Ecological Engineering 144 (2020) 105704

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Effects of shading and herb/liana eradication on the assembly and growth of woody species during soil translocation in Southwest China

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ARTICLE INFO

Keywords:
Soil translocation
Shading treatment
Seedling reassembly
Eradication of weeds
Ecological restoration
Soil seed bank

ABSTRACT

Due to the intensification of human activities and global climate change, large areas of forest have been degraded and converted to other land uses. Soil translocation, which transfers the topsoil of donor forest to the receiving site to allow for the germination and reestablishment of soil seed bank and seedling, is a promising method for restoring vegetation that is similar to the donor forest. However, the lower similarity between the germinated community and donor forest has diminished its application against the ecological restoration and biodiversity compensation. We hypothesized that the exposure of donor forest soil to strong sunlight and early herb/liana competition may block germination and establishment of woody species (trees and shrubs) following soil translocation. To test this, here we investigated the effect of shading and weeding treatment on woody species assembly and seedlings growth at a karst rocky desertification area in southwest China. The results showed that soil translocation in blank control significantly increased the richness and similarity of woody species compared with receiving site. Moreover, soil translocation with shade treatment not only increased the richness and density of species during the germination period, but it also improved the survival and growth of most species—especially *Osteomeles anthyllidifolia*, *Fraxinus malacophylla*, *Quercus baronii*, and *Rhamnus parvifolia*—when compared with soil translocation in blank control after 18 months. Additionally, although soil translocation with blank control and weeding, and soil translocation with shade and weeding increased neither the number of woody species nor the density of shrubs species, they improved the density and similarity of tree species as well as the similarity of shrub species. We concluded that soil translocation with shade and weeding is likely more effective and helpful to restore the vegetation that is more similar to the donor forest in semi-humid regions of southwest China and comparable regions worldwide. But in practice, only soil translocation with moderate shade is deemed the optimal restoration method because it maintain the “recovery effect” while decrease the labor cost. Nevertheless, we should further assess the longer-term development and stabilization of established vegetation.

1. Introduction

As a consequence of the intensification of human activities and global climate change, large areas of forest have been degraded and converted to other land uses, reducing available habitats and resources for forest-dependent species and people, and compromising the ecosystem services that support all life on earth (Bierregaard et al., 1992; Lewis et al., 2015). Conservation and sound management of remaining forest are essential to stem further losses of biodiversity (Gibson et al., 2011) and supply the perquisite seed sources for use in the restoration of neighboring degraded sites (Asner et al., 2009). But these steps only slow the loss of natural forests; they are insufficient for conserving species diversity, mitigating climate change, and providing the levels of ecosystem services required by growing human populations (Chazdon et al., 2009; Harvey et al., 2008; Houghton et al., 2015; Martinez-Ramos et al., 2016). In short, we urgently need new methods and strategies to reproduce forests that are higher similarity to the donor forests.

Many scientists and practitioners aim to restore degraded forest to a state with high similarity to natural forest. Forest degradation destroys

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https://doi.org/10.1016/j.ecoleng.2019.105704
Received 15 March 2019; Received in revised form 15 December 2019; Accepted 21 December 2019
Available online 09 January 2020

propagule banks, including soil seed bank and reproductive tissues (Sanou et al., 2018), potentially impacting the restoration of preferred woody species (Dilrukshi and Ranwala, 2016; Morici et al., 2009). Hence, replacing the topsoil layer of a degraded site with natural forest topsoil offers a promising method for restoring vegetation (Hong et al., 2012; Wang et al., 2016), primarily because it carries many seeds and vegetative propagates that possess regionally specific species composition and hereditary characters, which should effectively sustain the diversity and stability of native species (Jalili et al., 2003). Soil translocation had been applied successfully in the recovery of mining wasteland in Australia (Tacey and Glossop, 1980), bauxite ore desert in Brazil (Parrotta and Knowles, 1999), marshy meadow (Madsen and Mindess, 1986), and prairie meadows in Canada (Vecrin and Muller, 2003). But for forest restoration in most subtropical and temperate areas, many researches confirmed that soil translocation led to either much of the existing vegetation in the donor forest, especially dominant species, undiscovered in the receiving site (Pywell et al., 2002b), or that similarity was low between the established vegetation and the donor forest (Ehrenfeld, 2000; Hodder and Bullock, 1997; Thompson and Grime, 1979), which restricted its application for the ecological restoration and biodiversity compensation (Shen et al., 2013; Valkó et al., 2011).

Forest gaps provide a favorable environment for preserving the soil seed bank and maintaining gap-phase regeneration dynamics of forest ecosystems (Lu et al., 2018). Even small canopy openings can alter environmental conditions mainly due to the increased light heterogeneity they provide (Galhidy et al., 2006; Rozenbergar et al., 2007) and afford diverse microsite patches for forest seedlings' regeneration (Nakashizuka, 1989; Orman et al., 2018; Orman and Szewczyk, 2015; Zielonka et al., 2006). Moreover, recent work showed that the formation of diverse forest gaps was also a strategy to inhibit the germination and growth of dormant seed and herbaceous seeds in the shaded understory (Tamura and Nakajima, 2017). Soil translocation involves the removal of an assemblage of plant species from a donor forest, with the aim to establish it as a functional community at a receiving site (Bullock, 1998). Nevertheless, this can lead to a changed habitat harsh for soil seed bank germination, mainly from exposure of donor topsoil to strong sunlight, which also breaks the dormancy of the persistent soil seed bank, especially herbaceous species (Metcalfe and Grubb, 1995a, 1995b; Pywell et al., 2002a, 2002b; Warr et al., 1993); both factors may limit the germination and establishment of most woody species.

This field study aimed at confirming the hypothesis that shading treatment and herb/liana eradication would improve the germination of woody species' seeds and their subsequent seedling growth and similarity following soil translocation. Specifically, our study addressed three questions: (1) How similar is the established community to the donor forest or soil seed bank of donor forest? (2) Is soil translocation with shade an effective technique to promote species diversity and growth? (3) Does weeding further increase the similarity between germinated seedlings and donor forest?

2. Materials and methods

2.1. Study site

This study was conducted in Jianshui County (E 102° 56′ 50.33″, N 23° 41′ 42.98″), located in south of Yunnan Province, China, which belongs to the representative Honghe dry-hot-valley rocky desertification region (Bulletin on the Status of Rocky Desertification in China, 2012). The annual average temperature is 19.6 °C, and the highest monthly average temperature is 24.3 °C (June) and the lowest monthly average temperature is 12.8 °C (January). Mean annual precipitation is 785.1 mm, most of it (about 80%) falling between May and October (rainy season), with a mean annual evaporation capacity (about 2000 mm) considerably greater than precipitation, which belongs to the typical of semi-humid climate regions (Jianshui Forestry Bureau, 2005–2015). Moreover, the soil belongs to limestone red soil in this region.

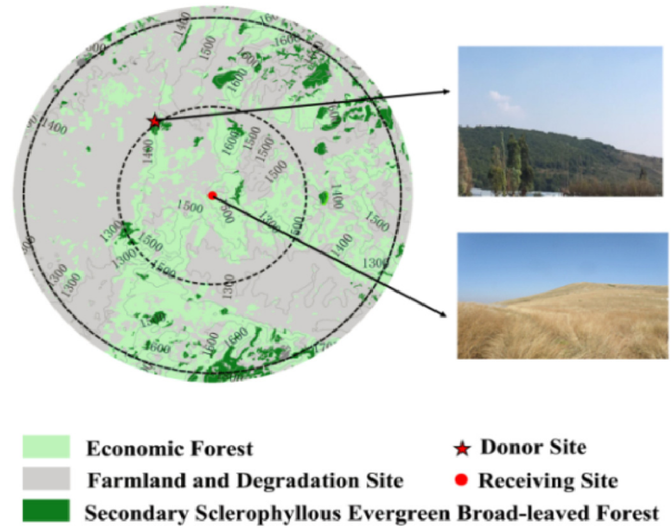

Fig. 1. Schematic diagram of the landscape of the donor forest and receiving site in Jianshui, southwest China.

Secondary sclerophyllous-evergreen broadleaved forest and rocky desertification herbland are two representative vegetation types in this region. The donor site consisted of a residual secondary broadleaved forest following forest destruction, characterized by small human disturbances and high plant diversity and dominated by several woody species, e.g. *Quercus baronii*, *Carissa spinarum*, *Osteomeles anthyllidifolia*, *Rhamnus parvifolia*, and *Albizia simeonis*. The receiving site was a severely damaged rocky desertification herbland, divided and surrounded by extensive economic forest and farmland, now dominated by annual and perennial herbs, e.g., *Heteropogon contortus*, *Arthraxon hispidus* and *Themeda hookeri*. Although it was closed for afforestation for many years, still no tree and shrub species are present there. Additionally, to avoid the effect of donor forest seed on soil translocation by wind and animals spread seeds, the receiving site was designated about 5 km away from the donor forest in same environmental condition (Fig. 1).

2.2. Vegetation survey and soil sampling

To provide more insight into vegetation characteristics, we surveyed key features in donor forest and receiving site. For donor forest, its overstory woody species were counted in 20 m × 20 m quadrats (n = 15 replicates) and the understory species (including trees, shrubs, herbs, and lianas) in 2 m × 2 m quadrats (n = 60 replicates). For receiving site, we investigated the richness and density of herbs in 2 m × 2 m quadrats (n = 60 replicates).

To obtain the soil containing seeds efficiently and to protect the donor forest site from damage, we collected the topsoil layer down to a 10 cm depth during April (Shen et al., 2007), amounting to 2% of the ground area (i.e., by sampling two 1 m × 1 m quadrats within a 10 m × 10 m plot) (Douterlungne et al., 2018). In total, we collected approximately 15,000 kg of topsoil from 300 1 m × 1 m quadrats in the donor forest. Following this topsoil collection, soil samples were stored in paper bags for later transport to the receiving site. After mixing them fully, the obtained soil was divided into two parts: a large proportion was used for the soil translocation field experiment while the rest was used for seed germination tests in a greenhouse. Additionally, in receiving site, we also obtained 200 soil samples from 20 cm × 20 cm quadrats for greenhouse tests.

2.3. Soil translocation procedure and greenhouse seed germination test

To eliminate confounding effects from pre-existing weeds and seeds on our experiment, at the receiving site, we randomly selected 20 plots (4 m × 4 m) in which all grasses and topsoil was removed manually prior to soil translocation. Soil translocation, which included stripping, transporting, homogenization, and re-spreading of topsoil, had to be implemented immediately after topsoil collection in May 2017, because June marks the onset of the rainy season (Jianshui Forestry Bureau, 2015). The collected forest topsoil was re-spread in an even amount to the prepared plots (700 kg each plot); 10 plots left in blank control (full sunlight), while the other 10 plots were covered with shade-net (shade treatment). The photosynthetically active radiation (PAR) was measured by using a 400–700 nm quantum sensor (Skye Instruments Ltd., Powys, UK) between 12:00–14:00 on cloud-free days. The average PAR of shade treatment (100.1) is ca. 50% of PAR of blank control (189.8).

1 m × 1 m quadrat was set within each plot for data monitoring in the germination period, when seedling emergence was also recorded (including the richness and density of species). Moreover, to illuminate test the effect of herb/liana species on woody species, another 10 quadrats (1 m × 1 m) were selected in shade and blank control for the eradication of weeds, including herbs and lianas. Furthermore, to understand the survival and growth indicator—including survival richness, height, and basal diameter—the seedlings of tree and shrub species were identified and measured in each treatment after 18 months.

Soil seed bank characteristics of donor forest and receiving site were quantified by using bulk germination test (40 cm × 40 cm × 5 cm, $n = 15$ replicates) under greenhouse conditions (annual average temperature 16.5 °C), with the best watering management applied throughout the whole germination period. Emerging seedlings (including species richness and respective density) were counted and removed every 10 days once in the first 2 months. After seedling emergence declined, counting was carried out once per month, until no new seedlings had emerged. Any unidentified seedlings were transferred to flowerpots and the species confirmed by a taxonomic professional.

2.4. Statistical analyses

One-way ANOVAs with LSD post-hoc means comparison tests were used to compare the species richness and species density among life forms in donor forest, receiving site, soil seed band of donor forest, and soil seed band of receiving site at the $P < .05$ level respectively. Means were likewise compared to test for growth differences between treatments. Normal distribution and homogeneity of variances were examined by the Shapiro-Wilk test and Levene's test before the above analysis was conducted. The one-way ANOVA was carried out in SPSS v16.0 for Windows (SPSS Inc., 2010). The relationship between donor forest and other vegetation types were calculated by using Jaccard similarity index. All graphs were drawn using SigmaPlot 13 software.

3. Results

3.1. Aboveground vegetation characteristics of donor forest and receiving site

The vegetation survey showed that vegetation structure and species density varied greatly across the two sites. A total of 50 plant species, belonging to 29 families and 46 genera, were recorded in donor forest, in which the richness of trees, shrubs, herbs, and lianas species were 16, 9, 19, and 6 species respectively. By contrast, 33 species, belonging to 16 families and 31 genera, were found in receiving site, of which 5 were shrubs (i.e., plants with heights < 1 m) and 28 were herb species, without any trees and lianas species present. Moreover, the species richness of all life forms in donor forest was greater than that in receiving site respectively, except for herb species (Fig. 2a).

Although total average plant density in donor forest (12.2 N/m^2) was far less than in receiving *site* (74.1 N/m^2), tree and shrub species dominated the donor forest while only annual and perennial herbs occurred in receiving site. The density of tree (5.1 N/m^2) and shrub species (4.3 N/m^2) in donor forest were greater than density of tree and shrub species in receiving site, respectively (Fig. 2b), and the dominant trees species in donor forest—e.g., *Quercus baronii* (2.2 N/m^2), *Rhamnus parvifolia* (0.9 N/m^2) and *Fraxinus malacophylla* (0.3 N/m^2)—and dominant shrubs species—e.g. *Myrsine Africana* (1.5 N/m^2), *Carissa spinarum* (1.4 N/m^2) and *Osteomeles anthyllidifolia* (1.2 N/m^2)—were monitored. In stark contrast, the density of herb species in receiving site accounted for 98.7 % of the total plant density there, and this was significantly greater than that in donor forest (1.98 N/m^2). The receiving site was dominated by *Eragrostis ferruginea* (22.1 N/m^2), *Themeda hookeri* (14.9 N/m^2), *Heteropogon contortus* (8.1 N/m^2), *Capillipedium parviflorum* (7.8 N/m^2), and *Arthraxon hispidus* (5.8 N/m^2) herbs, which together comprised 79.2 % of the total density there.

3.2. Soil seed banks of donor forest and receiving site

The greenhouse germination test revealed 52 species (belonging to 29 families and 51 genera) and 23 species (belonging to 13 families and 23 genera) in soil seed bank of donor forest and receiving site, respectively. The richness of tree, shrub, herb, and liana species were 8, 9, 29, and 6 in soil seed bank of donor forest, which were greater than the richness in soil seed bank of donor forest respectively, except for herb species (Fig. 3a).

The average density in soil seed bank of receiving site and donor forest were respectively 2296.3 and 575.7 N/m^2 respectively. In soil seed bank of donor forest, the density of trees (79.3 N/m^2) (dominants were *Psidium guajava*, *Quercus baronii*, *Albizia simeonis*), shrubs (29.8 N/m^2) (dominants were *Rubus corchorifolius*, *Osteomeles anthyllidifolia*, *Carissa spinarum*) and lianas (29.1 N/m^2) (dominants were *Bauhinia scandens*, *Vignavexillata*) were greater than the density in soil seed bank of receiving site, respectively. On the contrary, the density of herb species in soil seed bank of receiving site was greater than the density in soil seed bank of donor forest (Fig. 3b), and *Heteropogon contortus*, *Arthraxon hispidus*, and *Themeda hookeri* in soil seed bank of receiving site accounted for 72.3%, 10.3%, and 12.4% of the total density respectively.

3.3. Effect of shading treatment on seeds germination following soil translocation

Throughout whole germination period (from June to November) following soil translocation, a total of 89 species belonging to 25 families and 45 genera, and 69 species belonging to 24 families and 41 genera, were recorded in shade treatment and blank control, respectively. Overall, shade treatment increased significantly the richness of tree, shrub and herbs species respectively compared with blank control (Fig. 4a). However, at the end of the germination stage (November 2017), only 52 species and 41 species in total were recorded in shade treatment and blank control, respectively, and the richness of trees, shrubs, herbs, and lianas were respectively 10, 9, 26, and 7 species in shade treatment and likewise 9, 5, 18 and 9 species in blank control. This revealed that some species were dying during the germination process, especially the herbs species because they died in the winter.

On average, the density of total species reached 28.3 and 58.6 N/m^2 respectively in blank control and shade treatment, and the density of all life forms in shade treatment were greater than the density of receiving site respectively (Fig. 4b). In blank control, the dominant species of each plant life form were recorded as follows: *Sapium sebiferum*, *Quercus baronii*, and *Albizia simeonis* trees; *Carissa spinarum*, *Solanum erianthum*, and *Rubus corchorifolius* shrubs; *Emilia sonchifolia*, *Themeda hookeri*, and *Heteropogon contortus* herbs; and *Vigna vexillata*, *Paederia yunnanensis*, and *Stephania japonica* lianas. However, with shade, a differing composition of the dominant species according to life forms was detected:

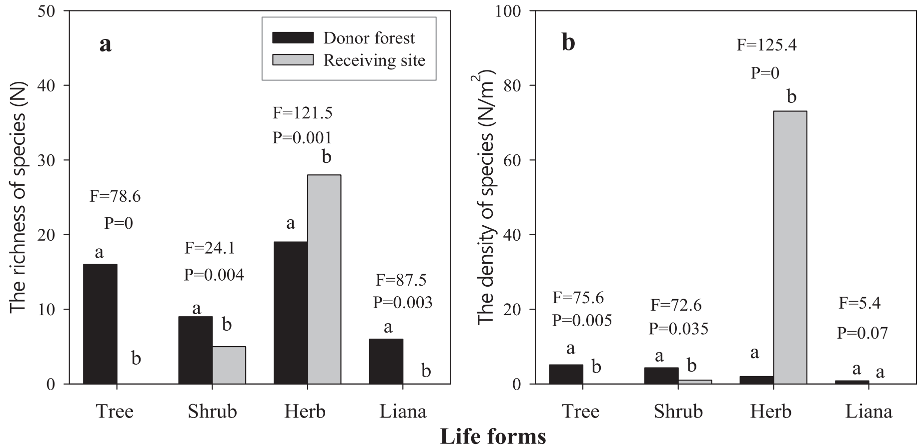

Fig. 2. Species richness (a) and density (b) of donor forest and receiving site in different life forms (Tree, Shrub, Herb and Liana). Different lowercase letters indicate significant differences between donor forest and receiving site in same life form.

Fraxinus malacophylla, *Quercus baronii*, and *Sapium sebiferum* trees; *Osteomeles anthyllidifolia*, *Rubus corchorifolius*, and *Sophora davidii* shrubs; *Nanophyton erinaceum*, *Arthraxon hispidus*, and *Emilia sonchifolia* herbs; and *Stephania japonica*, *Paederia yunnanensis* and *Smilax china* lianas.

3.4. Effects of eradication of weeds on germination of tree and shrub species following soil translocation

In total, 18 and 21 woody species were respectively recorded in blank control with weeding and shade with weeding after soil translocation. Shade treatment with weeding increased significantly the richness of shrub species (Fig. 5a). All species found in blank control with weeding was recorded in shade with weeding, but others detected in shade with weeding—e.g. *Morus alba*, *Bauhinia variegata*, and *Strychnos ignatii*—were not found in blank control with weeding.

The average species density in blank control with weeding and shade with weeding significantly differed, at 8.1 and 20.8 N/m^2, respectively. The density of tree (4.2 N/m^2) and shrub species (3.9 N/m^2) in blank control with weeding were lower than the density of tree (13.7 N/m^2) and shrub species (7.1 N/m^2) in shade with weeding, respectively (Fig. 5b). Additionally, the density of some species in shade with weeding—e.g., *Maytenus variabilis*, *Strychnos ignatii*, *Osteomeles anthyllidifolia*, *Fraxinus malacophylla*, and *Quercus baronii*—was significantly greater than in blank control with weeding, but certain species presented the opposite trend (e.g., *Myrsine Africana*, *Sapium sebiferum*, and *Rhus chinensis*). More importantly, the density of several species, namely *Carissa spinarum*, *Sophora davidii*, *Paliurus hemsleyanus*, *Quercus baronii*, and *Sapium sebiferum*, performed well between blank control with weeding and shade with weeding.

3.5. Effects of shading treatment on the survival and growth of tree and shrub seedlings following soil translocation

After 18 months, the total survival plant individuals of tree and shrub species reached 688 and 1783 in blank control and shade treatment, respectively, with several species (e.g., *Pistacia chinensis*, *Chionanthus retusus*, *Ligustrum lucidum*, and *Celtis kunmingensi*) only recorded in shade treatment. Overall, the survival number of most plant species in shade treatment was significant greater than those in blank control. Remarkably, the survival number of *Osteomeles anthyllidifolia*, *Fraxinus malacophylla*, and *Quercus baronii* reached 505, 528, and 117 in shade treatment, but far less at 69, 54 and 70 in blank control, respectively (Table 1).

From the plant growth indicator, the height of most species in shade treatment was significantly greater than in blank control. The tallest occurring were *Campylotropis macrocarpa* (106.7 cm), *Strychnos ignatii* (113.4 cm), *Rubus corchorifolius* (101.6 cm), and *Rhus chinensis* (118.5 cm), but heights of *Maytenus variabilis*, *Carissa spinarum*, *Quercus baronii,* and *Albizia simeonis* reached just 10.0, 12.1, 13.4, and 13.9 cm respectively. It is noteworthy that no significant differences were detected among *Carissa spinarum*, *Quercus baronii* and *Sapium sebiferum* in both blank control and shade treatment, independently of the survival number, height, and basal diameter of species, suggesting that these species had better adaptability and wider niche (Table 1).

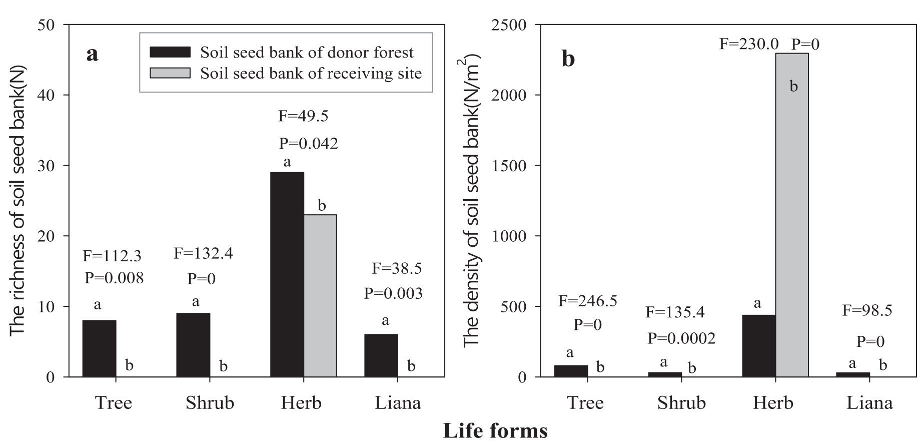

Fig. 3. The richness (a) and density (b) of donor forest and receiving site soil seed bank in different life forms (Tree, Shrub, Herb and Liana). Different lowercase letters indicate significant differences between donor forest soil seed bank and receiving site soil seed bank in same life form.

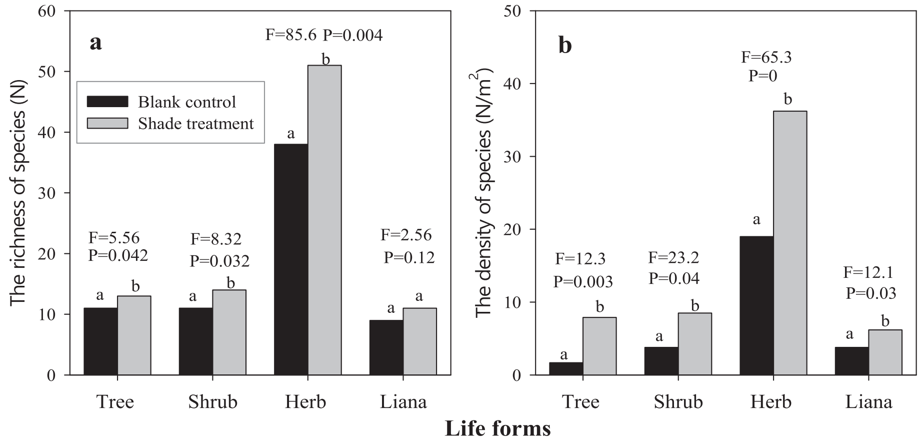

Fig. 4. The effect of shading treatment on species richness (a) and density (b) of different life forms (Tree, Shrub, Herb and Liana) following soil translocation. Different lowercase letters indicate significant differences between soil translocation in blank control and soil translocation with shade treatment in same life form.

3.6. Similarity between donor forest and receiving site, soil translocation in blank control, soil translocation with shade, soil translocation in blank control and weeding, and soil translocation with shade treatment and weeding

The richness of tree and shrub species of donor forest was higher than others and the allocation proportion of species was more reasonable. The receiving site and donor forest were defined respectively as degraded grassland and secondary climax succession communities in this region, and soil translocation with shade and/or weeding accelerated the species compositional shift from receiving site to donor forest. As expected, the similarity index was low between donor forest and receiving site. However, soil translocation increased the similarity index compared with receiving site, independently of life forms. Moreover, compared with soil translocation in blank control, soil translocation with shade improved the similarity of trees species and maintained the similarity index of other life forms. Importantly, soil translocation in blank control with weeding and soil translocation in shade and weeding increased further the similarity index of trees, shrubs, and total species, hastening the recovery process and succession's direction (Table 2).

4. Discussion

4.1. Can the community reassembled by soil translocation with blank control resemble the aboveground vegetation and soil seed bank of donor forest?

The soil seed bank is defined as the viable seeds that exist on the soil surface or are buried in soil (Walck et al., 2005). As such, it represents the pooled progeny of the current plant community as well as the potential species pool available for future communities to develop at a given place and time (Fisher et al., 2009). Understanding the characteristics of soil seed bank and its aboveground vegetation is essential not only for assessing the vulnerability of degraded sites, but especially for informing restoration strategies centered on soil translocation (Williams-Linera et al., 2016). However, the feasibility of vegetation restoration using the soil seed bank is largely dependent on its species composition and density (Duncan et al., 2009). Our vegetation survey and greenhouse germination testing indicated that species richness was high in donor forest and soil seed bank of donor forest, yet tree and shrub species were lacking in receiving site and soil seed bank of receiving site (Fig. 2), demonstrating that soil translocation from donor forest should be carried out for the restoration of receiving site, in agreement with other findings (Li et al., 2017; Li et al., 2012; Valkó et al., 2011). But the germinated vegetation via soil translocation in blank control was dominated by *S. sebiferum*, *Q. baronii*, *S. erianthum*, *P. hemsleyanus*, *H. contortus*, and *A. hispidus* and positive changes in

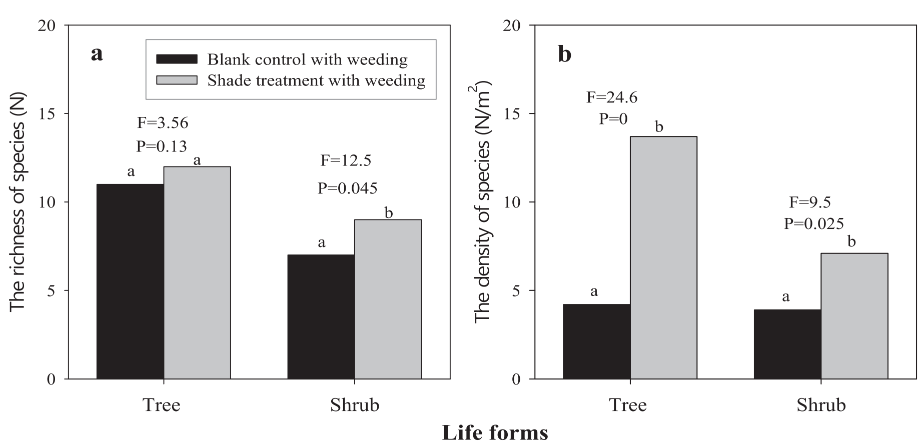

Fig. 5. The effect of shade treatment with weeding on the richness (a) and density (b) of tree and shrub species following soil translocation. Different lowercase letters indicate significant differences between soil translocation in blank control with weeding and soil translocation in shade treatment with weeding in same life form.

Table 1
The total number, average height (Mean ± SE) and base diameter (Mean ± SE) of the common woody species between soil translocation in blank control and soil translocation with shading treatment after 18 months of soil translocation.

Indicator	Number (N)		Height (cm)		Base diameter (cm)	
Species name	Control	Shade	Control	Shade	Control	Shade
Dodonaea viscosa	2	4	30.00 ± 2.10a	95.50 ± 2.10b	0.40 ± 0.10a	1.00 ± 0.10a
Campylotropis macrocarpa	5	18	106.6 ± 58.5a	72.08 ± 45.04a	0.65 ± 0.25a	0.46 ± 0.26a
Carissa spinarum	51	49	12.07 ± 2.83a	14.73 ± 6.51a	0.48 ± 0.18a	0.40 ± 0.18a
Solanum erianthum	33	55	20.7 ± 11.26a	43.49 ± 29.26b	0.59 ± 0.22a	0.81 ± 0.52a
Sophora davidii	80	33	21.15 ± 6.26a	26.48 ± 9.18a	0.54 ± 0.36a	0.26 ± 0.11a
Strychnos ignatii	11	23	48.0 ± 23.18a	113.39 ± 15.57b	1.08 ± 0.68a	1.44 ± 0.42a
Maytenus variabilis	24	30	9.96 ± 3.85a	16.16 ± 7.30b	0.37 ± 0.12a	0.29 ± 0.12a
Indigofera tinctoria	5	7	98.9 ± 35.56a	84.69 ± 35.38a	1.12 ± 0.14a	0.54 ± 0.19b
Rubus corchorifolius	49	77	59.2 ± 19.93a	101.55 ± 40.15b	0.78 ± 0.35a	0.70 ± 0.24a
Paliurus hemsleyanus	57	27	48.6 ± 18.31a	71.40 ± 25.06a	1.08 ± 0.41a	0.90 ± 0.30a
Osteomeles anthyllidifolia	69	505	15.10 ± 5.91a	18.05 ± 9.52a	0.35 ± 0.17a	0.23 ± 0.14a
Myrsine africana	39	52	53.88 ± 14.8a	81.56 ± 13.21b	0.63 ± 0.34a	0.69 ± 0.32a
Fraxinus malacophylla	54	528	14.67 ± 2.60a	34.06 ± 10.86b	0.30 ± 0.10a	0.45 ± 0.40b
Albizia simeonis	47	42	13.85 ± 3.73a	22.33 ± 7.95b	0.47 ± 0.12a	0.42 ± 0.13a
Psidium guajava	4	15	18.17 ± 11.8a	30.38 ± 12.30a	0.27 ± 0.21a	0.49 ± 0.20a
Broussonetia papyrifera	4	16	35.97 ± 8.10a	72.35 ± 9.67b	0.83 ± 0.34a	0.87 ± 0.58a
Morus alba	3	7	23.25 ± 3.23a	78.05 ± 6.54b	0.30 ± 0.10a	0.60 ± 0.08b
Pittosporum tobira	11	2	59.15 ± 7.54a	35.25 ± 4.53a	0.55 ± 0.05a	0.30 ± 0.10a
Quercus baronii	70	117	13.36 ± 3.07a	15.07 ± 7.49a	0.24 ± 0.08a	0.24 ± 0.07a
Sapium sebiferum	54	57	81.52 ± 21.7a	89.69 ± 23.04a	1.26 ± 0.53a	1.10 ± 0.33a
Rhamnus parvifolia	2	21	26.10 ± 4.66a	48.59 ± 5.47b	0.65 ± 0.35a	0.35 ± 0.29a
Rhus chinensis	4	11	35.17 ± 6.94a	118.47 ± 10.32b	0.76 ± 0.12a	1.45 ± 0.29b
Gardenia jasminoides	3	24	25.50 ± 2.54a	45.00 ± 5.68b	0.27 ± 0.21a	0.55 ± 0.12a

Different lowercase letters in same row indicate significant differences between soil translocation in blank control and soil translocation with shade treatment in same indicator of each species.

vegetation composition were noticed after soil translocation, despite the disappearance of some species and declines in abundance of most species after 18 months. In short, we found important vegetation differences between the donor forest, soil seed bank of donor forest, and soil translocation in blank control (Fig. 2 and Fig. 3).

Although the number of total and herb species were ranked soil translocation in blank control > soil seed bank of donor forest > donor forest, the richness of tree and shrub species were ranked donor forest > soil translocation in blank control > soil seed bank of donor forest. This rank order shift in community composition suggests that many tree and shrub species that occurred as standing vegetation performed poorly in soil translocation with blank control and soil seed bank of donor forest, while herb species absent from standing vegetation germinated arbitrarily (Pywell et al., 2002a; Warr et al., 1993), probably because the greenhouse and field conditions did not satisfy the germination requirements of all woody species but contributed disproportionately to the germination of herb species (Li et al., 2017) which are capable of a persistent seed bank (Bekker et al., 1999; Ma et al., 2012). This result is consistent with the view that forest canopy cover and gap provide a favorable environment for the preservation and germination of soil seed bank of trees and shrubs (Lu et al., 2018) and that light and moisture contributed to the germination of annual herbs (Milberg et al., 1996). Moreover, 28 common species were found in donor forest and soil translocation in blank control (similarity index = 0.464), and 18 common species were shared between soil seed bank of donor forest and soil translocation in blank control (similarity index = 0.314), suggesting that the newly established vegetation resembled the donor forest from a species composition perspective.

However, the exclusive species—*D. hupeana*, *P. serrulata*, *P. weinmannifolia*, and *C. camphora* (Appendix table)—were still missing in soil translocation with blank control, probably because their reproduction or establishment strategy hindered their establishment during soil translocation (Kameyama and Nakajima, 2018). Conversely, some species— namely *S. sebiferum*, *S. erianthum*, *R. corchorifolius*, *E. sonchifolia*, *B. pilosa*, and *E. adenophora*—that could be present in the soil seed bank of donor forest without being present in donor forest, were overrepresented in soil translocation with blank control and would likely form a persistent soil seed bank (Hou et al., 2014; Pereira et al., 2018; Shen et al., 2006; Yamashita et al., 2009). In this respect, *R. corchorifolius*, *B. pilosa*, and *E. adenophora* are noteworthy (Appendix table); since these species occur in a wide range of habitats and are drought resistant and so they may interfere with other species' growth (Shen et al., 2006).

Although species richness was not identical for different life forms across donor forest, soil seed bank of donor forest, and soil translocation in blank control, it was clear that the abundance of species in soil seed bank of donor forest, especially that of *H. contortus, A. hispidus*, *E. sonchifolia*, and *O. corniculata*, exceeded the others considerably, likely

Table 2
Jaccard similarity index of different life forms between donor forest and receiving site, donor forest and soil translocation in blank control, donor forest and soil translocation with shade treatment, donor forest and soil translocation in blank control and weeding, donor forest and soil translocation with shade treatment and weeding.

Similarity index Life forms	Donor forest and receiving site	Donor forest and blank control	Donor forest and shade	Donor forest and blank control with weeding	Donor forest and shade with weeding
Tree	–	0.400	0.519	0.519	0.571
Shrub	0.429	0.737	0.750	0.750	0.778
Herb	0.171	0.246	0.229	–	–
Liana	–	0.875	0.778	–	–
Total	0.169	0.464	0.431	0.634	0.625

because watering benefited their germination under greenhouse conditions (Fedotov et al., 2018; Oconnor and Pickett, 1992) whereas many of their seeds died because the rain was not obtained in time during soil translocation. Additionally, the abundance of herb and liana species in soil translocation with blank control was greater than in donor forest; the increased occurrence of herbs and lianas following soil translocation was not unexpected because these species tended to form a persistent seed bank and can avoid unfavorable conditions for germination and establishment, a so-called bet-hedging strategy (Lewandrowski et al., 2018). But it was expected that their richness and abundance would gradually decrease and revert to their previous level (Vecrin and Muller, 2003) because most herb species will die in winter at the end of germination period, and the richness and abundance of woody species would gradually occupy the advantages in our result. Thus, our results are relatively reasonable since the species richness and abundance of the established vegetation after soil translocation in blank control were correlated with donor forest, although the similarity coefficient was only 0.464.

4.2. *Effects of shading treatment on seed germination and seedling growth following soil translocation*

Seed germination is a critical and vulnerable stage in the life cycle of plants and is restricted in space and time to locations that meet a specific set of environmental conditions (Donohue et al., 2010), suggesting that seedling emergence is key to the successful restoration of terrestrial ecosystems (Liu et al., 2009). The effect of light on seed germination is mainly as a signal stimulus to break seed dormancy, rather than as a source of energy directly involved in the seed germination process (Bewley and Black, 1982). In our study, soil translocation with shade treatment not only increased the richness and abundance of species, but it also improved the growth indicator of most woody species compared with the soil translocation in blank control after 18 months. This result agrees with findings that moderate shading offered suitable conditions for seed germination and seedling establishment, especially for dormant and herb species (Lee and Lopez-Molina, 2012), but is inconsistent with shading found to promote the germination of tree and shrub species without inhibiting the germination of herbaceous seeds in an understory forest (Tamura and Nakajima, 2017), perhaps due to the high disturbance and low shade degree used in our study.

The common species—*H. contortus*, *E. sonchifolia*, *P. hemsleyanus*, *C. macrocarpa*, *S. davidii*, *R. chinensis*, among others—were found in both blank control and shade (Appendix table), suggesting that these species are present in a wide range of habitats and can adjust to different environmental conditions (Rodriguez-Trejo and Pompa-Garcia, 2016; Yamashita et al., 2009), which were agree with the result that most seeds were light neutral seeds Metcalfe and Grubb, 1995a, 1995b) and there is not dormancy period (Baskin and Baskin, 1998). Additionally, the exclusive species—*P. laciniata*, *G. affine, A. australis*, *P. chinensis* and other—that occurred in soil translocation with shade failed to perform in blank control (Appendix table), which indicates that shade is an important germination cue for stimulating germination across time and space (Michael Fenner and Thompson, 2005). Conversely, since exclusive species such as *Zanthoxylum bungeanum* that occurred in soil translocation with blank control didn't get performance in shade treatment, this indicated that these species belonged to phototropic species (Bu et al., 2017; Simlat et al., 2016). Additionally, soil translocation with shade increased the abundance and growth indicator of most tree and shrub species, primarily because shading reduced soil moisture loss. But it also decreased the similarity of shrub, herb, and total species since the shade treatment likely contributed to the exclusive species occurrence of shrubs and herbs, and improved the common tree species occurrence (Martins et al., 2012; McLaren and McDonald, 2003) and is likely related to seed other vegetation characteristics (Appendix A.).

4.3. *Effects of shading treatment with weeding on woody species germination following soil translocation*

It is noteworthy that both treatments, soil translocation in blank control and weeding and soil translocation with shade and weeding, neither increased the number of tree and shrub species nor the abundance of shrub species when compared with soil translocation in blank control and soil translocation with shade, probably because either weeding changed the soil microbiota and mobilized soil substrates (Wubs et al., 2016) or impacted one or more germination mechanisms (Gardener et al., 2010), which agreed with other reports (Felix and Owen, 1999; Portych, 1995). Moreover, since soil translocation with shade and weeding increased the richness and abundance of tree and shrub species compared with soil translocation in blank control and weeding. Other studies have also shown that weeding destroyed the germination condition of shrub species (Lai and Wong, 2005; Marriage and Quamme, 1980; Murali and Setty, 2001). By contrast, weeding significantly increased the abundance of tree species in our results, possibly because weeding could provide more nutrients and water for their successful germination. More importantly, soil translocation with shade and weeding as well as soil translocation in blank control and weeding both significantly increased the similarity of species compared with soil translocation with shade and soil translocation in blank control, irrespective of life forms, which was mainly driven by removal of the exclusive herb species and germination of the common tree and shrub species (Appendix A.).

4.4. *Strategies for the restoration of rocky desertification herbland during soil translocation*

Although the feasibility of vegetation restoration using soil translocation depends mainly on its species composition and density (Duncan et al., 2009), the similarity between germinated vegetation and donor forest could influence potential community recovery because this seed bank is primarily supplied by seeds dispersed from aboveground vegetation; in turn, seedling resources will drive the development and succession of aboveground vegetation (Olano et al., 2012). According to our results, soil translocation with shade sustained the highest richness of woody species. Moreover, the greatest density of tree and shrub species was 13.7 and 8.5 N/m^2 in soil translocation with shade and weeding, and soil translocation with shade, respectively. The similarity index of total species attained its maximum of 0.634 in soil translocation in blank control and weeding, while that of trees and shrubs species reached 0.571 and 0.778, respectively, in soil translocation with shade and weeding (Table 2). In theory, soil translocation with shade and weeding should offer the most effective method to restore the vegetation that is more similar to the donor forest because it increased the abundance of trees species and the similarity of woody species; But in practice, only soil translocation with shade is deemed the optimal restoration method because it maintain the “recovery effect” while decrease the labor cost, although the similarity index of tree, shrub and woody species were 0.519, 0.609, and 0.431, respectively (Table 2).

The cost of translocating soil is possibly higher than other recovery methods. However, the ecological benefits, especially on biodiversity is very high as indicated in our results. Moreover, natural forests had been decline globally, and continued to decline in recent years, i.e. some natural forest was inevitably destroyed during the construction of highways and high-speed rail all over the world. Our results bring a new light to find ways to rescue and restore those natural forests facing threats. However, we still need long term observation on the development of established vegetation, and we also need further experiment to define the effect of shading quantitatively on seed germination and seedling establishment, thus to fulfill the technological demand for soil translocation.

Author contribution section

Gaojuan Zhao: The first author, participate in experiment design, experiment conduct, experiment management, data recording, data analysis and manuscript writing.

Youxin Shen: corresponding author, participate in test design and manuscript revision.

Wenyao Liu: corresponding author, participate in test design and manuscript revision.

Zhenjiang Li: participate in experiment operation and data recording.

Beilin Tan: participate in data recording.

Zhimeng Zhao: participate in data recording.

Juan Liu: participate in data recording.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by the National Key Research and Development Program of China (2016YFC0502504), the CAS 135 Program (No.2017XTBG-F01), and the National Natural Science Foundation of China (41671031). We are also very grateful to Jianshui Research Station, School of Soil and Water Conservation, Beijing Forestry University.

Appendix A

List of the woody species used in the different treatments following soil translocation and vegetation characteristics, indicating the occurrence of seedlings (blank control, shade treatment, blank control and weeding, shade treatment and weeding); flowering period; fruiting time; fruit type (capsule, legume, berry, drupe, samara, syncarp, follicle, and nut); dispersal mode (wind, frugivore, and gravity), dormancy (yes or no); and shade tolerance (gap, medium tolerance, and shade tolerant).

Woody species	Occurrence of seedlings	Flower period	Fruit time	Fruit type	Dispersal mode	Dormancy	Shade tolerance
Dodonaea viscosa	Control; Shade	Sep	Dec	Capsule	Wind	Yes	Gap
Phyllanthus emblica	Shade	Apr	Aug	Capsule	Frugivore	Yes	Medium
Campylotrpis macrocarpa	Control; Shade; Control and weeding; Shade and weeding	Jun	Oct	Legume	Frugivore	No	Medium
Carissa spinarum	Control; Shade; Control and weeding; Shade and weeding	Apr	Dec	Berry	Gravity	Yes	Shade
Solanum erianthum	Control; Shade; Shade and weeding	Sep	Dec	Berry	Gravity	Yes	Medium
Sophora davidii	Control; Shade; Control and weeding; Shade and weeding	Apr	Sep	legume	gravity	no	medium
Strychnos ignatii	Control; Shade; Control and weeding; Shade and weeding	Aug	Dec	Berry	Gravity	Yes	Gap
Maytenus variabilis	Control; Shade; Control and weeding; Shade and weeding	Apr	Sep	Capsule	Gravity	No	Shade
Indigofera tinctoria	Control; Shade; Shade and weeding	Jun	Nov	Legume	Gravity	No	Medium
Rubus corchorifolius	Control; Shade	Mar	Jun	Drupe	Frugivore	Yes	Medium
Paliurus hemsleyanus	Control; Shade; Control and weeding; Shade and weeding	May	Aug	Drupe	Wind	Yes	Medium
Osteomeles anthyllidifolia	Control; Shade; Control and weeding; Shade and weeding	May	Sep	Drupe	Frugivore	Yes	Shade
Myrsine africana	Control; Shade; Control and weeding; Shade and weeding	May	Oct	Drupe	Frugivore	No	Shade
Fraxinus malacophylla	Control; Shade; Control and weeding; Shade and weeding	Jun	Oct	Samara	Wind	No	Gap
Albizia simeonis	Control; Shade; Control and weeding; Shade and weeding	May	Nov	Legume	Frugivore	Yes	Medium
Psidium guajava	Control; Shade; Control and weeding; Shade and weeding	Jun	Oct	Berry	Frugivore	No	Medium
Broussonetia papyrifera	Control; Shade; Control and weeding; Shade and weeding	Apr	Jul	Syncarp	Frugivore	Yes	Gap
Zanthoxylum bungeanum	Control	May	Sep	Follicle	Gravity	Yes	Gap
Pistacia chinensis	Shade	Apr	Sep	Drupe	Gravity	No	Medium
Chionanthus retusus	Shade	Jun	Sep	Drupe	Gravity	No	Medium
Ligustrum lucidum	Control; Shade; Control and weeding; Shade and weeding	Jun	Dec	Drupe	Gravity	No	Medium
Celtis sinensis	Control; Control and weeding; Shade and weeding	May	Nov	Drupe	Frugivore	No	Medium
Morus alba	Control; Shade; Shade and weeding	May	Jul	Syncarp	Frugivore	No	Medium
Pittosporum tobira	Control; Shade	Apr	Oct	Capsule	Gravity	Yes	Medium
Quercus baronii	Control; Shade; Control and weeding; Shade and weeding	May	Oct	Nut	Frugivore	No	Medium
Sapium sebiferum	Control; Shade; Control and weeding; Shade and weeding	Jun	Dec	Capsule	Frugivore	Yes	Gap
Rhamnus parvifolia	Control; Shade; Control and weeding; Shade and weeding	Apr	Sep	Drupe	Gravity	No	Medium
Rhus chinensis	Control; Shade; Control and weeding	Aug	Oct	Drupe	Gravity	No	Gap
Gardenia jasminoides	Control; Shade	Jun	Sep	Drupe	Frugivore	No	Medium
Bauhinia variegata	Shade and weeding	Sep	Mar	Legume	Frugivore	Yes	Medium

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