

Carbon Mineralization Potential in Soils of Different Habitats in the Semiarid Horqin Sandy Land: A Laboratory Experiment

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Soil organic carbon mineralization potential in four different sandy habitats (shifting, semi-fixed, fixed sand dune, and interdunal lowland) and the effects of litter addition from shrubs and annual plants on soil microbial respiration were measured using a laboratory soil incubation experiment. Soil samples were collected from beneath and outside the canopies of shrubs in all habitats. Soils were incubated for 33 days with and without litter addition. It was concluded that the differences in C mineralization of soils among habitats correlated with the vegetation cover, litter accumulation, and soil structure, organic C, and N contents. Very poor organic C and N as well as very weak microbial respiration were found in soils of the shifting sand dune, suggesting that sandy desertification strongly depleted both bulk of soil organic C and soil labile C pool. Caragana microphylla litter amended soils and annual plant litter amended soils had the greatest and the lowest microbial respiration, respectively, which might in part be attributed to the N contents and C/N ratios in litters. Shrubs accumulated more organic material and created fertile islands with larger organic C and nutrients and microbial activity under their canopies, and therefore, significantly contributed to C sequestration.

Keywords shrubs, annual plants, litter, CO₂-C release, sandy desertification

The biochemical cycle of organic C plays a key role in the relationships between the soil, the vegetation, and the surrounding environment (Santa Regina & Tarazona, 2000). The mineralization of soil organic C is an important process regulating the functioning of natural and managed ecosystems (Johnson, 1995). Since soil nutrient availability is constrained by the energy sources to maintain microbial populations (Núñez et al., 2001), mainly by the availability of soil organic C, Carbon

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mineralization rate controls the fluxes of the nutrients (Saggar et al., 2001). Further, because most detrital C in the terrestrial ecosystems is found in mineral soil, C mineralization rate is also predicted to control how terrestrial C storage responds to changes in climate or vegetation (Giardian et al., 2001). Therefore, accurate modeling of soil C mineralization rate and its response to a changing environment is therefore required for better understanding of biological process of ecosystem evolution.

Carbon mineralization in soil varied with a number of factors including chemical characteristics of plant material (e.g., content of lignin, nitrogen, and C:N ratios) that affect the activity of the decomposer community (Côté et al., 2000; Melillo et al., 1982; Yang et al., 2002) and soil environmental conditions such as soil structure (Côté et al., 2000; García & Hernández, 1996; Parton et al., 1987), pH, soil moisture, temperature, and the nature of soil microorganisms and fauna (Huang et al., 2002; Kirschbaum, 1995; van der Lingden et al., 1987) during the mineralization process. In arid and semiarid desert ecosystems, soil organic matter, nutrients, moisture, and temperature conditions, soil microorganisms, and litterfall mass exhibit high spatial heterogeneity, with higher contents under the canopies of shrubs, because soils from under and outside shrubs are subjected to different environmental conditions that affect erosion, deposition, and above- and belowground litter inputs (Schlesinger et al., 1990; Schlesinger et al., 1996). This plant-induced, small-scale spatial heterogeneity of resource distribution may lead to the spatial heterogeneity of C mineralization, and in turn further influence plant distribution patterns and biological processes of ecosystem evolution.

In semiarid Horqin sandy land of north China, one of the most seriously desertified regions of China (Wang, 2000), soil nutrients are scarce and patchily distributed (Su et al., 2002). Some shrubs and annual forbs and grasses are the dominant plant forms. Litter from these plants plays a fundamental role in the nutrient turnover and in the transfer of energy between plants and soil in this ecosystem where the vegetation depends in large part on the recycling of the nutrients contained in the plant detritus. In a recent study, Su et al. (2002) found significant differences in the contribution to the improvement of the "fertile island" among different shrub species. They also suggested that this difference may have resulted from the quantity and quality of litterfall and its decomposition. However, no information is available on mineralization of the residues from shrubs and whether soil from beneath the canopies of shrubs can affect mineralization rates. The objectives of this study were to investigate soil C mineralization potential in different sandy habitats and the influences of litter addition from shrubs and annual plants on soil microbial respiration in the semiarid Horqin sandy land. Knowledge gained should help to increase our understanding for the biological feedback of desertification and for the mechanism of vegetation restoration.

Materials and Methods

Site Descriptions

The study was conducted at the Naiman Desertification Research Station (N 42° 55', E 120° 42') of Chinese Academy of Sciences, located in the southwest end of the Horqin sandy land (Naiman county, Inner Mongolia, north China). This region has a semiarid climate with an average rainfall ca. 360 mm and an average annual temperature of 6.8°C. The mean annual evaporation is about 1935 mm. Geomorphologic landscape in this region is characterized by dunes crisscross with gently undulating lowlands. The zonal soils are characterized by coarse texture and loose structure, which are mostly equivalent to the Orthi-Sandic Entisols of sand origin in terms of the FAO-UNESCO system (Chinese Soil Taxonomy Cooperative Research Group, 1995). These soils are highly susceptible to wind erosion.

A representative sand land was selected as the sampling site. Its characteristic landscape was highly fragmented and patchily distributed with small shifting sand dunes with less than 10% vegetation cover, semifixed sand dunes with 30~50% vegetation cover, fixed sand dunes with 50~70% vegetation cover (average height: 3~5 m) and interdunal lowlands with more than 70% vegetation cover (Chang & Wu, 1997). The dominant plant in the shifting sand dunes is *Agriophyllum squarrosum* (Bieb.ex C.A. May) Moq., with sparse distribution of *Artemisia halodendron* Turcz. ex Besser, a native perennial shrub, and annual *Salsola collina* Pall. The dominant plant in the semifixed sandy land is *A. halodendron*, with lesser numbers of *Caragana microphylla* Lam., a leguminous shrub, and some annual forbs such as *A. squarrosum*, *S. collina*, *Setaria viridis* (L.) P.Beaur. *C. microphylla* are distributed widely in the fixed sand dune and lowlands. *Artemisia scoparia* Waldst. & Kit, *S. collina* and *S. viridis* are the major annual plants in the semifixed, fixed sand lands and lowlands. Also, there exists *A. halodendron* in the fixed sand dunes and lowlands, which is in degradative process. *A. halodendron* and *C. microphylla* play an important role not only in fixing mobile sand dunes and reducing the intensity and extent of wind erosion (Liu et al., 1996), but also in maintaining and improving soil fertility by “fertile island” effect (Su et al., 2002; Wezel et al., 2000).

Sampling

Three types of litter including two shrub species, *C. microphylla* and *A. halodendron*, and a mixture of annual plants were collected in September 2001. We selected these two shrub species as the experiment because they are the dominant plant life form in Horqin sandy land and have been widely used in reforestation programs to stabilize shifting sand. The *C. microphylla* litter was the fallen senescent leaves. The *A. halodendron* litter consisted of fallen leaves and fallen glumes. Annual plant litter was the mixture of the leaves and stems of the three dominant species *A.scoparia*, *S.collina*, and *S.viridis*. Litter from the annual plants was harvested directly from the plants at the end of the growing season when annual plants were standing dead. All litters were dried at 35°C for five days, individually ground to pass a 0.5 mm sieve, and kept in sealed plastic bags.

Twenty-four soil samples (0–5 cm depth) were taken on July 2002 from four different habitats: (1) shifting sand dune (2) semifixed sand dune (3) fixed sand dune, and (4) interdunal lowland. Each habitat encompasses three sites as three replicates. On each site, two sampling locations were distinguished: one from beneath the canopies of *C. microphylla* and another from the open areas among the shrubs. For the shifting sand dune, one sample was taken from beneath *A. halodendron* and another from bare patches. Each sample was obtained by mixing five subsamples collected from five randomly selected points. Soil samples were placed in sealed plastic bags. At the laboratory, each soil sample was thoroughly mixed and sieved to 2 mm to remove roots and incorporated litters. Part of each sieved sample was air-dried for particle size distribution and chemical analysis. The remaining fresh samples were sealed in plastic bags and stored at 4°C for C mineralization determination.

In addition, aboveground fallen litter on each site was collected in 20 × 20 cm quadrants. Soil at 0–5 cm depth was taken in an area of 20 × 20 cm to determine the litter incorporated into soil. Five points were measured in each site of each habitat.

Laboratory Analysis

Soil water content was measured by dry weight at 105°C. Soil particle size distribution was determined by the pipette method in a sedimentation cylinder, using Na-hexamethaphosphate as the dispersing agent (Day, 1965). Soil pH and electrolytic conductivity (EC) were determined with a combination pH electrode (Multiline F/SET-3, Germany) in a 1:1 soil-water slurry and 1:5 soil-water aqueous extract,

respectively. Soil organic C was measured by the $K_2Cr_2O_7-H_2SO_4$ oxidation method of Walkey and Black (Nelson & Sommers, 1982), total N by the Kjeldahl procedure (UDK140 Automatic Steam Distilling Unit, Automatic Titroline 96, Italy) (ISSCAS, 1978). The same method for soil samples was employed to determine the C and N concentration of litter samples.

Mineralization Incubation Experiment

Potential C mineralization was measured by incubation of soil. Each soil sample was designed four treatments (without litter, with *C. microphylla* litter, *A. halodendron* litter, and annual plant litter). Twenty g samples of fresh soil were thoroughly mixed with 0.05 g of litter and placed in 250-mL incubation stoppered glass jar. Soil controls were run without any litter. Distilled water was added to the soil-litter mixtures and the soil samples (2–4 mL) in order to bring their water content to 60% of their maximum water-holding capacity. Then the jars were kept in dark at 28°C for 33 days. A 20 mL polypropylene vial containing 10 mL 0.2 mol NaOH solution was placed inside each jar. At 3-day interval the vial was taken out and CO₂ emitted was determined by titration of the NaOH solution with 0.2 mol HCl in an excess of BaCl₂, using phenolphthalein as indicator. The values of CO₂-C evolved were divided by the soil samples (on an over-dried weight soil basis). All incubations were carried out in duplicate.

Statistical Analysis

One-way analysis of variance (ANOVA) procedures were used to detect the difference in C mineralization of soils under different habitats and compare the effects of different litter treatments on C mineralization within each soil in each habitat. The LSD tests were performed to determine the significance of treatment means at $P < 0.05$. A paired-samples *t*-test was applied to test for the difference between soils from beneath and outside the canopy on each habitat.

Results

Comparison of C Mineralization of Soil Among Habitats

The litter mass and the contents of soil organic C, total N, and fine particle fractions varied greatly among the habitats, with the greatest values in the lowland and the lowest in the shifting sand dune (Table 1). Also, significantly higher organic materials and contents of organic C and total N, silt, and clay were found in soils from beneath the canopies of shrub compared with soils from the outside shrub canopies within the same microhabitats, showing the typical effect of “fertile island” in arid and semiarid desert systems (Schlesinger et al., 1996; Wezel et al., 2000).

The differences in C mineralization among soils from different habitats was significant ($F = 136$, $P < 0.0001$). Also, significant differences were observed between soils amended with the same litter in different habitats ($P < 0.0001$). Regardless of the addition of litter, the lowland soil had significantly higher C mineralization (total CO₂-C evolved: 552–702 $\mu\text{g C g}^{-1}$) than the fixed sand dune (313–575 $\mu\text{g C g}^{-1}$), the semifixed sand dune (287–354 $\mu\text{g C g}^{-1}$), and the shifting sand dune (27–59 $\mu\text{g C g}^{-1}$) (Figure 1). This pattern agrees with that of the soil organic C amounts, which also vary according with the phytomass and litter production gradients. Within the same habitat, C mineralization of soil from beneath shrub was significantly higher than that of soil from the outside shrub ($t = 6.8$, $P < 0.0001$). After 33 days of incubation, the addition of litter to the soil caused an increase of 164% on average C mineralization in all habitats. The mean total CO₂-C evolved was $935 \pm 326 \mu\text{g C g}^{-1}$ in the

TABLE 1 Characteristics of Soils in Different Microhabitats

Habitat	Sampling location	Particle size distribution (%)					Organic C g kg ⁻¹	Total N g kg ⁻¹	C/N ratio	pH(H ₂ O)	EC μ s cm ⁻¹	Soil water content g kg ⁻¹	Below-ground	Aboveground
		Coarse-fine sand	Very fine sand	Silt	Clay	Litter mass* g m ⁻²							Litter mass g m ⁻²	
Shifting sand dune	outside	97.2±0.9	1.6±0.3	0.7±0.4	0.4±0.2	0.42±0.04	0.078±0.006	5.38±0.12	7.75±0.05	16±1	7.2±0.3	3±4	19±6	
	canopy under	95.7±0.8	3.4±0.7	0.4±0.1	0.5±0.2	0.61±0.10	0.096±0.012	6.35±0.49	7.71±0.03	17±2	9.2±0.3	13±6	44±12	
Semifixed sand dune	outside	90.7±2.6	5.9±1.4	2.5±1.1	0.8±0.3	2.22±0.28	0.284±0.035	7.82±0.20	7.74±0.03	33±7	5.5±0.3	76±21	132±24	
	canopy under	88.3±1.9	7.6±0.9	3.5±0.9	0.7±0.2	2.78±0.37	0.303±0.028	9.17±0.54	7.72±0.04	51±8	8.8±1.6	198±34	268±34	
Fixed sand dune	outside	81.5±3.1	10.6±1.9	5.7±0.8	2.2±0.5	2.56±0.50	0.288±0.028	8.89±0.99	7.68±0.04	48±7	11.0±2.0	133±22	425±30	
	canopy under	77.8±2.9	13.5±2.5	7.1±1.3	1.6±0.4	3.54±0.53	0.361±0.050	9.8±0.39	7.55±0.07	52±11	21.2±2.7	320±40	526±84	
Interdunal lowland	outside	62.5±1.9	25.5±1.7	9.6±0.6	2.4±0.6	5.85±0.22	0.526±0.029	11.12±0.18	7.58±0.04	54±4	25.4±1.2	163±25	486±105	
	canopy under	58.0±2.8	26.3±2.2	12.9±2.1	2.8±0.2	6.05±0.45	0.549±0.027	11.02±0.47	7.25±0.18	83±18	30.7±3.4	681±133	784±100	

Values are means (±standard deviation) of n = 3,
*litter mass incorporation into soil (0–5 cm depth).

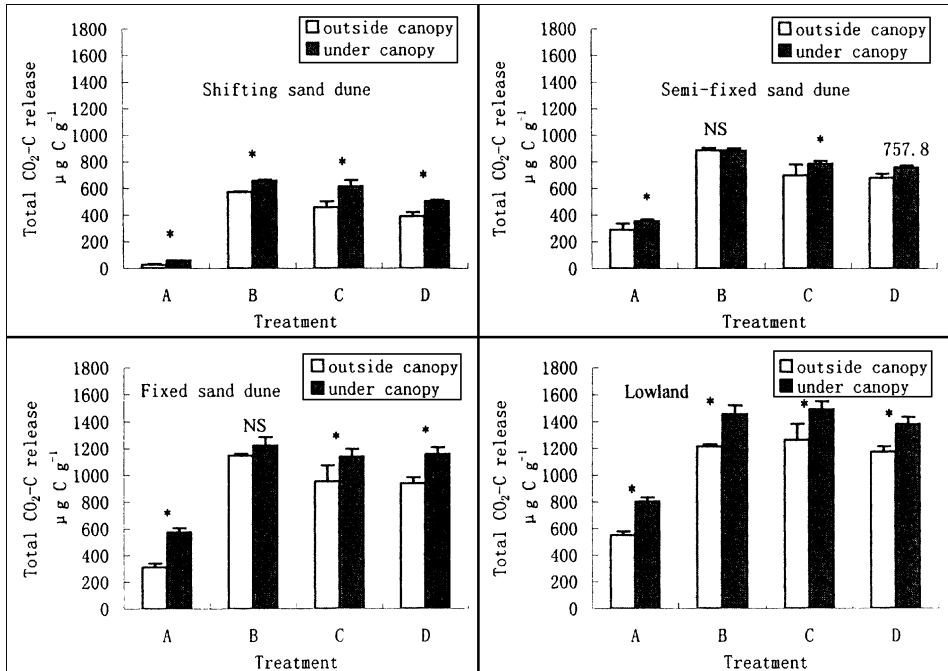


FIGURE 1 Total of CO₂-C evolved during 33 days of incubation of soils from the four sandy habitats. Treatments: (A) soil without litter; (B) *C. microphylla* litter amended soil; (C) *A. halodendron* litter amended soil; (D) Annual plant litter amended soil. *: significant ($P < 0.05$); NS: not significant ($P > 0.05$) with paired-samples t -test. $n = 3$. Bars represent one standard error of the mean.

litter addition treatment, compared to the $359 \pm 242 \mu\text{g C g}^{-1}$ in the treatment without litter. Also, the relationship between the CO₂-C respired and time of incubation (Figure 2) indicated that, at any given time, CO₂-C respired was greater for all the litter treated soils over the without litter treated soils within all the same microhabitats.

Comparison of Effect of Different Litters on C Mineralization

The litters used in this study varied in C and N contents and C/N ratios (Table 2). Carbon concentrations were similar between the *C. microphylla* litter, *A. halodendron* litter, and the annual plant litter, but N concentration in the *C. microphylla* litter was about two times and three times higher than that in the *A. halodendron* litter and in the annual plant litter, respectively. Thus, the C/N ratio was much lower in the *C. microphylla* litter.

Carbon mineralization potential of the three types of litter amended soils under all habitats followed the same trend during 33 days of incubation: an early stage of fast decomposition followed by a subsequent slow decomposition stage (Figure 2). For instance, the *C. microphylla* litter amended soil under the canopy of shrub in the fixed sand dune averaged $696 \mu\text{g CO}_2\text{-C}$ respired in the first nine days of incubation, accounting for 57% of total cumulative CO₂-C in the 33 days of incubation. After 33 days of soil incubation, total respiration between the three types of litter addition was significantly different in the shifting sand dune ($F = 8.2$, $P = 0.004$) and in the semifixed sand dune ($F = 18.7$, $P < 0.0001$), with the greatest for *C. microphylla* litter-amended soil and the lowest for annual plant litter treated soil (Figure 1). In the fixed sand dune and lowland habitats, the total respiration followed treatments

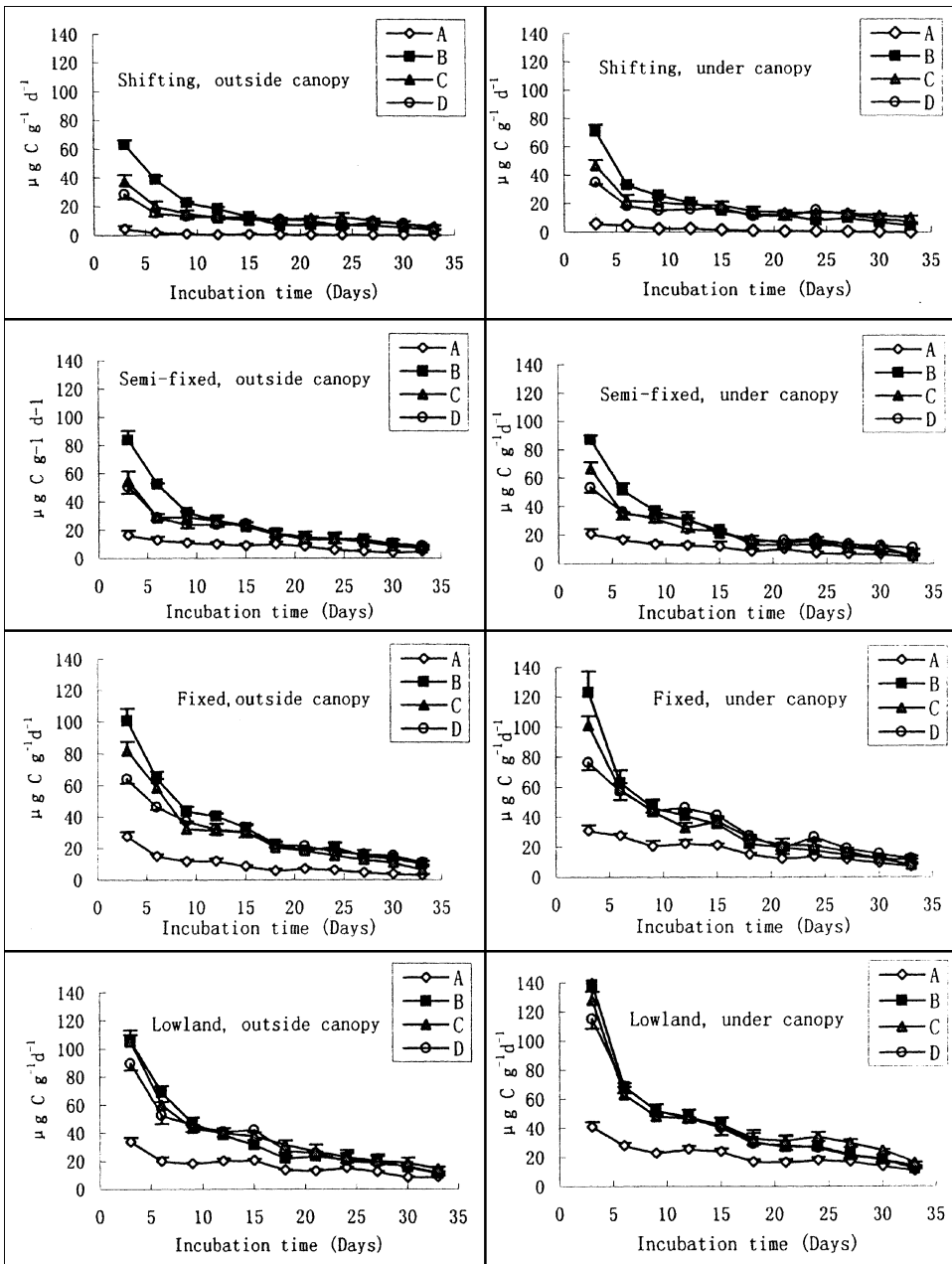


FIGURE 2 Patterns of CO₂-C evolved during 33 days of incubation of soils from the four sandy habitats. Treatments: (A) soil without litter; (B) *C. microphylla* litter amended soil; (C) *A. halodendron* litter amended soil; (D) annual plant litter amended soil. n = 3. Bars represent one standard error of the mean.

in the order of: *C. microphylla* litter-amended soil \approx *A. halodendron* litter-amended soil > annual plant litter amended soil. There were, however, little statistical significant differences ($F = 3.1$, $P = 0.08$; $F = 0.75$, $P = 0.49$, respectively). The differences in C mineralization between the three types of litter addition were mainly attributed to accumulative CO₂-C respired in the first nine days of incubation. Figure 2 shows

TABLE 2 Characteristics of Litters

Litter types	C	Total N g kg ⁻¹	C/N ratio
<i>C. microphylla</i> ¹ (leaves)	416	26.5	15.7
<i>A. halodendron</i> (leaves + glumes)	395	13.1	30.2
Annual plants ² (leaves + stems)	385	9.7	39.7

¹Leguminous shrub.

²Mixture of *Artemisia scoparia*, *Salsola collina* and *Setaria viridis*.

high N content *C. microphylla* litter decomposed more quickly in the first six days or nine days of incubation, compared with the low N content *A. halodendron* litter and annual plant litter, but in subsequent stage of incubation, differences have disappeared.

Discussion

In arid and semiarid desert ecosystems, soil organic matter concentration is one of the most important factors in the storage of nutrients in nutrient-poor sandy soils (Wezel et al., 2000). Also, soil organic C as an energy source for microbial processes is a determinant for soil N and P availability (Gallardo & Schesinger, 1992) which has been considered as the main limiting nutrients for plant productivity in arid and semiarid desert ecosystems (Ettershank et al., 1978; Fisher et al., 1987). However, soil organic C content is strongly affected by plant productivity and litter inputs (Hook et al., 1991). In the semiarid Horqin sandy land ecosystem, the development and reversion of desertification strongly affected the vegetation dynamics, and in turn the loss and sequestration of soil organic C. The results in this present study indicated that in the habitat transformation from the fixed sand dune to the shifting sand dune, 91% of soil organic C was lost (Table 1). Carbon mineralization, as an indicator of soil microbial activity, was in accordance with the spatial patterns of soil organic C. This indicated that desertification not only reduced the bulk of organic C, but also seriously depleted soil labile C pool. Land desertification is, in fact, a process depleting soil C pool.

Carbon mineralization was influenced by a number of factors including soil structure, soil water content, temperature, and the nature of soil microorganisms and fauna (Côté et al., 2000; García & Hernández, 1996; Huang et al., 2002; Parton et al., 1987; Yang et al., 2002). In laboratory studies that control temperature and moisture, soil respiration reflected soil availability of easily mineralizable organic C and differences in soil environmental factors (Mazzarino et al., 1991). Some studies suggested that soil structure is a dominant factor in organic matter breakdown in ecosystems, and organic C of sandy soils is mineralized more rapidly than that of clayey soils (García & Hernández, 1996). In our studies, soils are very sandy and organic C contents are largely varied among sites. Despite there being a close linear relationship between organic C content and silt and clay content (Figure 3), the protection of clay and silt on soil organic C is limited. The results showed that the relationship between accumulative soil C mineralization rate (on an organic C basis) and clay and silt content was not in agreement with other researchers (Christensen, 1992), who suggested that soil C mineralization rates declined with increasing soil clay content (Figure 3). In contrast, soil C mineralization rates of the shifting sand dune, even with addition of exogenous substrates, were the lowest. Further, from the shifting sand dune to the fixed sand dune, C mineralization rates increased with

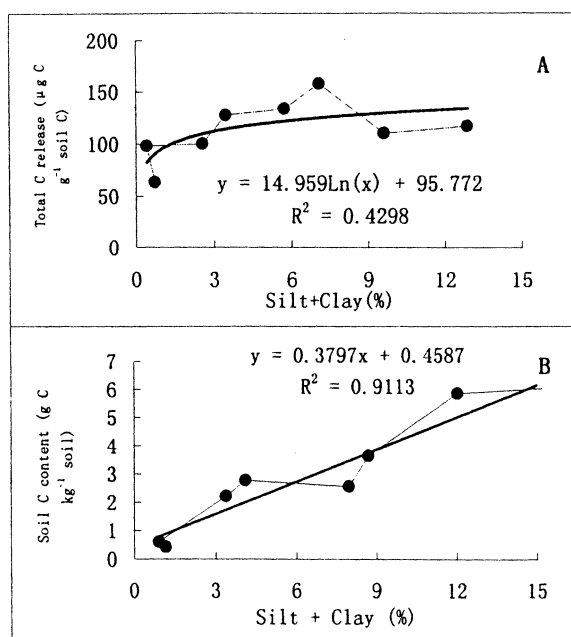


FIGURE 3 (A) Relationship between soil organic C content (g kg^{-1} soil) and soil silt + clay content (%) for sandy soils; (B) Relationship between total C release ($\mu\text{g C g}^{-1}$ soil C) over 33 days and soil silt + clay content (g kg^{-1}) for sandy soils.

increasing soil fine particle fractions (Figure 3). When soil clay and silt content reached a relatively higher level, soil C mineralization rates declined with increasing soil clay content. A rational explanation is that soil microorganisms as decomposer of organic matter are very poor in sandy soils. Hence, even with addition of exogenous substrates, the poor microorganisms in sandy soils had limited response to a new C input, and the decomposition is very weak. This suggested that the natural restoration of soils in serious desertification land could be a very slow process.

In addition, the litter quality added to soils can exert a profound influence on C mineralization, as revealed by the use of the content of lignin and N, and C/N and lignin/N ratios (Côté et al., 2000; Melillo et al., 1982; Yang et al., 2002). High litter N contents have been considered to greatly increase decomposition rates, and positive correlation between C mineralization and N contents had been reported in many studies (Iyamuremye et al., 2000; Yang et al., 2002). Also, the C/N ratio was mostly related to the litter mass loss in the early stage of mineralization (Taylor et al., 1989). In line with these results, Figure 2 shows that soils with *C. microphylla* litter which had the higher N content and lower C/N ratio exhibited the larger microbial respiration rate in the first days of incubation. While the reverse was true for soils with annual plants litter, which had the lowest microbial respiration in the first days of incubation due to its lower N content and wider C/N ratio. The results suggested that soil microbial activity could be improved by amending with *C. microphylla* litter with a higher N content. However, little significant differences in total $\text{CO}_2\text{-C}$ respired over the incubation period were found in the fixed sand dune and lowland habitats among the three types of litter-amended soils. This indicated that improved soil conditions such as soil structure, sources of labile C, and nutrients could reduce the effect of litter quality on C mineralization.

The activity of microorganisms mainly depends on the substrate N availability. Nitrogen inputs from litters could contribute well in meeting the N requirement

of the decomposers and produce a stimulating effect on C mineralization (Vestergaard, 2001). The initial N content of the litter may exert a great influence on C mineralization. In the present work, the amount of CO₂-C released from litter (evolution of CO₂-C in samples with litters minus that from the respective control soil) was in the range of 14.7% ~ 28.2% higher for the N-rich leguminous shrub litter compared to nonleguminous shrub litter and annual plants litter with relatively lower N contents. The stimulating effect of litter N on decomposition existed only in the first phase of the incubation. During the 0~9 days of incubation, the cumulative amount CO₂-C released from *C. microphylla* litter was 34.8% ~ 60.6% higher than that from *A. halendroden* litter and the annual plant litters. However, no significant difference was found for the cumulative respiration during the 9~33 days of incubation among the three litters. This was most likely due to a high initial use of litter N, resulting in less difference among the three litters with incubation time. Results also showed that the cumulative respiration was significant for the leguminous shrub litter amendment only in the shifting and semifixed sand dune areas in comparison with the nonleguminous shrub litter and annual plant litter treatments (Figure 1). These results suggested that there is a spatial pattern of N availability, in which the fixed sand dune and lowland habitats have relatively higher N availability to microbes due to larger plant biomass, especially N-fixers. Compared to the shifting and semifixed sand dunes, the development and growth of leguminous *C. microphylla* have been altering the nutrient status of soil microbes by increasing soil N availability through inputs of litters and N fixation in the fixed sand dunes and lowlands. Thus, availability of N from the soils might have obscured differences in litter N on C mineralization among the studied litters.

Desert shrubs have a profound effect on the distribution of soil resources and biochemical processes (Halvorson et al., 1995). Not only were significantly higher concentrations of organic C and nutrients accumulated under the canopies of shrub (Schlesinger et al., 1996; Su et al., 2002; Wezel et al., 2000), but also the greatest moisture concentration, greatest shade, and lowest daytime temperature as well as the major source of food for most herbivores and animals that prey on them were distributed under shrub (Garner & Steinberger, 1989). These factors would stimulate the growth and activity of microorganisms which in turn affects the mineralization of organic C favoring plant mineral nutrients (Aguilera et al., 1999). In line with these results, it was found that *C. microphylla* and *A. halodendron* in the Horqin sandy land ecosystems created islands of fertility with larger soil organic C, N contents and microbial activities compared to the outside shrubs. Further, *C. microphylla* and *A. halodendron*, acting as seed accumulators and fertile islands, may also facilitate the colonization of annual plant species by shielding wind-dispersed seeds of these species beneath their canopies and increasing the possibility of their recruitment. The growth of annual plants increases the vegetation cover and sandy land productivity. Therefore, shrubs significantly contributed to C sequestration in sandy land ecosystems.

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