Effects of different types of vegetation recovery on runoff and soil erosion on a Wenchuan earthquake-triggered landslide, China

S. Fusun, W. Jinniu, L. Tao, W. Yan, G. Haixia, and W. Ning

Abstract: In order to find suitable vegetation types for wider earthquake-triggered landslide rehabilitation in the eastern Longmenshan, we chose six vegetation types, which included three artificial restoration vegetation types (shrub *Paeonia decomposita*, deciduous tree *Betula albo-sinensis*, and evergreen tree *Cryptomeria fortunei*), two natural restoration vegetation types (middle and high coverage of grasses), and one residual vegetation. Soil quality, runoff, and soil loss were evaluated for the six vegetation types. We found that high coverage of grass prevented surface runoff and soil erosion more effectively than other vegetation types, and the deciduous tree and shrub were more suitable for soil quality recovery than the evergreen tree after the landslide. Among the three artificially planted vegetation types, the roots of the deciduous tree had stronger expansion ability than those of the shrub and evergreen tree. Our results indicated that high coverage of grass and deciduous trees could complement each other to achieve a good restoring effect, which would not only help reduce surface runoff and soil erosion but also facilitate the formation of fertile islands and enhance the stability of subsurface soils. Therefore, the two vegetation types could be used to form an effective vegetation restoration pattern for wider earthquake-triggered landslide rehabilitation in this region.

Key words: earthquake-triggered landslide—fertile island—runoff—soil erosion—soil quality—vegetation type

On May 12, 2008, a catastrophic earthquake with a magnitude of Mw 8 and a focal depth of 19 km (11 mi) occurred at the Wenchuan area of the Longmenshan fault in Sichuan Province, China. The earthquake caused a colossal fault rupture with a distance of approximately 270 km (168 mi) and triggered enormous landslides; it was the worst mountain disaster in the 20th and 21st centuries (Chigira et al. 2010). After the earthquake, investigations were conducted using Beijing No. 1 and IKONOS earth observation satellite images with ground resolution of 32 m (105 ft) and 1 m (3 ft), respectively (Di 2008). The total area of landslides induced by this earthquake was 2,260 km² (873 mi²), which was far larger than that of recent earthquakes in mountainous areas, such as the Chi-Chi earthquake in 1999 that occurred in central Taiwan (Lin et al. 2006), the Mid-Niigata Prefecture earthquake in 2004 that occurred in north-west Japan (Chigira and Yagi 2005), and the Kashmir earthquake in 2005 that occurred in northern Pakistan (Sato et al. 2007).

The earthquake-triggered landslides changed green vegetation into naked rock and bare soil. The absence of a thick soil layer discouraged the percolation of rainfall, facilitated flow over the slopes as runoff, and increased the possibility of severe soil erosion when intense prolonged rainfall occurred. A preliminary estimation of soil erosion in landslides resulting from the earthquake was about 55.86 × 10⁸ t (61.58 × 10⁸ tn) (Chen et al. 2009). In order to reduce soil erosion and protect the environment, different types of perennial vegetation, such as shrubs, deciduous trees, and evergreen trees, were applied in renewing the battered landslides.

Soil physical and hydrological properties are related to vegetation type (Martinez-Meza and Whitford 1996). The physical structure of vegetation protects the soil surface against the impact of raindrops, reduces the energy of runoff, and controls how water is channeled into and through the soil (Martinez-Meza and Whitford 1996; Bochet et al. 1999). Among the physical structures of vegetation, coverage has the effect of reflecting critical stages of ecosystem development and functionality, so it is often taken as an important indicator of restoration success (Vallauri et al. 2005; Moreno-de las Heras et al. 2009). Some researchers (Bochet et al. 1998; Martinez-Mena et al. 1999; Sanchez et al. 2002; Xu et al. 2008) have documented that increasing vegetation cover is an important measure to control water erosion and to improve soil quality. Vegetation type also has been shown to alter soil quality and hydrological characteristics, including increasing soil organic matter and improving soil structure (Thompson et al. 2005), which can increase soil infiltration capacity (Ks), water retention, and decrease soil erodibility (Gutierrez et al. 1995; Bochet et al. 1999; Xu et al. 2009). Furthermore, some studies have proved that some vegetation types can facilitate the development of fertile islands (Thompson et al. 2005; Xu et al. 2009). The effectiveness of vegetation in improving soil quality and controlling runoff and soil loss depends on vegetation types (Xu et al. 2009). For this reason, knowledge about the effectiveness of different vegetation types on soil quality, runoff, and soil loss is needed in order to select suitable vegetation types for postdisaster ecological restoration.

This study was carried out on a typical landslide in the eastern Longmenshan, where rainfall is abundant and many rainstorms occur. Some grass species had naturally invaded the landslide two years after the earthquake. Invading pioneer plants also can be used as a natural revetment to mitigate the impacts of landslide erosion (Lin et al. 2006). Based on our investigation, we selected six vegetation types in the landslide for field monitoring; they were middle cov-
Table 1
Characteristics of runoff plots of different vegetation rehabilitation patterns.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Slope (°)</th>
<th>Projected area (m²)</th>
<th>Gravel &gt;2mm (%)</th>
<th>Soil texture</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con</td>
<td>23 to 30</td>
<td>0.12 to 0.13</td>
<td>47.52 to 72.63</td>
<td>Sandy loam</td>
<td>Soil surface layers were completely destroyed by earthquake and remained bare up to now.</td>
</tr>
<tr>
<td>MCG</td>
<td>28 to 32</td>
<td>0.13 to 0.14</td>
<td>46.11 to 63.91</td>
<td>Sandy loam</td>
<td>Soil surface layers were completely destroyed by earthquake and naturally restored by grass species.</td>
</tr>
<tr>
<td>HCG</td>
<td>31 to 33</td>
<td>0.13 to 0.14</td>
<td>40.04 to 64.58</td>
<td>Sandy loam</td>
<td>Soil surface layers were completely destroyed by earthquake and naturally restored by grass species.</td>
</tr>
<tr>
<td>SR</td>
<td>26 to 34</td>
<td>0.14 to 0.15</td>
<td>38.59 to 51.79</td>
<td>Sandy loam</td>
<td>Soil surface layers were completely destroyed by earthquake and then artificially restored by shrub ( P. ) decomposita.</td>
</tr>
<tr>
<td>DTB</td>
<td>27 to 32</td>
<td>0.13 to 0.14</td>
<td>35.25 to 52.39</td>
<td>Sandy loam</td>
<td>Soil surface layers were completely destroyed by earthquake and then artificially restored by deciduous tree ( B. ) albo-sinensis.</td>
</tr>
<tr>
<td>ETC</td>
<td>24 to 30</td>
<td>0.14 to 0.15</td>
<td>34.89 to 50.96</td>
<td>Sandy loam</td>
<td>Soil surface layers were completely destroyed by earthquake and then artificially restored by evergreen tree ( C. ) fortunei.</td>
</tr>
<tr>
<td>RV</td>
<td>24 to 32</td>
<td>0.14 to 0.15</td>
<td>21.84 to 28.71</td>
<td>Loam</td>
<td>Soil surface layers were heavily disturbed by earthquake, and some epibiotic plants such as ( F. ) spathacea and ( Z. ) jujube survived.</td>
</tr>
</tbody>
</table>

Notes: Con = control. MCG = middle coverage of grass. HCG = high coverage of grass. SR = shrub \( P. \) decomposita. DTB = deciduous tree \( B. \) albo-sinensis. ETC = evergreen tree \( C. \) fortunei. RV = residual vegetation.

erage of grass, high coverage of grass, shrub (\( P. \) decomposita), deciduous tree (\( B. \) albo-sinensis), evergreen tree (\( C. \) fortunei), and residual vegetation, respectively. The aim of this study was to evaluate the different effectiveness of the six vegetation types on soil quality, runoff, and soil loss, then scientifically select suitable vegetation types for wider earthquake-triggered landside rehabilitation.

Materials and Methods

Site Descriptions. The research was carried out in Pengzhou county of Sichuan Province in southwest China, which belongs to the hit area of the Wenchuan earthquake in the eastern Longmenshan tectonic zone. According to the investigation that was carried out after the earthquake, the number of earthquake-triggered landslides in this area is 405, and most of them happened in the elevation between 900 m (2,953 ft) and 2,300 m (7,546 ft). The climate is subtropical, moist weather. Mean annual temperature is 15.6°C (60°F), and mean annual precipitation is 932.5 mm (36.7 in), with most of the precipitation in summer. Because of the temperate climate and abundant rainfall in this area, restorative measures for the landslide mainly included tree planting, such as some shrubs, deciduous trees, and evergreen trees. These practices were different from those employed to the west of the Longmenshan tectonic zone, which is part of the dry-warm river valley of upper reach of Minjiang River and where restorative measures for the landslide were mainly in engineering methods.

The study site is located at a typical earthquake-triggered landslide in Pengzhou County \( (31°13.49′ \, N, \, 103°44.85′ \, E) \). The furthest longitudinal length of the landslide is 850 m (2,789 ft), and the furthest width is 220 m (722 ft). The altitudes of the landslide range from 1,170 to 1,315 m (3,839 to 4,314 ft) above sea level, and slopes are between 23° and 34° (table 1). The soil surface layers were heavily or completely destroyed by the earthquake; the content of gravel (>2 mm) ranges from 21.84% to 72.63%, and sandy loam is the predominant soil type. Some epibiotic plants, such as \( F. \) spathacea and \( Z. \) jujube, survived in the study area. The soil under epibiotic plants can be considered a fertile island.

Runoff and Soil Loss Measurements. The runoff collection system was designed by Xu et al. (2008). Each runoff collection system was enclosed with PVC material \((40 \times 40 \, \text{cm} \, [16 \times 16 \, \text{in}])\), including a sediment collector and a runoff collector. In the present study, we built 35 natural runoff plots on a southeast 30° slope on the landslide at the end of June of 2010, of which 30 were for the six target vegetation types (5 for each), and the remaining 5 were bare ground plots (control treatment) with a similar slope angle as the target vegetation type plots. A runoff collector for each plot was inserted into the soil at a depth of 5 cm (2 in). A rain gauge was also installed to measure rainfall events near the plots. Observation was conducted from July to October of 2010. The runoff volume was measured by measuring the cylinder after each rainfall event and then dividing this volume by the projected area of
hot-drying at 105°C (221°F). One sample used to measure soil bulk density (BD) and cores (100 cm³ [6.1 in³]). Two samples were

In runoff plots, we reselected other points near those in runoff plots. In total, five sites for each treatment were selected. We divided those in runoff plots and to simultaneously measured soil particle size distribution. The remaining portion was passed through a 2 mm (0.08 in) sieve to determine soil chemical properties. Soil cation exchange capacity (CEC) was measured with EDTA-ammonium salt rapid method, soil organic C was measured with the potassium dichromate oxidation method, and total N was measured with the alkaline persulfate oxidation method (Institute of Soil Science, Chinese Academy of Sciences 1978).

Statistical Analysis. Standard error of each treatment was calculated. One-way analysis of variance (ANOVA) was performed on the data. The significance level was set at p < 0.05. Differences among treatments were compared using Tukey’s honestly significant difference (HSD) test.

Results and Discussion

Plant Characteristics for Different Vegetation Types. The coverages of invading grass species were significantly different in the sampled plots of the landslide and ranged from 8.35% to 85.78% (table 2). High coverage of grass had the greatest community height and root density. Among the three artificially planted vegetation types, the plant height of B. albo-sinensis was 2.23 and 1.69 times higher than that of P. decomposita and C. fortunei (table 2). The coverage of B. albo-sinensis (40.67%) and P. decomposita (47.34%) were significantly greater than that of C. fortunei (29.65%). Compared to the three artificially planted vegetation types, the residual vegetation had the greatest plant height, tree coverage, and grass coverage (table 2). For root density and diameter distribution, high coverage of grass had the greatest root density with its diameter less than 1 mm (0.04 in), while B. albo-sinensis, P. decomposita, and residual vegetation had greater root density with its diameter more than 2 mm (0.08 in) (table 2).

Soil Properties for Different Vegetation Types. The relationship between mechanical composition and different levels in soil aggregates for different vegetation types are shown in figure 1. All vegetation types facilitated the accumulation of soil aggregates compared to the bare ground controls. Soil aggregates (>3 mm [=>0.1 in]) were highest for residual vegetation, B. albo-sinensis, and high coverage of grass, then followed by P. decomposita, C. fortunei, middle coverage of grass, and the control treatment, respectively (table 3). Residual vegetation had the low-

Table 2

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Community/plant height (cm)</th>
<th>Canopy of tree (%)</th>
<th>Canopy of grass (%)</th>
<th>Root density (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt;1 mm</td>
</tr>
<tr>
<td>Con</td>
<td>7.82 ± 0.93e</td>
<td>—</td>
<td>8.35 ± 0.36d</td>
<td>19 ± 2c</td>
</tr>
<tr>
<td>MCG</td>
<td>42.67 ± 8.79d</td>
<td>—</td>
<td>37.45 ± 2.04b</td>
<td>32 ± 3b</td>
</tr>
<tr>
<td>HCG</td>
<td>67.22 ± 15.46c</td>
<td>—</td>
<td>85.78 ± 2.81a</td>
<td>47 ± 3a</td>
</tr>
<tr>
<td>SR</td>
<td>52.67 ± 8.36dcd</td>
<td>47.34 ± 7.96ab</td>
<td>13.44 ± 4.83d</td>
<td>23 ± 2b</td>
</tr>
<tr>
<td>DTB</td>
<td>117.64 ± 12.62b</td>
<td>40.67 ± 5.45b</td>
<td>11.13 ± 3.76d</td>
<td>27 ± 4b</td>
</tr>
<tr>
<td>ETC</td>
<td>69.35 ± 3.18c</td>
<td>29.65 ± 2.72c</td>
<td>8.62 ± 3.29d</td>
<td>31 ± 3b</td>
</tr>
<tr>
<td>RV</td>
<td>182.64 ± 25.03a</td>
<td>51.34 ± 4.70a</td>
<td>28.17 ± 9.22b</td>
<td>34 ± 7b</td>
</tr>
</tbody>
</table>

Notes: Con = control. MCG = middle coverage of grass. HCG = high coverage of grass. SR = shrub B. albo-sinensis. ETC = evergreen tree C. fortunei. RV = residual vegetation. The values are means ± standard error of five replicates. Values in each column that do not share the same letter are statistically different (p < 0.05) between the treatments when analyzed by one-way analysis of variance.
Rainfall Effects on Runoff and Soil Loss. A total of 43 rainfall events were recorded during the experiment period, of which 9 ranged from 0 to 10 mm (0 to 0.4 in), 16 from 10 to 25 mm (0.4 to 1 in), 11 from 25 to 50 mm (1 to 2 in), 5 from 50 to 100 mm (2 to 4 in), and 2 from 100 to 250 mm (4 to 10 in). Based on rainfall events less than 80 mm (3 in), we attained the relationships of rainfall to runoff and soil loss (figures 5 and 6). For all six vegetation types and control treatments, runoff increased with increasing rainfall ($p < 0.01$). Among the seven fitted lines, the control line was at the highest position, followed by middle coverage of grass, C. fortunei, P. decomposita, B. albo-sinensis, residual vegetation, and high coverage of grass, respectively. Soil loss was significantly correlated with rainfall ($p < 0.05$) for the control only. The trend line of the control was also at the highest position, followed by the trend lines of middle coverage of grass, C. fortunei, P. decomposita, B. albo-sinensis, residual vegetation, and high coverage of grass, respectively. The three trend lines of B. albo-sinensis, residual vegetation, and high coverage of grass were adjacent with each other and at a lower level.

![Mechanical composition in soil aggregates for different vegetation rehabilitation patterns](image)

**Legend**
- Con = control. MCG = middle coverage of grass. HCG = high coverage of grass. SR = shrub P. decomposita. DTB = deciduous tree B. albo-sinensis. ETC = evergreen tree C. fortunei. RV = residual vegetation.

**Table 3**

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Accumulated runoff depth (mm)</th>
<th>Accumulated soil loss (g m$^{-2}$)</th>
<th>Steady Ks (mm min$^{-1}$)</th>
<th>&gt;3 mm soil aggregates (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con</td>
<td>192.01 ± 7.52a</td>
<td>611.85 ± 107.39a</td>
<td>0.47 ± 0.03d</td>
<td>45.76 ± 8.03c</td>
</tr>
<tr>
<td>MCG</td>
<td>151.04 ± 8.39b</td>
<td>299.18 ± 32.57b</td>
<td>0.71 ± 0.07c</td>
<td>65.77 ± 5.68b</td>
</tr>
<tr>
<td>HCG</td>
<td>30.33 ± 14.55c</td>
<td>76.50 ± 12.68c</td>
<td>0.80 ± 0.08c</td>
<td>84.04 ± 3.97a</td>
</tr>
<tr>
<td>SR</td>
<td>124.24 ± 6.04c</td>
<td>231.41 ± 18.94c</td>
<td>0.98 ± 0.11bc</td>
<td>79.55 ± 4.09ab</td>
</tr>
<tr>
<td>DTB</td>
<td>114.02 ± 3.49cd</td>
<td>184.33 ± 36.70c</td>
<td>1.20 ± 0.12b</td>
<td>86.53 ± 3.13a</td>
</tr>
<tr>
<td>ETC</td>
<td>148.67 ± 4.92b</td>
<td>288.06 ± 29.16b</td>
<td>0.72 ± 0.05c</td>
<td>70.05 ± 3.52b</td>
</tr>
<tr>
<td>RV</td>
<td>97.74 ± 7.48d</td>
<td>131.39 ± 20.94d</td>
<td>1.67 ± 0.05a</td>
<td>87.21 ± 2.46a</td>
</tr>
</tbody>
</table>

Notes: Con = control. MCG = middle coverage of grass. HCG = high coverage of grass. SR = shrub P. decomposita. DTB = deciduous tree B. albo-sinensis. ETC = evergreen tree C. fortunei. RV = residual vegetation. The values are mean ± standard error of five replicates. Values in each column that do not share the same letter are statistically different ($p < 0.05$) between the treatments when analyzed by one-way analysis of variance.
Methods (Morgan and Rickson 1995; Yu et al. 2009). On the one hand, canopy cover intercepts rainfall, thus reducing the kinetic energy of the raindrops and preventing soil crusting (Liu et al. 1996). On the other hand, plant stems and litter alleviate runoff flow velocity, thus decreasing runoff energy (Edwards et al. 1994; Dabney et al. 1995; Xu et al. 2006). Our experimental results indicated that the amount of runoff and soil erosion was reduced with the increasing of coverage. The results were corroborated with other researchers (Cerda 1997; Kosmas et al. 2000; Xu et al. 2009), who documented that increasing coverage had positive effects on reducing runoff and soil erosion. From field surveys, we found that over two years of natural vegetation succession, the invading pioneer grass species grew rapidly and formed dense cover of plant communities on some parts of steep slopes. Our experimental results also indicated that the natural vegetation type of high coverage of grass could more effectively prevent runoff and soil erosion than other vegetation types. The results of this study revealed that maintaining or facilitating some rapid growth grass species to form stable plant communities could be more effective in controlling water runoff and soil loss in early renewal processes for battered landslides than planting shrubs, deciduous trees, and evergreen trees.

Soil quality is the other key factor in controlling water runoff and soil loss (Fu et al. 2004; Arbelo et al. 2006; Xu et al. 2009). Generally, increased soil BD would decrease infiltration rates and increase the risk of soil erosion (Lal et al. 1994; Descheemaeker et al. 2006). In this study, we found the six vegetation types had lower soil BD and higher SWC, soil organic C, total N, CEC, microbial biomass C and N, and relative steady infiltration rates than adjacent bare surfaces. The results mean that all vegetation types play an important role in improving soil quality. The reasons might be similar to some other research (Ziegler and Giambelluca 1998; Thompson et al. 2005) that found that vegetation can add litterfall to the ground surface, thereby increasing soil organic matter and improving soil structure. However, we also found that different vegetation types

position than other four lines (figure 6). This indicated that B. albo-sinensis, residual vegetation, and high coverage of grass were more effective in controlling soil loss.

Discussion. Because of the earthquake damage, much of the standing vegetation on the landslide was eliminated (table 1); thus, increasing bare ground vegetation cover is a key ecological recovery measure in controlling water runoff and soil loss on the landslide. Vegetation cover is widely used as an important measure for soil and water conservation methods (Morgan and Rickson 1995; Yu et al. 2009). On the one hand, canopy cover intercepts rainfall, thus reducing the kinetic energy of the raindrops and preventing soil crusting (Liu et al. 1996). On the other hand, plant stems and litter alleviate runoff flow velocity, thus decreasing runoff energy (Edwards et al. 1994; Dabney et al. 1995; Xu et al. 2006). Our experimental results indicated that the amount of runoff and soil erosion was reduced with the increasing of coverage. The results were corroborated with other researchers (Cerda 1997; Kosmas et al. 2000; Xu et al. 2009), who documented that increasing coverage had positive effects on reducing runoff and soil erosion. From field surveys, we found that over two years of natural vegetation succession, the invading pioneer grass species grew rapidly and formed dense cover of plant communities on some parts of steep slopes. Our experimental results also indicated that the natural vegetation type of high coverage of grass could more effectively prevent runoff and soil erosion than other vegetation types. The results of this study revealed that maintaining or facilitating some rapid growth grass species to form stable plant communities could be more effective in controlling water runoff and soil loss in early renewal processes for battered landslides than planting shrubs, deciduous trees, and evergreen trees.

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### Table 4

Soil properties of different vegetation rehabilitation patterns.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>BD (g m⁻³)</th>
<th>SWC (%)</th>
<th>Organic C (g kg⁻¹)</th>
<th>Total N (g kg⁻¹)</th>
<th>CEC (cmol kg⁻¹)</th>
<th>Microbial biomass C (mg kg⁻¹)</th>
<th>Microbial biomass N (mg kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Con</td>
<td>1.54 ± 0.03a</td>
<td>10.07 ± 0.62d</td>
<td>5.90 ± 0.55d</td>
<td>1.07 ± 0.06d</td>
<td>9.17 ± 0.61d</td>
<td>17.60 ± 2.34e</td>
<td>8.03 ± 3.94d</td>
</tr>
<tr>
<td>MCG</td>
<td>1.39 ± 0.05b</td>
<td>16.86 ± 1.05c</td>
<td>14.97 ± 1.03bc</td>
<td>1.38 ± 0.05c</td>
<td>11.46 ± 0.52c</td>
<td>27.23 ± 3.69d</td>
<td>17.98 ± 3.88c</td>
</tr>
<tr>
<td>HCG</td>
<td>1.33 ± 0.05b</td>
<td>21.11 ± 1.58b</td>
<td>16.95 ± 1.91b</td>
<td>1.81 ± 0.17ab</td>
<td>14.39 ± 0.59ab</td>
<td>85.91 ± 8.42b</td>
<td>25.41 ± 3.80ab</td>
</tr>
<tr>
<td>SR</td>
<td>1.35 ± 0.02b</td>
<td>14.80 ± 1.24c</td>
<td>16.14 ± 1.99b</td>
<td>1.66 ± 0.07b</td>
<td>14.45 ± 0.94ab</td>
<td>50.52 ± 12.80c</td>
<td>23.12 ± 3.93b</td>
</tr>
<tr>
<td>DTB</td>
<td>1.31 ± 0.06b</td>
<td>15.45 ± 2.32c</td>
<td>17.81 ± 1.62b</td>
<td>1.96 ± 0.09ab</td>
<td>14.67 ± 0.97ab</td>
<td>56.57 ± 14.23c</td>
<td>22.37 ± 0.81b</td>
</tr>
<tr>
<td>ETC</td>
<td>1.36 ± 0.09b</td>
<td>14.83 ± 2.04c</td>
<td>12.22 ± 1.64c</td>
<td>1.37 ± 0.07c</td>
<td>12.37 ± 0.64bc</td>
<td>40.58 ± 4.23d</td>
<td>17.95 ± 0.67c</td>
</tr>
<tr>
<td>RV</td>
<td>1.13 ± 0.07c</td>
<td>27.61 ± 2.45a</td>
<td>24.51 ± 1.47a</td>
<td>2.32 ± 0.33a</td>
<td>15.98 ± 0.97a</td>
<td>109.29 ± 6.43a</td>
<td>33.58 ± 0.72a</td>
</tr>
</tbody>
</table>

Notes: Con = control. MCG = middle coverage of grass. HCG = high coverage of grass. SR = shrub P. decomposita. DTB = deciduous tree B. albo-sinensis. ETC = evergreen tree C. fortune. RV = residual vegetation. BD = bulk density. SWC = soil water content. C = carbon. N = nitrogen. CEC = cation exchange capacity. The values are mean ± standard error of five replicates. Values in each column that do not share the same letter are statistically different (p < 0.05) between the treatments when analyzed by one-way analysis of variance.
had effects on soil properties to different degrees. As shown in this study, soil physical and chemical properties under residual vegetation were better than those of other vegetation types (tables 1 and 4). These areas acted as fertile islands, could effectively decrease runoff and soil loss (figures 3 and 4), and also had positive effects on grass species recruitment (table 2). Though soil under residual vegetation was subjected to relatively small disturbance compared to that under other vegetation types, the results also could provide some necessary information for us in order to select suitable vegetation types for ecosystem restoration on the landslide.

Among the three artificially planted vegetation types in the present study, we found \textit{B. albo-sinensis} and \textit{P. decomposita} could improve soil quality and control runoff and soil loss more efficiently than \textit{C. fortunei}. This might be because the dead leaves of \textit{B. albo-sinensis} and \textit{P. decomposita} more easily fell off and onto the ground than those of \textit{C. fortunei}, thereby increasing litter and organic matter and decreasing soil erodibility. The results indicated that deciduous trees and shrubs were more suitable for soil quality recovery than evergreen trees.

Different than in some degraded ecological systems, such as the Loess Plateau (Ni et al. 2004; Fu et al. 2005; Chen et al. 2010) and dry-warm river valley (Li et al. 2005; Yan et al. 2006; Xu et al. 2009), soil stratification on the landslides was seriously damaged by the earthquake. As described in this study, a mass of gravel and rock debris was scattered on the landslides (table 1). The effects of soil components on the hydrological behavior have been addressed in several studies (Katra et al. 2007; Ruiz Sinoga et al. 2010). These researchers found that rock fragments on the surface would influence the continuity of overland runoff and that rock fragments in the soil would increase the gap between soil components, thus decreasing the time that the water remained in the soil. Similar to these results, we found that the hydrological processes on the landslides were disadvantageous for increasing soil water retention capacity and facilitating overland runoff (table 4 and figure 5). Much of the rainfall flowing downwards along the gaps would surely increase the instability of soils between rock fragments. Plant roots play an important role in binding the soil and reducing its erodibility (Zhu and Li 1989; Zhang et al. 2010). Thus, the vegetation type with

**Figure 3**
Accumulated runoff depth for different vegetation rehabilitation patterns from July 1 to October 29, 2010. Con = control. MCG = middle coverage of grass. HCG = high coverage of grass. SR = shrub \textit{P. decomposita}. DTB = deciduous tree \textit{B. albo-sinensis}. ETC = evergreen tree \textit{C. fortunei}. RV = residual vegetation.

**Figure 4**
Accumulated soil loss for different vegetation rehabilitation patterns from July 1 to October 29, 2010. Con = control. MCG = middle coverage of grass. HCG = high coverage of grass. SR = shrub \textit{P. decomposita}. DTB = deciduous tree \textit{B. albo-sinensis}. ETC = evergreen tree \textit{C. fortunei}. RV = residual vegetation.
developed roots would be more suitable for controlling subsurface soil stability on the landslides. Based on this suggestion, we found the roots of artificially planted vegetation types had deeper distribution capability than those of grass species, and among the three artificially planted vegetation types, the roots of B. albo-sinensis had stronger expansion ability than those of shrubs and evergreen trees; therefore, deciduous trees were more suitable for controlling subsurface soil stability on the landslides. To achieve the best restoration effect on the landslide, the characteristics, such as coverage, the ability of improving soil quality, and roots, might be taken as the criteria for selecting a suitable vegetation type. Our results indicated that high coverage of grass and deciduous trees could combine to achieve a good recovery effect and can be used to design an effective vegetation restoration pattern for rehabilitation of wider earthquake-triggered landslides. That is, on the landslides where grass recovered well naturally, we should plant some deciduous trees thereby facilitating the formation of fertile islands and enhancing the stability of subsurface soils.

To restore an ecosystem, both vegetation and soils should be taken into consideration. As described in this study, the management of landslide recovery not only needs to restore the landslide vegetation and improve soil quality, but also needs to facilitate the stability of subsurface soils. Coevolution of vegetation and soils might result in more effective restoration (Arbejo et al. 2006; Xu et al. 2009). Our experimental results indicated that any single vegetation pattern in the present study couldn’t achieve the best recovery effect, but some vegetation patterns could be combined to achieve a good restoring effect, such as high coverage of grass and deciduous tree B. albo-sinensis. Thus, we should put emphasis on the vegetation pattern design for ecosystem restoration. For example, on the landslides where grass recovered well naturally, we should plant some deciduous trees thereby facilitating the formation of fertile islands and enhancing the stability of subsurface soils. On the bare ground landslides, we should not only plant some deciduous trees, but also take some measures to increase the ground vegetation cover since some researchers (Valentin et al. 1999; Martínez Raya et al. 2006; Xu et al. 2009) have documented that the banded or stripped pattern of grass would reduce much more water runoff and could facilitate faster succession.

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