total nitrogen content **(b)** as a function of soil depth. (*n* = 3 for track B, track C and the native steppe, and *n* = 1 for track A). Bars indicate standard errors.

and soil compaction. As compared to the native steppe, soil ground at the current vehicle track (track A) was considerably compacted (figure 4). Soil surface hardness of the upper 4 cm soil at Track A was about 150 times of that at the native steppe. This physical modification to the soil extended vertically to a depth of 30 cm or more. With the vegetation recovery on the abandoned tracks (track B and track C), the surface hardness decreased. After a greater than ten to fifteen year long recovery period, the surface hardness at track C showed no significant difference from that of the native steppe ($P < 0.001$) (figure 4).

3.4 *Carbon and nitrogen content in SOM*

Percent C content in SOM was relatively constant at less than 0.5% on weight basis throughout the soil profile at track A, where it was considerably lower than those of the other three sites ($P < 0.001$) (figure 5A). In contrast, C content in SOM of track B, track C, and the adjacent native steppe decreased with depth ($P < 0.05$) (figure 5a). Site-to-site difference in C content of SOM was greatest at the surface layers (0 – 10 cm) ($F = 5.162$, $P < 0.05$), but were not evident below 10 cm ($F = 2.977$, $P = 0.127$). Despite the fact that track C was abandoned about ten to fifteen years ago, its C content at the upper 10 soil layer (1.0%) was only slightly higher than that of track B (0.8%)

($P < 0.05$), which was abandoned recently, and was substantially lower than that of the native steppe (2.0%) ($P < 0.001$) (figure 5a).

Percent nitrogen (N) content in SOM displayed a similar pattern as C content in SOM with respect to depth (figure 5b). The N content of SOM was fairly low (< 0.1%) throughout the soil profile at track A. At track B, track C, and the native steppe, an obvious decrease in N content with depth was observed ($P < 0.05$). N content of the upper 10 cm showed a tendency of slight increase with recovery. Mean N content over the depth of 0 to 10 cm was 0.3% at track B, 0.3% at track C, and 0.4% at the native steppe, respectively.

4. Discussion

Vehicle travel-induced steppe desertification is one of several severe environmental issues in Mongolia. Abandoned tracks are commonly found in many places of the steppe in the country. Natural vegetation recovery on these tracks is worth researching since it provides useful information of how desertified steppe can be converted to its original conditions. The aim of our study was to evaluate vegetative

recovery on abandoned vehicle tracks in the central Mongolia steppe.

Vehicle travel, by its very nature, causes destruction of surface vegetation, soil compaction, loss of soil aggregation, changes in soil texture, partial or complete removal of the top layer of soil, and loss of soil organisms, especially on slopes or steep terrain. Soil compaction reduces the water infiltration and holding capacity of topsoil, and increases the risk of water erosion under summer rain storms (Bainbridge 1993). Bareness of abandoned tracks may increase the possibility of rapid depletion of surface soil moisture by increasing evaporation (Webb and Wilshire 1983). These surface conditions, together with low precipitation, extreme temperatures and intense sunshine commonly experienced in the region, may hamper recruitment and colonization of plants on the abandoned tracks (Webb and Wilshire 1983; Aronson *et al* 1993a). Therefore, successful invaders should have the potential to endure these harsh surface conditions. Tumbleweed (*Salsola collina*), fringed sagebrush (*Artemisia frigida*) and Chinese wild-ryegrass (*Leymus chinensis*) were among the pioneering plant species on the abandoned tracks (table 2). Tumbleweed, as an aggressive weed, was among the most successful colonizers at recently abandoned tracks (table 2). At the beginning of colonization, the arrival and establishment of this annual C_4 plant may be more opportunistic and stochastic in response to rainfall than perennials. Furthermore, it may germinate, root and grow in compacted track soils more successfully compared to other species. This is consistent with reports in the literature that tumbleweed shows great ability to colonize disturbed soils, especially under drought conditions, but competes poorly with well-established vegetation for water and nutrients (Allen 1982, Young 1991). Fringed sagebrush, a woody mat-forming shrub, can grow in dry and cold climates like that of the Great Plains and the Mongolian steppe (USDA 1937). This plant has a strong capacity to withstand and survive harsh drought by growing deep taproots (Coupland and Johnson 1965). Relative to other steppe species, fringed sagebrush can reproduce through both clonal propagation and sexual reproduction (Coupland 1950; Wilson 1982). It thus has an advantage over other species in establishment on abandoned tracks (Shantz 1917). This species generally increases under long-term overgrazing and in the degraded steppe (Li Y H 1989; Li S-L 1998). Chinese wild-ryegrass, a xerophytic cool-season grass, grows naturally on arid and alkaline soils (Clayton and Renvoize 1986), and is distributed widely in Eurasia (Lu *et al* 1987). This plant exhibits strong tolerance to drought and grazing (Yang and Du 1989; Wang and Li 1997). It also has strong colonizing ability under dry climatic conditions by means of its plentiful rhizomes (Clayton and Renvoize 1986). In summary, we believe that the pioneering plant species described above have the

ability to germinate, root and survive on the denuded surfaces of the abandoned tracks, and thus the vegetation recovery process began with their invasion.

The pioneering plant species, once established, will improve site microenvironmental conditions (Webb and Wilshire 1983; Aronson *et al* 1993b). Formerly compacted track soils may become loose due to root growth (figure 4), and rich in nutrient due to organic matter input from the plants (figure 5). Establishment of the pioneering plant species may thereby reduce water and wind erosion, trap fine soil, organic matter and wind-dispersed seeds, and thus favour recruitment and establishment of other plants for further vegetation recovery (Bainbridge and Virginia 1990; Burke *et al* 1995).

Species composition, species diversity, and vegetation cover increased with recovery (tables 1 and 2). Comparison of these parameters at adjacent native steppe with those at revegetated tracks makes it possible to infer to what extent the steppe heavily-disturbed by vehicle travel could be restored. Fully recovered vegetation on the abandoned tracks should ideally be structurally and functionally equivalent to the native steppe. This calls for recovering the approximate species composition of the native steppe. However, needle-leaf sedge (*Carex duriuscula*), which was widely common in the native steppe, was not dominant in frequency in the newly abandoned tracks (table 2). Feather-grass (*Stipa krylovii*), the dominant species, has not occurred at the tracks after over ten to fifteen years of recovery (table 2). This is likely to be due to loss of soil aggregation (Webb and Wilshire 1983). Also, success of recruitment by needle-leaf sedge and/or feather-grass may depend on their ability to compete with pioneering plant species. It has been reported that the time estimated for full or partial recovery of species diversity from disturbed soils in dry arid areas of California is over hundreds or even thousands of years (Lovich and Bainbridge 1999). In addition, it must be emphasised here that the similarities and differences in the revegetation process between road tracks and heavily degraded steppe communities is also likely to be influenced by other factors such as overgrazing.

Carbon and nitrogen content in soil organic matter (SOM) remained lower at the revegetated tracks than in the native steppe (figure 5). Leguminous perennials (e.g. *Melissitus ruthenicus*, table 2), may help to increase the supply of nutrients through nitrogen fixation to SOM, and benefit the later phase of recovery. It is reported that recovery of soil properties to pre-disturbed levels may take decades or even centuries in prairie ecosystems in USA (Burke *et al* 1995; Kindscher and Tieszen 1998). Dregne (1983) estimated that desert soils might take over ten thousand years to form. Thus, once the steppe soil is disturbed by human activities, it may take a very long time to recover. Additionally, one important point to make here is that the recovery may be retarded or

disrupted due to re-travel and may vary depending on the intensity of disturbance in the past (determined by the number and type of passing vehicles) and on inter- and intra-seasonal variation in the grazing intensity at the site.

Site-to-site differences in the stable carbon isotope ratio of SOM ($\delta^{13}C_{SOM}$) were largest in the upper-most soil layer (top 2 cm in this study) (figure 2). Since SOM at the near-surface layer represented the most recent carbon isotope input from the vegetation, this difference could be used to infer overlying vegetation dynamics (Dzurec *et al* 1985; McPherson *et al* 1993; Schwartz *et al* 1996; Boutton *et al* 1998). The depletion in ^{13}C at the topmost surface with recovery probably reflects C_3/C_4 species compositional shifts during the natural recovery on the abandoned tracks. At the early recovery stage, vegetation seemed to be dominated by more C_4 plants as indicated from the $\delta^{13}C_{SOM}$ signatures of the recently abandoned track soils (figure 2). This is likely to be associated with the biological and ecological characteristics of C_4 plants that exert comparative advantages over C_3 when the air temperature is high and water is limited (Ehleringer *et al* 1997). C_4 contribution decreased with recovery (figure 3). This is probably the consequence of invasion of more C_3 species into C_4-established habitats in which microenvironmental conditions become unfavourable to or disadvantageous in competition for C_4 relative to C_3 counterparts. Therefore, it appears that the vegetation dynamics inferred by the plant-soil isotopic equilibration is the process of decreasing C_4 contribution and increasing C_3 contribution to the community. The full recovery will be represented by a C_3-dominated community, which is the same as the native steppe in association with the zonal climate. However, the assumption of the mass balance approach that $\delta^{13}C_{SOM}$ is equivalent to the weighted average $\delta^{13}C$ of C_3 and C_4 plants may not hold in the field because there may exist isotopic fractionation during litter decay and SOM decomposition by microbes (Stout *et al* 1981; Nadelhoffer and Fry 1988). Also, the relationship between SOM $\delta^{13}C$ signature and the vegetation history may be confounded by the fact that the relative abundance of overlying C_3 and C_4 plants is likely to be not the same as the relative contribution of C_3- and C_4-derived carbon to SOM. Furthermore, since the recovery occurred in the context of present grazing, the grazing impact should not be neglected. In particular, overgrazing may strongly affect the revegetation process at road tracks. Therefore, inferring vegetation from $\delta^{13}C_{SOM}$ should be used with caution. It also should be stressed here that the C_3/C_4 compositional shifts implied by this study were based on spatial comparison among various sites rather than temporal dynamics at the same site.

Acknowledgements

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