Effects of ecological restoration on soil properties of the aeolian sandy land around Lhasa, southern Tibetan Plateau

CHENRUI LIAO,1,2,3,4 HAIDONG LI,2 GUOPING LV,1,3 JIARONG TIAN,1,3 AND YANNAN XU1,3,

1Nanjing Forestry University, Nanjing, 210037 China
2Nanjing Institute of Environmental Sciences, Ministry of Ecology and Environment, Nanjing, China
3Centre of Co-Innovation for Sustainable Forestry in Southern China, Nanjing Forestry University, Nanjing 210037 China
4School of Forestry and Environmental Studies, Yale University, New Haven, Connecticut 06511 USA

Citation: Liao, C., H. Li, G. Lv, J. Tian, and Y. Xu. 2020. Effects of ecological restoration on soil properties of the aeolian sandy land around Lhasa, southern Tibetan Plateau. Ecosphere 11(1):e03009. 10.1002/ecs2.3009

Abstract. The ecological restoration of aeolian sandy land has not only improved the function of ecosystem services, such as wind prevention and sand fixation, but also indirectly reduced the regional economic losses caused by sandstorms. However, the interaction between vegetation and soil properties after natural and artificial restoration of the sandy land in southern Tibetan Plateau has not been sufficiently studied. In the present study, we selected four vegetation types, including artificial forest (A), revegetated shrub (B), natural shrub (C), and natural grassland (D), in the sandy land in the middle reaches of the Yarlung Zangbo River basin, Tibet, China, and investigated the changes in soil particle size and nutrients at depths of 0–20 cm and 20–40 cm, finally examining the potential relationships between soil properties and leaf nutrients. Our results indicated that in the topsoil (0–20 cm), the natural shrub (C) and natural grassland (D) have greater silt content, recorded as 50.77% and 62.16%, respectively, compared to the artificial forest (A) and revegetated shrub (B). Natural grassland (D) had the highest silt content and the lowest soil bulk density (SBD) among the four vegetation types. There was no significant difference in the soil organic matter (SOM) in the topsoil of the different vegetation types. However, at the depth of 20–40 cm, the SOM content of the different vegetation types was in the following order: natural grassland (D) (23.37 g/kg) > natural shrub (C) (17.42 g/kg) > revegetated shrub (B) (14.85 g/kg) > artificial forest (A) (8.43 g/kg). The ammonium nitrogen content (NH₄-N) in the revegetated shrub (B) was higher compared to the other vegetation types. The SOM content was significantly correlated with the total phosphorus (TP) and available phosphorus (AP) of the sandy land. The leaf total carbon, nitrogen, and phosphorus exhibited a positive correlation with SBD, AP, and available potassium. These findings can provide useful information to optimize the patterns of natural and artificial restoration for controlling desertification in similar eco-regions.

Key words: aeolian sandy land; ecological restoration; soil properties; Tibetan Plateau.

INTRODUCTION

Land degradation is considered as one of the major global problems closely related to food security threats, reduction of ecosystem services, and biodiversity losses (Chen et al. 2017, Wolff et al. 2018). Globally, 169 countries are experiencing negative effects of land degradation and/or drought, and the global economy would have lost $23 trillion by 2050 (UNCCD 2018a); for example, the most productive areas in Somalia are experiencing the highest risk of degradation...
due to deforestation, overgrazing, and poor cultivation practices (UNCCD 2018b). Aeolian desertification is a form of land degradation process that is mainly caused by climate change and irresponsible human activities in arid, semiarid, and some sub-humid regions (Zheng et al. 2006, Shen et al. 2012, Guan et al. 2017). The Tibetan Plateau, located in southwestern China, is one of the world’s most sensitive areas to global warming and human activities, as the mean elevation is over 4000 m above sea level (Wang et al. 2016). Aeolian desertification in the Tibetan Plateau is primarily controlled by climatic conditions and landforms, which act differently on the different eco-regions of the plateau (Zhang et al. 2018). The area of desertified land in the Tibet Autonomous Region and Qinghai Province was 34.04 × 10^6 ha in 2014 (State Forestry Administration, P. R. China 2015). The damage caused by sandstorms has caught the attention of scholars and local governments alike (Li et al. 2013). The internal driving forces for the development and external driving forces for the increase in aeolian sandy lands are climate change and human activities (Shen et al. 2012, Li et al. 2016a, b).

Types of ecological restoration include artificial and natural restoration, which are considered as two effective measures for the management of degraded ecosystems (Jin et al. 2014, Liao et al. 2019). In 2015, the General Office of State Council of China promulgated “the opinions on accelerating the construction of an ecological civilization,” proposing that natural restoration is the main measure in the process of ecological restoration and should be combined with artificial recovery; both these measures have been used to control desertification in the Tibetan Plateau (Li et al. 2019a). Natural restoration is an ecosystem management approach to reduce the adverse effects of unreasonable human activities, such as overgrazing, extensive land reclamation, and excessive firewood collection (Shen et al. 2012, Peng et al. 2019). Artificial restoration mainly includes afforestation and revegetation of a seriously degraded land (Kang et al. 2018, Liao et al. 2019). Many scholars have initiated studies on ecological restoration to control the spread of aeolian desertification and restore degraded grasslands. These studies have explored the artificial restoration of ecosystems (Li et al. 2008), screening of suitable plant species (Li et al. 2019a), the effects of fencing enclosures on soil seed banks (Shang et al. 2013), and the effects of micro-topography on revegetation (Li et al. 2019a). Li et al. (2013) investigated the spatiotemporal variability of soil moisture in an aeolian riparian ecotone in an extremely dry year and found that the soil moisture content showed great spatial and temporal variability, and had a great effect on artificial restoration of the sandy land. Previous studies have shown that Artemisia sphaerocephala, Artemisia younghusbandii, and Heteropappus gouldii are suitable as the pioneer species for revegetation of a sandy land (Li et al. 2019a, Liao et al. 2019). However, few studies have been conducted to investigate the effect of ecological restoration on soil properties of sandy land, as well as the relationships between soil and plants in a phase of vegetation recovery, in the middle reaches of the Yarlung Zangbo River basin.

Understanding the effects of ecological restoration on soil properties is important to clarify the rules governing artificial restoration of the aeolian sandy land in the Tibetan Plateau. Here, we carried out a case study to (1) investigate the variation in soil properties for the different vegetation types of the aeolian sandy land, (2) explore the correlation between soil properties and plant characteristics, and (3) provide suggestions for the ecological restoration of the aeolian sandy land. Our initial hypotheses were as follows: (1) Natural and artificial restoration lead to significant changes in soil properties, especially in the soil particle size and soil organic matter (SOM), and (2) unlike other ecologically fragile areas, there are no significant differences in the soil properties between 0–20 cm and 20–40 cm, due to strong sand movement in the alpine valley.

**Methods**

**Study area**

This study was conducted in the middle reaches of the Yarlung Zangbo River, in Shannan City, Tibet, China (Fig. 1). The study region had a temperate forest–grassland climate. The annual mean temperature was 6.3°–8.8°C, and the total number of sunshine hours ranged from 2600 to 3300 hours. The average annual rainfall was 410 mm, the majority of which occurred from June to September. In winter and spring, winds
were frequent and strong in the alpine valley of the river basin. The annual average wind speed was about 3 m/s, and the monthly maximum wind velocity was 17 m/s in the area. The soil was sandy with gravel, accumulated by blowing winds or wind erosion, and characterized by short formation time, coarse texture, and low water retention and fertilizer conservation (Li et al. 2013).

To prevent and control sandstorms, the local government has implemented a series of ecological protection and restoration projects, including afforestation, revegetation of the sandy land, and grassland restoration (Li et al. 2016a). A series of continuous investments in vegetation recovery has improved regional ecosystem services and mitigated the damage of sandstorms. The species for revegetation included Salix alba L., Artemisia wellbyi, Sophora moorcroftiana, Stipa bungeana Trin., Populus alba var. pyramidalis, Oxytropis sericeopetala, A. younghusbandii, Hedysarum scoparium, Caragana microphylla Lam., and Orinus thoroldii (Li et al. 2019a).

Experimental design

We selected four experimental sites in the aeolian sandy land (Fig. 2 and Appendix S1, Table S2): (A) artificial forest, (B) revegetated shrub, (C) natural shrub, and (D) natural grassland. (Table 1). The artificial forest (A) and revegetated shrub (B) represented artificial restoration sites, while natural shrub (C) and natural grassland (D) were natural restoration sites. Both these measures, that is, natural and artificial restoration, had been undertaken over 10 yr. Three of the sites were located on flat ground, while the natural grassland had a slope of ~ 5°–10° with a north-facing aspect. We set up twelve quadrats at the experimental sites for field investigation in July 2017, with three quadrats per vegetation type. The quadrat sizes were different for forest, shrub, and grassland vegetations; that is, the quadrat size was 30 × 30 m in artificial forest (A), 5 × 5 m in revegetated and natural shrubs (B and C), and 1 × 1 m in natural grassland (D). In total, 24 soil samples and 24 soil cores were collected at depths of 0–20 cm and 20–40 cm, with six samples and six cores per vegetation type. Each soil sample consisted of five subsamples collected from five points (four corners and one central point) in each quadrat. In addition, a vegetation survey was conducted in each quadrat. The diameter at breast height (dbh) was only investigated in artificial forest.
The crown diameter (long × short) was investigated in revegetated and natural shrubs (B and C). The height and coverage were measured in revegetated shrub (B), natural shrub (C), and natural grassland (D). Leaf samples were collected separately from the dominant species of each quadrat. For the artificial forest (A), revegetated shrub (B), and natural shrub (C), leaves were collected from 20 randomly selected plants in each quadrat and combined to form one sample per quadrat. For artificial forest (A), fresh leaves were sampled from 20 trees, from the middle of the branches of the lower and middle outer canopies, and then pooled for each quadrat. For natural grassland (D), all plants (*S. bungeana*) were cut at the root collar to separate the aboveground parts (leaves) in each quadrat. Twelve leaf samples were collected in total from the dominant species, that is, *S. alba* L., *A. wellbyi*, *S. moorcroftiana*, and *S. bungeana*, with three samples per plant species (totaling 240 plants, that is, 20 plants per quadrat × 3 quadrats per vegetation type × 4 revegetation types).

**Determination of soil properties**

Soil bulk density (SBD) was measured for the soil core (100 cm³) taken from each quadrat. Fresh soil samples were used to determine the nitrate nitrogen (NO₃-N) and ammonium nitrogen (NH₄-N). The NO₃-N was extracted with sodium chloride and detected by colorimetry. The micro-Kjeldahl method was used to test for NH₄-N (Latifah et al. 2017). The soil moisture content (SMC) was determined immediately after sampling from the field, in triplicate, by drying in an oven at 105°C for 24 h. After air-
drying, a part of soil samples were sieved, by mechanical sifting, into four categories of particle diameters (<0.1, 0.1–0.5, 0.5–1, and 1–2 mm), of which the <0.1 mm category was further divided into clay (<0.002 mm), silt (0.002–0.05 mm), and very fine sand (0.05–0.1 mm), using the hydrometer method. The soil particle sizes were identified according to the USDA soil texture classification system (Zhao et al. 2016). The remaining soil samples were sieved to <0.1 mm for the determination of soil pH, soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), available phosphorus (AP), and available potassium (AK). The soil pH was determined in 1:5 soil:water extracts with a digital pH meter (Cyberscan 2100 model, Beijing, China). The dichromate oxidation method for SOM, the micro-Kjeldahl method for TN, the ammonium molybdate spectrophotometric method for AP, and the atomic absorption spectrophotometry for AK were adopted. The detailed protocols of Lu (2004) were used for the analyses of soil properties.

Analysis of leaf nutrients

All leaf samples were dried to a constant weight, for 2 h at 105°C, and 48 h at 80°C. The dried samples were ground, weighed, and analyzed for total carbon (TC) with the wet combustion method (Bowles et al. 2016). After digestion with H2SO4-H2O2, leaf samples (0.5 g) were analyzed for TN and TP using the micro-Kjeldahl and spectrophotometric methods, respectively (Santos et al. 2006).

RESULTS

Analysis of leaf nutrients

All leaf samples were dried to a constant weight, for 2 h at 105°C, and 48 h at 80°C. The dried samples were ground, weighed, and analyzed for total carbon (TC) with the wet combustion method (Bowles et al. 2016). After digestion with H2SO4-H2O2, leaf samples (0.5 g) were analyzed for TN and TP using the micro-Kjeldahl and spectrophotometric methods, respectively (Santos et al. 2006).

Data analysis

A one-way analysis of variance (ANOVA) was used to analyze the differences between mean values. Duncan’s multiple range tests were used to compare the means. The soil parameter values at 0–20 cm and 20–40 cm depths were compared using the independent t-test, for each vegetation type.

To examine the correlations between soil properties and leaf nutrient contents, the Pearson coefficients (r) were calculated and presented in a rectangular correlation matrix. All statistical analyses were performed in SPSS 20.0 software.
of which the very fine sand content increased to 80.99% and silt content decreased to 11.68% at 20–40 cm. In the natural grassland (D), the silt content was 62.16% and 44.28%, while the very fine sand content was 34.38% and 51.47%, at 0–20 cm and 20–40 cm, respectively. Very fine sand and silt contents were significantly different at 0–20 cm and 20–40 cm for the natural grassland (D). In comparison with other vegetation types at the same depth, natural grassland (D) had the lowest very fine sand content and the greatest silt content.

There was a statistically significant \((P = 0.049)\) difference between the SBD of the different vegetation types (Fig. 3 and Appendix S1, Fig. S1). Natural grassland \((D; 1.55 \text{ g/cm}^3)\) exhibited a significantly lower SBD than revegetated shrub \((B; 1.80 \text{ g/cm}^3)\). The SBD of natural shrub \((C)\) was remarkably lower \((1.65 \text{ g/cm}^3)\) than that of revegetated shrub \((B)\), while the SBD of natural grassland \((D)\) was lower than that of artificial forest \((A; 1.70 \text{ g/cm}^3)\). In general, there was no significant difference in the SMC, which was about 9.5% for all vegetation types.

**Soil nutrient content.**—The sandy land was alkaline, and the pH did not vary greatly (ranging from 8.06 to 8.73) between the four vegetation types at each depth (Table 3). Significant differences between different vegetation types were found for TP at 0–20 cm, and SOM, NH_4-N, and AK at 20–40 cm (Table 3).

In the topsoil (0–20 cm), the SOM content ranged from 14.52 g/kg in artificial forest \((A)\) to 22.42 g/kg in natural grassland \((D)\). The TN content ranged from 1.35 g/kg in natural grassland \((D)\) to 2.24 g/kg in revegetated shrub \((B)\). However, they were not significantly different for the four vegetation types. The smallest TP content was recorded for the artificial forest \((A; 0.4 \text{ g/kg})\). The NH_4-N content was highest in revegetated shrub \((B; 18.67 \text{ mg/kg})\), followed by in artificial forest \((A)\), natural shrub \((C)\), and natural grassland \((D)\), but it was not significantly different. The AK content in artificial forest \((A)\) was the highest \((47.47 \text{ mg/kg})\).

At the depth of 20–40 cm, there was a statistically significant \((P < 0.05)\) difference in all chemical indicators of the four vegetation types, except TN, NO_3-N, TP, and AP contents (Table 3). The highest SOM content was observed in natural grassland \((D; 23.37 \text{ g/kg})\), while the lowest was observed in artificial forest \((8.43 \text{ g/kg})\). The AK content was 37.76 mg/kg in revegetated shrub \((B)\), which was higher than at other sites. The NH_4-N content had the highest value in revegetated shrub \((B; 18.78 \text{ mg/kg})\). The TP

---

**Table 2. Soil particle size of different vegetation types in depths of 0–20 and 20–40 cm in the middle reaches of Yarlung Zangbo River basin.**

| Depth   | Vegetation types | Very coarse sand \((1-2 \text{ mm})\)/% | Coarse sand \((0.5-1 \text{ mm})\)/% | Medium-fine sand \((0.1-0.5 \text{ mm})\)/% | Very fine sand \((0.05-0.1 \text{ mm})\)/% | Silt \((0.002-0.05 \text{ mm})\)/% | Clay \(<0.002 \text{ mm})$/% |
|---------|------------------|--------------------------------------|-------------------------------------|------------------------------------------|-------------------------------|-----------------------------|--------------------------|
| 0–20 cm | Artificial forest | 0.02 ± 0.03                          | ...                                 | 2.96 ± 0.88 a                           | 89.58 ± 12.10 a              | 7.44 ± 11.27 a             | ...                      |
|         | Revegetated shrub| 0.01 ± 0.01                          | ...                                 | 3.81 ± 1.19 a*                          | 76.67 ± 5.45 a               | 19.52 ± 6.32 a            | ...                      |
|         | Natural shrub     | ...                                  | ...                                 | 3.16 ± 0.38 a                           | 46.03 ± 6.60 b*              | 50.77 ± 6.25 b*           | 0.04 ± 0.07             |
|         | Natural grassland | 0.02 ± 0.03                          | ...                                 | 3.45 ± 1.41 a                           | 34.38 ± 5.41 b*              | 62.16 ± 6.13 b*           | ...                      |
| 20–40 cm| Artificial forest | 0.02 ± 0.03                          | ...                                 | 2.81 ± 2.21 ac                          | 83.55 ± 0.94 a               | 13.62 ± 3.09 a            | ...                      |
|         | Revegetated shrub| 0.01 ± 0.01                          | ...                                 | 8.39 ± 1.04 b*                          | 79.86 ± 4.91 a               | 11.75 ± 3.95 a            | ...                      |
|         | Natural shrub     | ...                                  | ...                                 | 7.26 ± 1.79 bc                          | 80.99 ± 5.50 a*              | 11.68 ± 7.35 a*           | 0.06 ± 0.10             |
|         | Natural grassland | 0.02 ± 0.03                          | ...                                 | 4.18 ± 1.36 c                           | 51.47 ± 5.63 b*              | 44.28 ± 5.75 b*           | 0.06 ± 0.10             |

Notes: Values are mean ± SD. The ellipses represented the null value or zero. Values at the same depth followed by the same letter within columns are not significantly different at \(P < 0.05\).

* Statistically significant differences between different depths in the same vegetation type \((P < 0.05)\).
content was 0.59 mg/kg in natural shrub (C), which was significantly higher than that in artificial forest (A; 0.39 mg/kg). Furthermore, AK at the depth of 0–20 cm was significantly higher than that at 20–40 cm.

Vegetation growth and leaf nutrients of dominant species in the aeolian sandy land

Four dominant species, including S. alba L., A. wellbyi, S. moorcroftiana, and S. bungeana, were analyzed in natural and artificial restoration (Table 4). The dbh and height of S. alba L. were 15.37 cm and 4.33 m, respectively. The height of A. wellbyi and S. moorcroftiana ranged from 0.43 to 0.49 m, and the mean value of crown diameter was higher in S. moorcroftiana (82.98 × 67.05 cm) than in A. wellbyi (39.12 × 29.53 cm). The height of S. bungeana was 0.28 m. The vegetation coverage of each type ranged from 46.67% to 63.33%.

The leaf total nitrogen (LTN) content varied remarkably in the different dominant species ($P < 0.01$) and was in the order of S. moorcroftiana (25.73 g/kg) > S. alba L. (22.77 g/kg) > A. wellbyi (18.81 g/kg) > S. bungeana (8.50 g/kg). For leaf total phosphorus (LTP), the highest content was detected in A. wellbyi (5.19 g/kg), followed by S. alba L. (4.95 g/kg), S. moorcroftiana (2.77 g/kg), and S. bungeana (2.12 g/kg), in decreasing order. The leaf total carbon (LTC) content did not differ significantly between the four dominant species, with values ranging from 439.38 g/kg to 488.31 g/kg.

**DISCUSSION**

**Effects of vegetation on soil properties after ecological restoration**

Soil is a key natural resource and an integral contributor of ecosystem services necessary to support plant-based life, and the soil structure is greatly influenced by the vegetation type (Merrill et al. 2013, Zhao et al. 2017). Our results showed that the soil silt content in the topsoil (0–20 cm) presented an increasing trend for the four vegetation types, as follows: artificial forest (A) < revegetated shrub (B) < natural shrub (C) < natural grassland (D). The very fine sand content was negatively correlated with silt content ($r = -0.943; P < 0.01$). The fixed sandy land was covered by biological soil crusts, which detained nutrient-rich dust and protected the soil from wind erosion in the middle reaches of the Yarlung Zangbo River (Yang et al. 2011, Li et al. 2013). Silt content increased with developing biological soil crusts, but the magnitude of increase declined with depth (Zhao et al. 2011). As fixed sandy lands, the silt content in natural shrub (C) and grassland (D) was higher than that in artificial forest (A) and revegetated shrub (B), and it visibly decreased with increasing soil depth in natural shrub (C) and grassland (D). Therefore, the effect of biological soil crusts on silt contents in different vegetation types and at different soil depths of the aeolian sandy land in the alpine valley needs further research. It must be noted...
that the highest silt content and the lowest SBD were recorded for natural restoration.

Soil nutrients are an important factor influencing the effectiveness of revegetation (Maestre et al. 2003). At present, the effect of SOM on the improvement of soil structure stability, such as resistance to erosion, has been extensively documented (Cerdan et al. 2010, Prosdocimi et al. 2016, Paul and Giménez 2017). Even under varying climatic conditions, many authors have shown that SOM is the key factor explaining aggregate formation and stability (Maiti 2013, Hondebrink et al. 2017). Fenton et al. (2005) concluded that surface SOM content gradually decreases with increasing erosion phase in cultivated soils. Jin et al. (2014) also found that natural restoration is more beneficial to surface organic carbon sequestration than artificial restoration, in the Loess Plateau of China. The same conclusion was reached for aeolian sandy land in the present study. Artificial forest (A) and revegetated shrub (B) had semi-fixed sandy land and higher erosion phase with lower SOM content. The SOM content was in the following order: natural grassland (D) > natural shrub (C) > revegetated shrub (B) > artificial forest (A); and exhibited a significant difference at the depth of 20–40 cm. However, contrary to our hypothesis, there was no significant difference in the SOM of the different vegetation types in the topsoil (0–20 cm), regardless of fixed or semi-fixed sandy land, and natural or artificial restoration. The possible explanation for this is that the surface soils are easily affected by erosion,

Table 3. Soil nutrient contents of different vegetation types in different depths in the middle reaches of Yarlung Zangbo River basin.

| Depth  | Vegetation types | pH  | SOM (g/kg) | TN (g/kg) | TP (g/kg) | NO3-N (mg/kg) | NH4-N (mg/kg) | AP (mg/kg) | AK (mg/kg) |
|--------|-----------------|-----|------------|-----------|-----------|---------------|---------------|------------|------------|
| 0–20 cm| Artificial forest| 8.67| 14.52 ± 11.0 a | 1.54 ± 0.64 a | 0.40 ± 0.01 a | 7.36 ± 10.65 a | 10.73 ± 4.10 a | 6.58 ± 1.33 a | 47.47 ± 10.89 a* |
|        | Revegetated shrub| 8.27| 15.70 ± 1.76 a | 2.24 ± 1.21 a | 0.51 ± 0.04 b | 1.33 ± 1.71 a | 18.67 ± 3.52 a | 5.46 ± 0.60 a | 38.49 ± 1.19 a |
|        | Natural shrub    | 8.11| 18.52 ± 3.60 a | 1.54 ± 0.24 a | 0.48 ± 0.05 ab | 5.23 ± 2.72 a | 8.28 ± 4.75 a | 5.92 ± 1.29 a | 34.67 ± 4.38 a* |
|        | Natural grassland| 8.38| 22.42 ± 6.23 a | 1.35 ± 0.49 a | 0.51 ± 0.03 b | 4.90 ± 1.54 a | 9.33 ± 5.80 a | 2.98 ± 2.26 a | 33.48 ± 2.87 a* |
| 20–40 cm| Artificial forest| 8.73| 8.43 ± 6.25 a | 0.79 ± 0.35 a | 0.39 ± 0.02 a | 0.52 ± 0.62 a | 9.10 ± 5.63 a | 5.01 ± 0.41 a | 28.54 ± 3.62 a* |
|        | Revegetated shrub| 8.24| 14.85 ± 2.46 ac| 2.43 ± 1.46 a | 0.48 ± 0.02 a | 0.19 ± 0.08 a | 18.78 ± 2.58 b | 5.66 ± 0.63 a | 37.76 ± 3.16 b |
|        | Natural shrub    | 8.06| 17.42 ± 1.05 bc| 1.63 ± 0.49 a | 0.59 ± 0.13 a | 2.52 ± 1.80 a | 5.95 ± 2.13 a | 5.07 ± 0.74 a | 23.55 ± 0.91 a* |
|        | Natural grassland| 8.41| 23.37 ± 1.97 c | 1.59 ± 0.22 a | 0.53 ± 0.07 a | 5.00 ± 4.14 a | 8.28 ± 5.70 a | 2.85 ± 2.15 a | 25.37 ± 1.73 a* |

Notes: Values are mean ± standard deviation. Values at the same depth followed by the same letter within columns are not significantly different at P < 0.05. SOM, soil organic matter; TN, total nitrogen; TP, total phosphorus; NO3-N, nitrate nitrogen; NH4-N, ammonium nitrogen; AP, available phosphorus; and AK, available potassium.

* Statistically significant differences between different depths in the same vegetation type (P < 0.05).

Table 4. The growth and leaf nutrients for four dominant species in different vegetation types.

| Dominant species | dbh (cm) | Long (cm) | Short (cm) | Height (m) | Coverage (%) | LTC (g/kg) | LTN (g/kg) | LTP (g/kg) |
|------------------|---------|-----------|------------|------------|--------------|------------|------------|------------|
| S. alba L.       | 15.37   | ...       | ...        | 4.33       | 46.67        | 488.31 ± 5.12 a | 22.77 ± 0.27 a | 4.95 ± 0.32 a |
| A. wellbyi       | ...     | 39.12     | 29.53      | 0.49       | 63.33        | 475.24 ± 26.13 a | 18.81 ± 1.15 c | 5.19 ± 0.60 a |
| S. moorecroftiana| ...     | 82.98     | 67.05      | 0.43       | 58.33        | 479.42 ± 30.12 a | 25.73 ± 1.66 b | 2.77 ± 0.16 b |
| S. bungeana      | ...     | ...       | 0.28       | 63.33      | 439.38 ± 25.36 a | 8.50 ± 0.56 d | 2.12 ± 0.27 b |

Notes: Values are mean ± standard deviation. The ellipses represented the null value. Values in the same column with the same letter are not significantly (P > 0.05). dbh, diameter at breast height; LTC, leaf total carbon; LTN, leaf total nitrogen; and LTP, leaf total phosphorus.
transportation, and deposition, of which aeolian processes are the key forces, in an aeolian sandy land (Wang et al. 2016).

In addition, *A. wellbyi* in revegetated shrub (B) may be slightly more beneficial to NH$_4^+$ adsorption, as the highest content of TN and NH$_4$-N was observed in revegetated shrub (B). In the process of ecological restoration, *A. wellbyi* has been considered as a pioneer plant to improve the growth of other species. Studies have shown that the contents of NO$_3$-N, TN, TP, and SOM generally decrease with increasing soil depth (Papiernik et al. 2009, Yang et al. 2012, Zhang et al. 2014, Wang et al. 2019). However, in this research, there was no significant difference in the TN, TP, and SOM between the depths of 0–20 and 20–40 cm, which was in line with our prediction, probably due to the effect of soil subsurface layer exposure at the soil surface in the eroded landscape (aeolian sandy land; Papiernik et al. 2009).

**Relationship between soil properties and leaf nutrients**

Soil organic matter is associated with primary mineral particles (i.e., sand, silt, and clay) in many soil types (Huang et al. 2017). Many studies have found that fine particles, especially clay and silt, have high absorption capacity for soil organic carbon (Ye et al. 2019, Zhang et al. 2019b). The natural grassland (D), with higher silt content, tended to have a higher SOM content (Tables 2, 3). SOM enhances soil biological activity and macro-pore development, resulting in a fast decrease in the SBD (Hondebrink et al. 2017). Thus, SBD in natural grassland (D) was the lowest (Fig. 3). Soil organic matter content was significantly correlated with TP and AP contents ($r = 0.452$ and $-0.489$, respectively; $P < 0.05$; Table 5). This relationship of SOM and P was consistent with that found in other ecosystems (Li et al. 2019b).

Plants can affect soil properties through the activation of C, N, and P nutrient cycles, and the degradation of organic compounds (Macci et al. 2012). In this study, to examine the potential factors related to plant growth, we correlated leaf nutrients with soil properties (Table 6). The results showed that leaf nutrients had a negative correlation with silt and SOM, while there was no significant correlation with the vegetation type. The type of revegetation, that is, forest, shrub, and grass, might explain the different soil particle sizes and nutrient acquisition patterns of leaves during the growth of such vegetation (Zhang et al. 2019a). Another possible explanation is that litter is blown away by sand movement in the alpine valley and cannot take part in the nutrient cycles. However, the recovered plants continued to consume soil nutrients, especially in the early stages of ecological restoration, which had a lower coverage (Li et al. 2013). The LTP content is restricted by the availability of P in the soil, and N fixation in plants can be affected by the soil AP, particularly by the lack of PO$_4^-$ (Zhang et al. 2019a). AP was positively correlated with LTN and LTP in this study ($r = 0.733$ and $0.584$, respectively; $P < 0.05$). Therefore, the early stages of ecological restoration need to be controlled and intervened artificially, for example, by the addition of fertilizer or topsoil, selection of mixed plants, and timely irrigation, to improve the soil nutrient content and rapidly increase the plant cover of the aeolian sandy land.

**Conclusion**

In this study, the changes in soil properties after natural and artificial restoration in the aeolian sandy land of the southern Tibetan Plateau were examined by field investigation and laboratory analyses. From 2009 to 2017, there was a significant improvement in the soil nutrient content due to ecological restoration; that is, the SOM content ranged from 8.43 to 23.37 g/kg in the four vegetation types in 2017, while in 2009 it ranged from 0.83 to 1.98 g/kg (Li et al. 2012).

Natural restoration is essential to prevent land degradation. The highest silt content, at the depth of 0–20 cm, was 50.77% and 62.16% in natural shrub (C) and natural grassland (D), respectively. The highest silt content at 20–40 cm (44.28%), as well as the lowest SBD (1.55 g/cm$^3$), was observed in natural grassland (D). There was no significant difference in the SOM of the four vegetation types in the topsoil (0–20 cm); however, it was significantly different at 20–40 cm. The SOM content was highest in natural grassland (D; 23.37 g/kg), followed...
by natural shrub (C; 17.42 g/kg), revegetated shrub (B; 14.85 g/kg), and artificial forest (A; 8.43 g/kg), in decreasing order. NH₃-N content in revegetated shrub (B) was 18.78 mg/kg, which was higher than in other vegetation types (5.95–9.10 mg/kg). The SOM was significantly correlated with the TP and AP contents of the aeolian sandy land (P < 0.05). The LTP was positively correlated with SBD, AP, and AK (P < 0.05), and the LTN was positively correlated with AP (P < 0.05).

Ecological restoration has significantly affected the soil properties of sandy land in the alpine valley of the southern Tibetan Plateau; that is, natural shrub (C) and natural grassland (D) have helped to maintain fine particles in the aeolian sandy land, compared to artificial restoration. It appears that changes in P can effectively reflect the dynamics of SOM and leaf nutrients. Our findings can provide useful information to optimize the patterns of ecological restoration in the southern Tibetan Plateau.

Table 5. Correlation matrix between different soil properties (n = 24) in different vegetation types.

| Soil properties | Silt | SBD | SMC | SOM | TN | TP | NO₃-N | NH₄-N | AP  |
|-----------------|------|-----|-----|-----|----|----|-------|-------|-----|
| Very fine sand  |      |     |     |     |    |    |       |       |     |
| Silt            |      |     |     |     |    |    |       |       |     |
| SBD             | 0.329 |     |     |     |    |    |       |       |     |
| SMC             | 0.150 | 0.583** |     |     |    |    |       |       |     |
| SOM             | -0.646** | -0.314 | -0.018 |     |    |    |       |       |     |
| TN              | 0.095 | -0.139 | -0.224 | -0.206 | 0.452* | 0.230 | 0.646** | 0.583** | 0.150 |
| TP              | -0.286 | 0.193 | 0.073 | 0.345 | -0.086 | 0.078 |       |       |     |
| NO₃-N           | -0.166 | -0.241 | 0.474* | 0.222 | -0.234 | 0.512* | -0.066 | -0.258 |     |
| NH₄-N           | 0.214 | -0.0515* | 0.192 | 0.056 | -0.489* | 0.303 | 0.107 | 0.157 | 0.452* |
| AP              | 0.471* | -0.042 | 0.372 | -0.108 | 0.263 | 0.263 | 0.445* | 0.474* |     |
| AK              | 0.256 | -0.227 | 0.294 | 0.372 |       |       |       |       |     |

Notes: SBD, soil bulk density; SMC, soil moisture content; SOM, soil organic matter; TN, total nitrogen; TP, total phosphorus; NO₃-N, nitrate nitrogen; AP, available phosphorus; and AK, available potassium.

* Correlation significant at the 0.05 level (2-tailed).
** Correlation significant at the 0.01 level (2-tailed).

Table 6. Correlation coefficient (r) between soil properties and leaf nutrients in the aeolian sandy land area (n = 12).

| Soil properties | LTC | LTN | LTP |
|-----------------|-----|-----|-----|
| Very fine sand  | 0.628* | 0.681* | 0.879** |
| Silt            | -0.605* | -0.692* | -0.886** |
| SBD             | 0.539 | 0.360 | 0.583* |
| SMC             | 0.146 | 0.082 | 0.125 |
| SOM             | -0.637* | -0.609* | -0.758** |
| TN              | -0.387 | 0.024 (0.999*) | 0.242 |
| TP              | -0.429 (−1.000§) | -0.210 (0.998¥) | -0.537 |
| NO₃-N           | -0.109 | -0.105 (0.998*) | -0.430 |
| NH₄-N           | -0.104 | -0.042 | 0.606* |
| AP              | 0.303 (−1.000†) | 0.733** | 0.584* (−1.000**)$ |
| AK              | 0.304 | 0.225 | 0.781** |

Notes: LTC, leaf total carbon; LTN, leaf total nitrogen; and LTP, leaf total phosphorus.

* Correlation significant at the 0.05 level (2-tailed).
** Correlation significant at the 0.01 level (2-tailed).
† Correlation coefficient in the revegetated shrub (n = 3).
‡ Correlation coefficient in the artificial forest (n = 3).
§ Correlation coefficient in the natural grassland (n = 3).
¥ Correlation coefficient in the natural shrub (n = 3).
ACKNOWLEDGMENTS

The research was funded by a Basic Special Business Fund for Research and Development for the Central Level Scientific Research Institutes, Nanjing Institute of Environmental Sciences, Ministry of Ecology and Environment (GYZX190101 and GYZX170201), Priority Academic Program Development of Jiangsu provincial universities (PAPD), supported by the Doctoral Fellowship Foundation of Nanjing Forestry University, and the National Natural Science Foundation of Nanjing Forestry University, and the National Natural Science Foundation of China (Grant No. 41301611). We would like to thank Mark S. Ashton for the suggestion in the review of manuscript and Professor Weishou Shen for his help in the field observation. Haidong Li conceived and designed the research; Yannan Xu helped to improve the hypothesis; Chengrui Liao wrote the paper; Haidong Li, Chengrui Liao, and Guoping Lv carried out the fieldwork and the analysis; and Jiarong Tian and Yannan Xu contributed to the discussion and paper revision (all photographs were photographed by Haidong Li in this article). The authors declare no competing interests.

LITERATURE CITED

Bowles, T. M., F. H. Barrios-Masias, E. A. Carlisle, T. R. Cavagnaro, and L. E. Jackson. 2016. Effects of arbuscular mycorrhizae on tomato yield, nutrient uptake, water relations, and soil carbon dynamics under deficit irrigation in field conditions. Science of the Total Environment 566–567:1223–1234.

Cerdan, O., et al. 2010. Rates and spatial variations of soil erosion in Europe: a study based on erosion plot data. Geomorphology 122:167–177.

Chen, Y. Z., et al. 2017. Modeling the regional grazing impact on vegetation carbon sequestration ability in Temperate Eurasian Steppe. Journal of Integrative Agriculture 16:2323–2336.

Fenton, T. E., M. Kazemi, and M. A. Lauterbach-Barrett. 2005. Erosional impact of organic matter content and productivity of selected Iowa soils. Soil & Tillage Research 81:163–171.

Guan, Q., et al. 2017. Spatial and temporal changes in desertification in the southern region of the Tengger Desert from 1973 to 2009. Theoretical & Applied Climatology 129:1–16.

Hondebrink, M. A., L. H. Cammeraat, and A. Cerdà. 2017. The impact of agricultural management on selected soil properties in citrus orchards in eastern Spain: a comparison between conventional and organic citrus orchards with drip and flood irrigation. Science of the Total Environment 581–582:153–160.

Huang, Z., J. Chen, X. Ai, R. Li, Y. Ai, and W. Li. 2017. The texture, structure and nutrient availability of artificial soil on cut slopes restored with OSSS - Influence of restoration time. Journal of Environmental Management 200:502–510.

Jin, Z., et al. 2014. Natural vegetation restoration is more beneficial to soil surface organic and inorganic carbon sequestration than tree plantation on the Loess Plateau of China. Science of the Total Environment 485–486:615–623.

Kang, D. W., J. Lv, S. Li, X. Y. Chen, X. R. Wang, and J. Q. Li. 2018. Integrating indices to evaluate the effect of artificial restoration based on different comparisons in the Wanglang Nature Reserve. Ecological Indicators 91:423–428.

Latifah, O., O. H. Ahmed, and N. M. A. Majid. 2017. Enhancing nitrogen availability from urea using clinoptilolite zeolite. Geoderma 306:152–159.

Li, D. M., Z. G. Guo, and L. Z. An. 2008. Assessment on vegetation restoration capacity of several grassland ecosystems under destroyed disturbance in permafrost regions of Qinghai-Tibet plateau. Chinese Journal of Applied Ecology 19:2182.

Li, H. D., Y. K. Li, Y. Y. Gao, C. X. Zou, S. G. Yan, and J. X. Gao. 2016a. Human impact on vegetation dynamics around Lhasa, Southern Tibetan Plateau, China. Sustainability 8:1146.

Li, H., W. Shen, C. Zou, J. Jiang, L. Fu, and G. She. 2013. Spatio-temporal variability of soil moisture and its effect on vegetation in a desertified Aeolian riparian ecotone on the Tibetan Plateau, China. Journal of Hydrology 479:215–225.

Li, H., W. Shen, C. Zou, L. Yuan, and D. Ji. 2012. Soil nutrients content and grain size fraction of Aeolian sandy land in the Shannan wide valley of the Yarlung Zangbo River, China. Acta Ecologica Sinica 32:4981–4992.

Li, Q., C. Zhang, Y. Shen, W. Jia, and J. Li. 2016b. Quantitative assessment of the relative roles of climate change and human activities in desertification processes on the Qinghai-Tibet Plateau based on net primary productivity. Catena 147:789–796.

Li, H., et al. 2019a. Assessing revegetation effectiveness on an extremely degraded grassland with terrestrial LiDAR, southern Qinghai-Tibet Plateau. Agriculture, Ecosystems and Environment 282:13–22.

Li, Y., et al. 2019b. Rhizosphere interactions between earthworms and arbuscular mycorrhizal fungi increase nutrient availability and plant growth in the desertification soils. Soil & Tillage Research 186:146–151.

Liao, C., B. Liu, Y. Xu, Y. Li, and H. Li. 2019. Effect of topography and protecting barriers on revegetation of sandy land, Southern Tibetan Plateau. Scientific Reports 9:6501.
Lu, R. K. 2004. Analysis method of soil agricultural chemistry. China Agricultural Science and Technology Press, Beijing, China.

Macci, C., S. Doni, E. Peruzzi, G. Masciandaro, C. Mennone, and B. Ceccanti. 2012. Almond tree and organic fertilization for soil quality improvement in Southern Italy. Journal of Environmental Management 95:S215–S222.

Maestre, F. T., J. Cortina, S. Bautista, J. Bellot, and R. Vallejo. 2003. Small-scale environmental heterogeneity and spatiotemporal dynamics of seedling establishment in a semi-arid degraded ecosystem. Ecosystems 6:630–643.

Maiti, S. K. 2013. Ecorestoration of the coalmine degraded lands. Springer, Dhanbad, India.

Merrill, S. D., M. A. Liebig, D. L. Tanaka, J. M. Krupinsky, and J. D. Hanson. 2013. Comparison of soil quality and productivity at two sites differing in profile structure and topsoil properties. Agriculture Ecosystems & Environment 179:53–61.

Papiernik, S. K., et al. 2009. Soil properties and productivity as affected by topsoil movement within an eroded landform. Soil & Tillage Research 102:67–77.

Paul, O. D. B., and R. Giménez. 2017. Assessing soil properties controlling interrill erosion: an empirical approach under Mediterranean conditions. Land Degradation & Development 28:1729–1741.

Peng, S., K. Yu, Z. Li, Z. Wen, and C. Zhang. 2019. Integrating potential natural vegetation and habitat suitability into revegetation programs for sustainable ecosystems under future climate change. Agricultural and Forest Meteorology 269–270:270–284.

Prosdocimi, M., A. Cerdà, and P. Tarolli. 2016. Soil water erosion on Mediterranean vineyards: a review. Catena 141:1–21.

Santos, U. M. D., J. F. de Carvalho Gonçalves, and T. R. Feldpausch. 2006. Growth, leaf nutrient concentration and photosynthetic nutrient use efficiency in tropical tree species planted in degraded areas in central Amazonia. Forest Ecology and Management 226:299–309.

Shang, Z. H., et al. 2013. The effects of three years of fencing enclosure on soil seed banks and the relationship with above-ground vegetation of degraded alpine grasslands of the Tibetan Plateau. Plant and Soil 364:229–244.

Shen, W., H. Li, M. Sun, and J. Jiang. 2012. Dynamics of aeolian sandy land in the Yarlung Zangbo river basin of Tibet, China from 1975 to 2008. Global & Planetary Change 86–87:37–44.

State Forestry Administration, P. R. China. 2015. The bulletin of desertification and sandification state of China. State Forestry Administration, P. R., Beijing, China.

UNCCD. 2018a. Poor land use costs countries 9 percent equivalent of their GDP. United Nations Convention to Combat Desertification, Bonn, Germany.

UNCCD. 2018b. Somalia national action programme for the United Nations convention to combat desertification. United Nations Convention to Combat Desertification, Bonn, Germany.

Wang, Y., J. Jiang, Z. Niu, Y. Li, C. Li, and W. Feng. 2019. Responses of soil organic and inorganic carbon vary at different soil depths after long-term agricultural cultivation in Northwest China. Land Degradation & Development 30:1229–1242.

Wang, X., et al. 2016. Aeolian processes and their effect on sandy desertification of the Qinghai-Tibet Plateau: a wind tunnel experiment. Soil & Tillage Research 158:67–75.

Wolff, S., E. A. Schrammeijer, C. J. E. Schulp, and P. H. Verburg. 2018. Meeting global land restoration and protection targets: What would the world look like in 2050? Global Environmental Change 52:259–272.

Yang, W. J., H. C. Chen, F. H. Hao, W. Ouyang, S. Q. Liu, and C. Y. Lin. 2012. The influence of land-use change on the forms of phosphorus in soil profiles from the Sanjiang Plain of China. Geoderma 189–190:207–214.

Yang, Z. P., W. S. Shen, M. Sun, J. Sun, and H. D. Li. 2011. Structural characteristics of Sophora moorecroftiana community on wind-sandy land in middle reaches of Yaluzangbu River. Chinese Journal of Applied Ecology 22:1121–1126.

Ye, C., et al. 2019. Spatial and temporal dynamics of nutrients in riparian soils after nine years of operation of the Three Gorges Reservoir, China. Science of the Total Environment 664:841–850.

Zhang, S., T. Huffman, X. Zhang, W. Liu, and Z. Liu. 2014. Spatial distribution of soil nutrient at depth in black soil of Northeast China: a case study of soil available phosphorus and total phosphorus. Journal of Soils & Sediments 14:1775–1789.

Zhang, X., W. Zhao, L. Wang, Y. X. Liu, Y. Liu, and Q. Feng. 2019b. Relationship between soil water content and soil particle size on typical slopes of the Loess Plateau during a drought year. Science of the Total Environment 648:943–954.

Zhang, C. L., et al. 2018. Monitoring of aeolian desertification on the Qinghai-Tibet Plateau from the 1970s to 2015 using Landsat images. Science of the Total Environment 619–620:1648–1659.

Zhang, W., et al. 2019a. Response of forest growth to C:N: P stoichiometry in plants and soils during Robinia pseudoacacia afforestation on the Loess Plateau, China. Geoderma 337:280–289.
Zhao, H. L., Y. R. Guo, R. L. Zhou, and S. Drake. 2011. The effects of plantation development on biological soil crust and topsoil properties in a desert in northern China. Geoderma 160:367–372.

Zhao, C. L., M. A. Shao, X. X. Jia, and C. C. Zhang. 2016. Particle size distribution of soils (0–500 cm) in the Loess Plateau, China. Geoderma Regional 7:251–258.

Zheng, Y. R., Z. X. Xie, C. Robert, L. H. Jiang, and H. Shimizu. 2006. Did climate drive ecosystem change and induce desertification in Otindag Sandy Land, China over the past 40 years? Journal of Arid Environments 64:523–541.

**Supporting Information**

Additional Supporting Information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/ecs2.3009/full