Revegetation as an efficient means of increasing soil aggregate stability on the Loess Plateau (China)

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A R T I C L E   I N F O

Article history:
Received 23 August 2012
Received in revised form 2 May 2013
Accepted 20 May 2013
Available online 4 July 2013

Keywords:
Soil aggregate stability
Le Bissonnais’ method
Loess Plateau
Grain for Green
Revegetation
Plant communities

A B S T R A C T

Soil aggregate stability influences several aspects of soil physical behavior, such as water infiltration and soil erosion (Amézketa, 1999). We investigated the soil aggregate stability characteristics in the framework of the ‘Grain for Green’ vegetation rehabilitation project at the Loess Plateau (China) by using the Le Bissonnais’ method (1996) and the modified Yoder (1936) methods. Both non-grazed grassland and afforestation revegetations were considered. The size distribution mode was always >2 mm for the fast wetting test (FW) in the non-grazed grassland communities. This fraction accounted for approximately 40% to 80% of the total soil weight. The wet stirring (WS) test showed a distribution similar to that determined by the FW test. For the slow wetting (SW) test, 80% or more of the non-grazed grassland soil fragments was >2 mm. The mean weighted diameter (MWD) that was determined by the Le Bissonnais’ method was different among the tests and land uses. For the FW test, all the plant communities were significantly different from that of the recently abandoned grazing on grassland at the 0–20 and 20–40 cm depths. In the Artemisia sacrorum community, the maximum MWD was approximately 3 mm for the 0–20 cm depth. There were no significant differences among the plant communities after 3 years of afforestation and 7 years of non-grazing of the grassland. The MWDs were lower in the afforestation area than in the non-grazed grassland area. The maximum MWD value from the FW test was approximately 1.8 mm and was significantly lower (<0.5 mm) for cropland. The MWD of the modified Yoder method was positively related to the slow wetting and wet stirring (WS) tests of the Le Bissonnais’ method (n = 20 and r = 0.83 and 0.87, respectively).

In the Loess Plateau, revegetations by non-grazed grassland and afforestation are efficient means of increasing aggregate stability and decreasing soil erodibility. The aggregate stability under non-grazed grasslands is higher than that under afforestation. The effect of revegetation is persistent, which makes it a suitable long-term management practice. Compared with the modified Yoder’s method, the FW test of the Le Bissonnais’ method is better at determining aggregate stability differences among land uses and is recommended for future studies.

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1. Introduction

Soil structure is a key soil property that impacts plant and animal life, moderates environmental quality changes through soil organic carbon sequestration, and impacts soil water quality. Soil structure can be defined in terms of form and stability (Bronick and Lal, 2005). Good soil structure is important for the productivity of sustainable agricultural and for the preservation of environmental quality (Peng et al., 2004). Soil structure depends on the presence of stable aggregates. In fact, aggregate stability influences several soil physical processes, such as...
water infiltration and soil erosion (Amézketa, 1999; Le Bissonnais et al., 2007). Specifically, aggregate stability impacts the movement and storage of water in soils, soil aeration, soil erosion, biological activity, and crop growth (Zhang and Miller, 1996). Thus, aggregate stability affects a wide range of physical and biogeochemical processes in natural and agricultural environments. Maintaining high soil aggregate stability is essential for preserving soil productivity and for minimizing soil erosion and environmental pollution that result from soil degradation. Arshad and Cohen (1992) proposed that aggregate stability is one of the physical soil properties that can serve as a soil quality indicator. Hortensius and Welling (1996) included aggregate stability in the international standardization of soil quality measurements. Aggregate stability is also used as an indicator of soil structure (Six et al., 2000).

Human activities have impacted Chinese ecosystems for millennia (Fu et al., 1999, 2002). In the last century, fragmentation and degradation of ecological environments accelerated due to increasing population pressure. To prevent further deterioration of natural ecosystems, the Chinese government has launched a series of nationwide conservation projects. These projects, such as the ‘Grain for Green’ project, focus on the rehabilitation and recovery of damaged ecosystems (McVicar et al., 2007; Stokes, et al., 2010). The impacts of human activity on the Loess Plateau can be attributed to continuous and widespread stress, such as over-grazing and large-scale monocultures (wheat and maize) (Fu et al., 2000). In this area, soil erosion is a major threat. One of the most urgent tasks for achieving sustainable agricultural development is the recovery of natural vegetation (Li et al., 2005). Among other impacts, revegetation could increase aggregate stability and decrease soil erosion. Soil water-stable aggregation research has been conducted at the Loess Plateau in relation to soil erosion (for example, Wang et al., 1994; Zha et al., 1992). According to this research, soil water-stable aggregation best reflects the ability of soils to resist erosion at the Loess Plateau. However, few papers are available regarding the evolution of soil water-stable aggregation during natural revegetation (e.g., Guo et al., 2010). Hence, the effect of revegetation on soil aggregate stability needs to be confirmed. At the Loess Plateau, two types of revegetation practices have been implemented: non-grazed grassland and afforestation, but no comparison between these vegetation types have been carried out yet.

Numerous research studies regarding soil aggregate stability on the Loess Plateau have been conducted (for example, Gao, 1991; Zhu, 1982). While many methods have been designed to measure aggregate stability, most of the results from the Loess Plateau have been obtained using a method based on Yoder (1936). These studies showed that the fraction of soil aggregates >0.25 mm is strongly related to soil erodibility (Gao, 1991; Zhu, 1982). Wet sieving by Yoder’s method involves several mechanisms of soil aggregate breakdown (Le Bissonnais, 1996). Other methods, such as that of Le Bissonnais (1996), have been designed to separate the mechanisms (such as slaking and differential clay swelling) and to provide more information regarding soil aggregation. The Le Bissonnais (1996) method recently became an ISO standard (ISO/DIS, 10930, 2012). Thus, it is important to compare the capabilities of the Le Bissonnais (1996) method with those based on the Yoder (1936) method.

The objectives of this study were to (1) investigate the changes in soil aggregate stability during vegetation rehabilitation in the Loess Plateau of China, (2) assess which revegetation practices improve soil aggregate stability the most, and (3) compare the suitability of the Le Bissonnais’ method with that of the modified Yoder’s method for the Loess Plateau soils.

Table 1
Geographic and vegetation characteristics of the sampling sites for the revegetation gradient of non-grazed grassland.

<table>
<thead>
<tr>
<th>Sample site name</th>
<th>Revegetation duration (years)</th>
<th>Elevation (m)</th>
<th>Geographical coordinates (N, E)</th>
<th>Slope (°)</th>
<th>Dominant species</th>
<th>Accompanying species</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST.G.</td>
<td>56</td>
<td>2058</td>
<td>36°15.143°106°23.204°</td>
<td>10°</td>
<td>Stipa grandis</td>
<td>Artemisia frigida Willd., Potentilla acaulis L., Medicago ruthenica Potentilla angustifolia</td>
</tr>
<tr>
<td>ST.B.</td>
<td>36</td>
<td>2097</td>
<td>36°15.223°106°22.935°</td>
<td>14°</td>
<td>Stipa bungeana</td>
<td>Artemisia sacrorum Thymus mongolicus Leymus selculinus Potentilla bifurca</td>
</tr>
<tr>
<td>At.S.</td>
<td>25</td>
<td>2082</td>
<td>36°15.751°106°23.415°</td>
<td>17°</td>
<td>Artemisia sacrorum Ledeb Stipa grandis P. Smirn</td>
<td>Heteropappus alticus Thymus mongolicus Carex rigescens (Franch.) V. Krecz, Medicago ruthenica (Linn.) Trautv Astragalus scaberrimus Bunge</td>
</tr>
<tr>
<td>Hi.O.</td>
<td>9</td>
<td>2080</td>
<td>36°15.807°106°23.238°</td>
<td>10°</td>
<td>Hierochloe ordorata Leymus selculinus (George) Tzvel.; Hierochloe ordorata (Linn.) Beauv.</td>
<td>Thymus mongolicus Artemisia scoparia</td>
</tr>
<tr>
<td>Ab.G.</td>
<td>3</td>
<td>2078</td>
<td>36°15.807°106°23.266°</td>
<td>6°</td>
<td></td>
<td>Potentilla bifurca</td>
</tr>
</tbody>
</table>

ST.G.: Stipa grandis P. Smirn (56 years); ST.B.: Stipa bungeana Trin Ledeb (36 years); At.S.: Artemisia sacrorum Ledeb (25 years); Th.M.: Thymus mongolicus Ronn. (15 years); Hi.O.: Hierochloe ordorata Beauv. (7 years); Ab.G.: recently abandoned grazing on grassland (3 years).

Table 2
General situation of selected plots for the revegetation gradient of afforestation.

<table>
<thead>
<tr>
<th>Plot name</th>
<th>Revegetation duration (years)</th>
<th>Elevation (m)</th>
<th>Slope (°)</th>
<th>Topography</th>
<th>Dominant species</th>
<th>Soil type</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.K.26</td>
<td>26</td>
<td>1670</td>
<td>25</td>
<td>Middle slope</td>
<td>C. korshinski</td>
<td>TyPIC loessic orthic primosols</td>
</tr>
<tr>
<td>C.K.16</td>
<td>16</td>
<td>1670</td>
<td>18</td>
<td>Middle slope</td>
<td>C. korshinski</td>
<td>TyPIC loessic orthic primosols</td>
</tr>
<tr>
<td>A.G.3</td>
<td>3</td>
<td>1675</td>
<td>16</td>
<td>Upper slope land</td>
<td>Stipa bungeana, Artemisia sacrorum Ledeb, Thymus mongolicus Ronn. Wheat</td>
<td>TyPIC loessic orthic primosols</td>
</tr>
<tr>
<td>Cr.</td>
<td>0</td>
<td>1620</td>
<td>&lt;5</td>
<td>Slope farmland</td>
<td></td>
<td>TyPIC loessic orthic primosols</td>
</tr>
</tbody>
</table>

C.K.26: Caragana korshinskii Kom. (26 years); C.K.16: C. korshinskii Kom. (16 years); A.G.3: abandoned grazing land (3 years); Cr.: slope cropland.
Table 3
Soil physical and chemical properties for the revegetation gradient of non-grazed grassland.

<table>
<thead>
<tr>
<th>Plant community</th>
<th>Depth (cm)</th>
<th>Bulk density (g/cm³)</th>
<th>OM (g · kg⁻¹)</th>
<th>Total N (g · kg⁻¹)</th>
<th>NO₃⁻N (mg · kg⁻¹)</th>
<th>NH₄⁺-N (mg · kg⁻¹)</th>
<th>Available P (mg · kg⁻¹)</th>
<th>Available K (mg · kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>St.G.</td>
<td>0–20</td>
<td>0.90</td>
<td>32.18</td>
<td>3.44</td>
<td>18.14</td>
<td>4.89</td>
<td>4.06</td>
<td>3.44</td>
</tr>
<tr>
<td></td>
<td>20–40</td>
<td>1.12</td>
<td>25.55</td>
<td>2.90</td>
<td>15.68</td>
<td>4.41</td>
<td>3.21</td>
<td>2.90</td>
</tr>
<tr>
<td>St.B.</td>
<td>0–20</td>
<td>0.91</td>
<td>27.83</td>
<td>3.13</td>
<td>16.77</td>
<td>3.95</td>
<td>3.53</td>
<td>3.13</td>
</tr>
<tr>
<td></td>
<td>20–40</td>
<td>1.14</td>
<td>21.22</td>
<td>2.65</td>
<td>13.70</td>
<td>4.80</td>
<td>2.73</td>
<td>2.65</td>
</tr>
<tr>
<td>At.S.</td>
<td>0–20</td>
<td>1.22</td>
<td>23.57</td>
<td>2.41</td>
<td>14.13</td>
<td>6.78</td>
<td>3.05</td>
<td>2.61</td>
</tr>
<tr>
<td></td>
<td>20–40</td>
<td>1.16</td>
<td>21.30</td>
<td>2.27</td>
<td>17.20</td>
<td>6.08</td>
<td>3.02</td>
<td>2.27</td>
</tr>
<tr>
<td>Th.M.</td>
<td>0–20</td>
<td>0.92</td>
<td>29.69</td>
<td>3.17</td>
<td>14.31</td>
<td>6.91</td>
<td>4.37</td>
<td>3.17</td>
</tr>
<tr>
<td></td>
<td>20–40</td>
<td>1.43</td>
<td>24.33</td>
<td>2.74</td>
<td>19.83</td>
<td>5.03</td>
<td>3.25</td>
<td>2.74</td>
</tr>
<tr>
<td>Hi.O.</td>
<td>0–20</td>
<td>1.23</td>
<td>20.31</td>
<td>2.19</td>
<td>10.25</td>
<td>5.01</td>
<td>3.37</td>
<td>2.19</td>
</tr>
<tr>
<td></td>
<td>20–40</td>
<td>1.16</td>
<td>17.44</td>
<td>2.03</td>
<td>8.86</td>
<td>4.25</td>
<td>2.53</td>
<td>2.03</td>
</tr>
<tr>
<td>Ab.G.</td>
<td>0–20</td>
<td>1.13</td>
<td>9.57</td>
<td>1.22</td>
<td>14.40</td>
<td>4.10</td>
<td>2.77</td>
<td>1.22</td>
</tr>
<tr>
<td></td>
<td>20–40</td>
<td>1.16</td>
<td>9.19</td>
<td>1.24</td>
<td>11.93</td>
<td>3.65</td>
<td>2.34</td>
<td>1.24</td>
</tr>
</tbody>
</table>

St.G.: Stipa grandis P. Smirn (56 years); St.B.: Stipa bungeana Trin Ledeb (36 years); At.S.: Artemisia sacrorum Ledeb (25 years); Th.M.: Thymus mongolicus Ronn. (15 years); Hi.O.: Hierochloe ordorata Beauv (7 years); Ab.G.: recently abandoned grazing on grassland (3 years).

2. Materials and methods

2.1. The study sites

The study sites were located within the Loess Plateau of China near the city of Yanzhoun (Ningxia province). In this area, 90% of the land area is hilly, 4% is occupied by villages and rivers, and only 6% is considered suitable for intensive agriculture. This area has a sub-arid climate characterized by heavy seasonal rainfall with periodic floods and droughts.

The average annual rainfall at the observatory is 400 mm (1941–2000; C.V. 18%), and the area has distinct wet and dry seasons. The rainy season starts in July and continues until September. The July rainfall accounts for 24% of the annual rainfall. The mean annual temperature is approximately 7°C. Most of the land is at an altitude between 1800 and 2040 m and is frequently dissected by steep and very steep gullies.

Two types of revegetation areas were selected: non-grazed grassland and afforestation. Altogether, ten sites were chosen. The non-grazed grassland area is located within the Yunwu Observatory for Vegetation Protection and Eco-environment (latitude 36° 13′–36° 36′ 19″ N and longitude 106° 24′–106° 28′ 28″ E). It is the only remaining non-grazed grassland on the Loess Plateau and is a protected area of approximately 1000 ha that is enclosed by fences. This non-grazed grassland area was formally established in 1982 and has not been grazed for 30 years. However, some sections of the non-grazed grassland have been protected from grazing for as many as 56 years. Based on the natural plant succession process in this area (Zou and Guan, 1997), we studied six sites that had been enclosed for different lengths of time to establish natural vegetation after 1982. The non-grazed grassland was used as grazing land prior to enclosure. The enclosure times were determined based on land use records and farmers’ indications. Depending on the time of natural succession, the studied plant communities from the longest to shortest enclosure duration were as follows: (a) Stipa grandis P. Smirn (St.G., 56 years), (b) Stipa bungeana Trin Ledeb (St.B., 36 years), (c) Artemisia sacrorum Ledeb (At.S., 25 years), (d) Thymus mongolicus Ronn. (Th.M., 15 years), (e) Hierochloe ordorata Beauv (Hi.O., 7 years), and (f) recently abandoned grazing on grassland (Ab.G., 3 years).

The basic information about these sites is listed in Table 1.

The afforestation area is located at the Guyuan Observatory for Vegetation Protection and Eco-environment (latitude 35° 59′–36° 02′ E and longitude 106° 26′–106° 30′ N), which is approximately 30 km south of the Yunwu Observatory for Vegetation Protection and Eco-environment. The site is a long-term and comprehensively managed field study site that was established in 1982. Several practical revegetation methods were implemented for soil and water protection, including shrub reconstruction and natural enclosure by a steel fence to protect the area from grazing and human activities. Under afforestation, four communities from the neighboring areas were studied, including (a) a 26-year-old Caragana korshinskii Kom. (C.K.26), (b) a 16-year-old C. korshinskii Kom. (C.K.16), (c) a 3-year-old abandoned grazing land (A.G.3), and (d) a slope cropland (Cr.). The basic information about these sites are listed in Table 2. The slope cropland is currently used by farmers for production (with very low fertilizer input) and represents the field conditions just before afforestation. The basic soil physical and chemical properties for the non-grazed grassland and afforested plant communities are listed in Tables 3 and 4, respectively. Based on data from previously-studied sites, the particle size distribution of the upper 0–20 cm of the soil at the non-grazed grassland area was 173–292 g · kg⁻¹ clay (<0.002 mm), 173–267 g · kg⁻¹ silt (0.2–0.002 mm), and 462–579 g · kg⁻¹ sand (>0.2 mm). At the afforestation area, the particle size distribution of the upper 0–20 cm of soil was 279–357 g · kg⁻¹ clay (<0.002 mm), 584–630 g · kg⁻¹ silt (0.2–0.002 mm), and 60–91 g · kg⁻¹ sand (>0.2 mm) (An and Huang, 2003; An et al., 2009).

2.2. Soil sampling and preparation

Soil samples were collected at 0–20 cm and 20–40 cm depths in March 2010. An area of 60 × 60 m² was delineated at each site.

Table 4
Soil physical and chemical properties for the revegetation gradient of afforestation.

<table>
<thead>
<tr>
<th>Plant community</th>
<th>Depth (cm)</th>
<th>Bulk density (g/cm³)</th>
<th>OM (g · kg⁻¹)</th>
<th>Total N (g · kg⁻¹)</th>
<th>NO₃⁻N (mg · kg⁻¹)</th>
<th>NH₄⁺-N (mg · kg⁻¹)</th>
<th>Available P (mg · kg⁻¹)</th>
<th>Available K (mg · kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.K.26</td>
<td>0–20</td>
<td>1.04</td>
<td>15.54</td>
<td>1.59</td>
<td>5.96</td>
<td>5.07</td>
<td>4.23</td>
<td>1.59</td>
</tr>
<tr>
<td></td>
<td>20–40</td>
<td>1.14</td>
<td>12.14</td>
<td>1.37</td>
<td>7.67</td>
<td>4.37</td>
<td>3.31</td>
<td>1.37</td>
</tr>
<tr>
<td>C.K.16</td>
<td>0–20</td>
<td>1.17</td>
<td>13.97</td>
<td>1.45</td>
<td>7.46</td>
<td>6.02</td>
<td>4.89</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td>20–40</td>
<td>1.30</td>
<td>8.33</td>
<td>0.90</td>
<td>6.40</td>
<td>6.43</td>
<td>3.56</td>
<td>0.90</td>
</tr>
<tr>
<td>A.G.3</td>
<td>0–20</td>
<td>1.28</td>
<td>17.74</td>
<td>1.88</td>
<td>6.29</td>
<td>3.96</td>
<td>3.43</td>
<td>1.88</td>
</tr>
<tr>
<td></td>
<td>20–40</td>
<td>1.16</td>
<td>11.81</td>
<td>1.29</td>
<td>5.64</td>
<td>3.99</td>
<td>2.71</td>
<td>1.29</td>
</tr>
<tr>
<td>Cr.</td>
<td>0–20</td>
<td>1.30</td>
<td>8.12</td>
<td>0.88</td>
<td>13.03</td>
<td>3.73</td>
<td>9.32</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>20–40</td>
<td>1.51</td>
<td>8.46</td>
<td>0.67</td>
<td>8.05</td>
<td>3.68</td>
<td>2.54</td>
<td>0.67</td>
</tr>
</tbody>
</table>

C.K.26: Caragana korshinskii Kom. (26 years); C.K.16: C. korshinskii Kom. (16 years); A.G.3: abandoned grazing land (3 years); Cr.: slope cropland.
Within this area, three 20 × 20 m² plots were selected for sampling. Undisturbed soil samples were taken from each plot. Three soil samples were collected at each depth at each site.

Samples were air-dried in the laboratory at room temperature. Undisturbed bulk soil was used for Yoder’s method. Each sample was dry-sieved to remove large roots, stones and the macrofauna.

For the Le Bissonnais’ aggregate stability method, soil aggregates between 5 and 3 mm were used.

### 2.3. Soil aggregate stability by the modified Yoder’s method

Soil aggregate stability was determined by using the modified Yoder’s method (Zhu, 1982) with a set of 5, 2, 1, 0.5, and 0.25 mm sieves. The sieves were rapidly immersed in distilled water and were oscillated for 3 min at a displacement of approximately 4 cm at 37 rounds per minute. All fractions were dried at 70 °C prior to weighing. The mean weighted diameter (MWD) was calculated as

Fig. 1. The soil aggregate fraction distributions from the Le Bissonnais’ method for the FW, WS and SW tests for the revegetation gradient of non-grazed grassland. (A) *Stipa grandis* P. Smirn (56 years), (B) *Stipa bungeana* Trin Ledeb (36 years), (C) *Artemisia sacrorum* Ledeb (25 years), (D) *Thymus mongolicus* Ronn. (15 years), (E) *Hierochloe ordorata* Beauv. (7 years), and (F) recently abandoned grazing on grassland (3 years). FW: Fast wetting; WS: Wet stirring; SW: Slow wetting. Error bars indicate the standard errors (n = 3).

![Fig. 1](image-url)
\[ \sum w_i x_i \] where \( w_i \) is the mean diameter of size fraction \( i \) and \( x_i \) is the proportion of the size fraction \( i \) in relation to the total sample weight. The summation was performed across all size fractions, including the fraction gone through the 0.25 mm sieve. For a given sample, three replicates were used, which led to nine measurements at a given depth at each site.

2.4. Soil aggregate stability by the Le Bissonnais’ method

Stability tests were performed with the Le Bissonnais (1996) method, which is the ISO standard #10930 (ISO/DIS, 10930, 2012). Three-gram samples containing aggregates of 3 to 5 mm were air-dried at 40 °C for 24 h. Three tests were conducted, including fast wetting (FW), slow wetting (SW), and wet stirring (WS). For the FW test, the aggregates were quickly immersed in deionized water. The FW test is sensitive to the slaking process. In contrast, the samples were moistened by placing them above humid foam for the SW test. The SW test determines the aggregate sensitivity for differential clay swelling. For the WS test, the aggregates are immersed in ethanol prior to transferring them to a flask of water and subsequent shaking. The use of ethanol inhibits slaking and differential clay swelling. Thus, the WS test is only sensitive to the mechanical breakdown process.

After applying the FW, SW or WS test, the size distribution was determined by sieving (0.05 mm, 0.1 mm, 0.2 mm, 0.5 mm, 1 mm and 2 mm). For a given soil sample, three replicates were analyzed for a total of nine measurements at a given depth at each site. Mean weighted diameters (MWDs) were computed from the fragment size distributions. As for Yoder’s method, the MWD is used as a structural stability index. For example, samples that have greater structural stability have a larger MWD (Le Bissonnais, 1996).

2.5. Statistical analyses

All statistical analyses were conducted in SPSS 11.0. A one-way ANOVA followed by the Newman–Keuls test (\( P < 0.05 \)) was used to compare differences among plant communities and land uses at depths of 0–20 cm and 20–40 cm.

3. Results

3.1. Distribution of soil aggregate fractions for different plant communities

3.1.1. The modified Yoder’s method

The results from the wet sieving method for soil aggregate stability at the non-grazed grassland communities are shown in Fig. 5 for the 0–20 and 20–40 cm soil depths. The main aggregate distribution...
fractions were always >5 mm and <0.25 mm, and the sum of these fractions accounted for between 50% and 80% of the total weight. The 0.5 mm to 0.25 mm fraction was always the lowest and only accounted for between 3% and 10% of the total weight. Except for Hi.O. and Ab.G., the other fractions decreased in the following order: >5 mm > 2–1 mm > 0.5–0.25 mm. The non-grazed grassland communities had a larger >5 mm fraction at the 20–40 cm depth, and upper case letters (for example, A, B, and C) are used for the 20 cm depth, and upper case letters (for example, A, B, and C) are used for the 20–40 cm depth. MWD: mean weighted diameter; FW: Fast wetting; WS: Wet stirring; SW: Slow wetting. Error bars indicate the standard errors (n = 3).

Fig. 3. MWD of the Le Bissonnais’ method FW, WS and SW tests for the revegetation gradient of non-grazed grassland. Means with the same letter in different rows are not significantly different at a 0.05 confidence level (Newman–Keuls). Lower case letters (for example, a, b, and c) are used for the 20 cm depth, and upper case letters (for example, A, B, and C) are used for the 20–40 cm depth. MWD: mean weighted diameter; FW: Fast wetting; WS: Wet stirring; SW: Slow wetting. St.G.: Stipa grandis P. Smirn (56 years); St.B.: Stipa bungeana Trin Ledeb (36 years); Al.S.: Artemisia sacrorum Ledeb (25 years); Th.M.: Thymus mongolicus Ronn. (15 years); Hi.O.: Hierochloe ordorata Beauv. (7 years); Ab.G.: recently abandoned grazing on grassland (3 years). Error bars indicate the standard errors (n = 3).

Fig. 4. MWD of the Le Bissonnais’ method FW, WS and SW tests for the revegetation gradient of afforestation. Means with the same letter in different rows are not significantly different at a 0.05 confidence level (Newman–Keuls). Lower case letters (for example, a, b, and c) are used for the 0–20 cm depth, and upper case letters (for example, A, B, and C) are used for the 20–40 cm depth. MWD: mean weighted diameter; FW: Fast wetting; WS: Wet stirring; SW: Slow wetting. C.K.26: Caragana korshinskii Kom. (26 years); C.K.16: C. korshinskii Kom. (16 years); A.G.: abandoned grazing land (3 years); Cr.: slope cropland (0 year). Error bars indicate the standard errors (n = 3).
2 mm. This fraction accounted for approximately 40% to 80% of the total weight in all but the recently abandoned grazing on grassland (Fig. 1F) (approximately 20%). There were obvious differences between the soils from the recently abandoned grazing on grassland and the other non-grazed grasslands that had been recovered for up to 56 years. The size fractions were evenly distributed in the recently abandoned grazing on grassland soils. The greatest content was approximately 20%, which was similar to the other fractions. The WS test resulted in distributions similar to those found by the FW test. For the SW test, all the soils had a >2 mm fraction that was close to or above 80%. In most cases, the 0–20 cm samples had coarser fragments than the 20–40 cm samples within a given land use.

The soil aggregate fraction distributions for the different types of afforestation are shown in Fig. 2. For the FW test, the main size fraction was >2 mm, which accounted for approximately 40% of the C.K.26, C.K.16 and A.G.3 fragments. The size distribution of the FW test in the Cr. community was close to 0% for the >2 mm fraction and more than 80% for the 0.2 mm fraction (for the 0–20 cm and the 20–40 cm depths). The WS test showed contrasting distributions that depended on the type of afforestation. The A.G.3 had a mode of >2 mm, which accounted for more than 40% of the total sample weight. In contrast, the mode for Cr was <0.05 mm (approximately 30% of the total sample weight). The C.K.26 and C.K.16 types had intermediate size distributions, with the >2 and <0.05 mm fractions accounting for approximately 20% of the total sample weight. For the SW test, all the afforested soils had high >2 mm fragment contents (approximately 80%) compared with the cropland soils (approximately 20%).

### 3.2. The MWD for different plant communities

#### 3.2.1. The modified Yoder’s method

The MWD values that were determined by the modified Yoder’s method are shown in Fig. 7. Among the non-grazed grasslands (Fig. 7A), the highest MWD value at the 0–20 cm soil depth was approximately 3 mm. For the 0–20 cm depth, the MWD values of At.S. and Ab.G. were significantly higher than the other MWD values. The MWD values at the 0–20 cm depth were lower than the corresponding MWD values from the 20–40 cm depth (except for the Hi.O community). At the 20–40 cm depth, the MWD was between 2.0 and 2.8 mm. In addition, except for the recently abandoned grazing on grassland, there were no significant differences between the non-grazed grasslands.

In the afforestation areas (Fig. 7B) at a depth of 0–20 cm, A.G.3 was the most stable (its MWD was the highest), C.K.26 and C.K.16 had statistically identical MWD values, and Cr had significantly lower MWD values than the afforested areas. At the 20–40 cm depth, no significant differences in the MWD values were found among the C.K.26, C.K.16 and A.G.3 communities. However, these plant communities are significantly more stable than the Cr. plant community.
3.2.2. The Le Bissonnais’ Method

The MWD by the Le Bissonnais’ method showed differences between tests and land uses (Fig. 3). For the FW test, all the plant communities were significantly different from the recently abandoned grazing on grassland (Ab.G.) at the 0–20 and 20–40 cm depths. The maximum MWD was approximately 3 mm for the At.S. community at the 0–20 cm depth, and the minimum MWD was approximately 1 mm for the recently abandoned grazing on grassland at the 20–40 cm depth. In addition, there were differences between the plant communities compared with the recently abandoned grazing on grassland. A similar trend resulted from the WS test. For the SW test, the plant communities were significantly different from the recently abandoned grazing on grassland at the 0–20 and 20–40 cm depths (P < 0.01). The maximum MWD was approximately 3.2 mm for the At.S. community at the 0–20 cm depth, and its minimum was approximately 2.7 mm for the recently abandoned grazing on grassland at the 20–40 cm depth. There was no significant difference between the plant communities and the Ab.G. community.

The MWDs at the afforestation sites were lower than that at the non-grazed grassland sites (Figs. 3 and 4). The maximum MWD value from the FW test was approximately 1.8 mm (Fig. 4A). In addition, no significant differences were found among the C.K.26, C.K.16 and A.G.3 communities at the 0–20 cm depth. At the same depth, the MWD was significantly lower for cropland, which had a MWD of <0.5 mm. For the WS test, the MWD was the highest for the A.G.3 community at the 0–20 cm and 20–40 cm depths. For the SW test, the MWD values were much higher than those for the WS and FW tests. For example, the MWD values were approximately 3 mm for the A.G.3, C.K.16, and C.K.26 communities, which is twice the FW test MWD value for cropland. However, the SW test results were similar to the WS and FW test results. For example, the Cr. land use had a significantly lower MWD than all the other land uses, regardless of depth.

4. Discussion

4.1. Effect of revegetation on soil aggregation and aggregate stability

Cropland on the Loess Plateau is characterized by continuous plowing and low organic and inorganic fertilizer inputs. The conversion of forestland to cropland, grazing land, or settlements has often resulted in soil degradation and nutrient losses (Dinesh et al., 2003). The soil erosion on the Loess Plateau is mainly caused by poor land use practices. Appropriate land use, such as afforestation and natural succession of non-grazed grassland on eroded areas, could be used to mitigate soil erosion. Such practices are reflected in the recent ecosystem reconstruction policy in Northwest China.

The natural soil structure is destroyed by plowing. Moreover, the stabilizing effects of root fibers become insignificant when they are shredded by tillage and decompose after harvesting. Because pore space increases due to mechanical cultivation, the air exchange and oxygen availability increases. This increase in oxygen availability enhances the microbial decomposition of organic matter. When coupled with accelerated soil erosion, enhanced decomposition rapidly depletes the soil organic matter content in the plow layer and reduces the aggregate stability (Zhang and Horn, 2001). Furthermore, the stability of non-cropped soil aggregates may benefit from hydrophobicity of soil organic carbon.

In the present study, the cropland soil had the lowest aggregate stability for all the Le Bissonnais’ (FW, SW and WS) and Yoder’s methods. This finding is consistent with the occurrence of erosion by water and was observed at many of the experimental cropland sites on the Loess Plateau (Zheng, 2006). Aggregate stability measurements on the Loess Plateau consistently indicate that the soil water-stable aggregate contents reflect the ability of the soils to resist erosion (An et al., 2009; Wang et al., 1994; Zha et al., 1992).

The aggregate stability was much higher in the non-grazed grassland soils than in the cropland soil (Figs. 3, 4 and 7). The MWD values were very high for several plant communities. In addition, the natural succession of non-grazed grasslands had a higher MWD value than the afforestation sites, especially for the FW and SW treatments. The MWD values were generally higher for the non-grazed grasslands than for the afforestation sites. Also, the non-grazed grasslands had the highest fraction of large aggregates (Fig. 1, 2, 5 and 6). These signify a strong soil structure and a high resistance to water erosion. Fattet et al. (2011) got results similar to ours (“herbaceous vegetation was more efficient than trees in improving aggregate stability.”). These traits are especially prevalent in the FW treatment, which measures aggregate stability to slaking. In addition, this trend is consistent with our field observations regarding water and soil erosion: no sediment was produced in this area (unpublished).

For the MWD of SW, there is no significant difference among the 3-to-27-year enclosure durations. But, for the FW, the 3-year non-grazed grassland MWD is quite lower than the other MWDs. Overall the aggregate stabilities of non-grazed grassland increase quickly after enclosure as shown by both Le Bissonnais’ and Yoder’s methods (Fig. 6A, C). After 7 years of non-grazing, an almost-constant aggregate stability is reached for all kinds of stability tests. In the afforestation area, an almost-constant aggregate stability is reached for all kinds of stability tests 3 years after planting (Fig. 8B, D).

Because of the ‘Grain for Green’ project that was launched in 1999 in the western part of China, the sloped cropland has been almost completely converted to forest and non-grazed grassland since then.
Our results indicate that these land use changes have significantly decreased soil erodibility. Based on the succession of communities, it was estimated that prohibiting grazing and cropping, by stabilizing soil aggregates, will continue to limit erosion.

From a soil aggregate stability enhancement and soil conservation standpoint, we can conclude that non-grazed grassland is more effective than afforestation, also it may take a few more years for aggregate stability to reach its maximum.

According to long-term monitoring and research studies on Loess Plateau soils (Guo et al., 2010; Jiao et al., 2012; Lv et al., 2012; Zheng, 2006), the vegetation structure and species diversity of afforested sites have improved. In our previous studies (An et al., 2009, 2010), soil microbiodiversities and soil nutrients increased for the first 20 years of enclosure, and then they kept a high level. Soil aggregate stability was probably influenced by many other factors such as soil organic carbon, soil inorganic carbon, and soil clay content. More research related to soil aggregate stability should be carried out to identify the mechanisms of soil aggregate stabilization depending on enclosure duration.

### 4.2. Comparison of the Yoder’s and Le Bissonnais’ methods

Yoder’s method combines two disaggregation mechanisms: slaking during sample immersion and mechanical breakdown during shaking. It makes it impossible to identify the sensitivity of a soil sample to the disaggregation mechanisms. On the contrary, comparing the MWDs between the three tests defined by Le Bissonnais (1996) help identify the sensitivity of soil aggregates to different disaggregation mechanisms: slaking for the FW test, differential clay swelling for the SW test and mechanical breakdown for the WS test. In the present study, the FW test was the most efficient for disrupting soil aggregates; the WS test was intermediate; and the SW test disrupted soil aggregates the least. Hence the soil aggregates were highly sensitive to slaking (FW test), less sensitive to mechanical breakdown (WS test) and the least sensitive to differential clay swelling (SW test). The summer rains of the studied area are often very intense. During these rains, the aggregates at the soil surface may undergo fast wetting, which causes high aggregate disruption. This finding potentially explains the high soil erodibility rates that are observed in the summer following heavy rains.

We hypothesize that the higher organic matter and carbohydrate contents of the surface layer (0–20 cm) contribute to aggregate stabilization by bridging between the mineral particles. Increased aggregate stability in mull A-horizons was reported in forests by Ma et al. (2005). With regard to improving semiarid soil structure, the soil organic matter concentration is the most important aggregate stability factor (Díaz et al., 1994). Organic matter and its biological origin are the main parameters responsible for aggregate stability. These parameters are usually developed in the rhizosphere. Increasing aggregate stability from microorganisms may be of a physical nature (Tisdall and Oades, 1982) or may be due to the formation and excretion of microbial polysaccharides that act as binding agents (Cheshire et al., 1983).

Some MWD by Yoder’s method were higher for the 20–40 cm depth than for the 0–20 cm depth (Fig. 7), suggesting a lower aggregate stability in the surface layer. These differences were not consistent with MWD by Le Bissonnais’ method for FW, SW and WS (Fig. 3). The cause of these inconsistencies is unclear.

The MWD of the modified Yoder method was positively correlated to the MWD of the Le Bissonnais’ method for SW ($r = 0.83$, $n = 20$) and WS ($r = 0.87$, $n = 20$) but was not related to that of the FW ($r = 0.29$, $n = 20$). This result is similar to the one of Guo et al. (2010), obtained on the Loess Plateau of China too. Le Bissonnais et al. (2007) (obtained on Mediterranean vineyards) and Guo et al.
also found the Le Bissonnais’s method more discriminant than the Yoder’s method. As such, the Le Bissonnais’ method should be preferred over the Yoder’s method while working on revegetation in the Loess Plateau of China.

To the credit of Yoder’s (1936) early work, it must be reminded that Le Bissonnais’ method was developed more recently and is based, among others, on Yoder (1936). Moreover, most authors of Yoder’s method are in fact (1) using a modified version, and (2) the changes are not always reported; making difficult to compare studies. Finally, considering the results of the comparisons between Yoder’s and Le Bissonnais’ method, and considering that Le Bissonnais’ method recently became an ISO standard (ISO/DIS, 2010, 2012), Le Bissonnais’ method should be considered as a preferred method.

5. Conclusions

At the Loess Plateau, non-grazed grassland and afforestation revegetations were efficient measures for increasing aggregate stability and decreasing soil erodibility. High aggregate stabilities were reached after 3 and 7 years under afforestation and non-grazed grassland, respectively. However, aggregate stability in the non-grazed grassland was higher than that under afforestation. This result was likely due to the higher organic matter content in the non-grazed grassland. The effect of revegetation on aggregate stability is persistent, which makes it a suitable long-term management practice.

The Le Bissonnais (1996) method was used to identify the processes responsible for disaggregation. Compared with the modified Yoder (1936) method, the Le Bissonnais (1996) method was better at determining aggregate stability (especially with the fast wetting test) between land uses at the Loess Plateau.

Acknowledgments

This research was supported by the French Minister of Foreign Affairs through a Hubert Curien grant (PFCC 2009–2010 #200919ZC), the National Natural Sciences Foundation of China (41171226, 41030532), and the Foundation for Youth Teachers by Northwest A&F University. In addition, the authors are grateful to Hervé Gaillard (UR0272, Soil Science Lab, INRA) for his technical assistance.

References


