Solid Earth Discuss., 6, 2803–2842, 2014
www.solid-earth-discuss.net/6/2803/2014/
doi:10.5194/sed-6-2803-2014

Solid Earth
Discussions
Open Access

Ecological restoration and soil improvement performance of the seabuckthorn flexible dam in the Pisha Sandstone area of Northwestern China

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Received: 20 August 2014 – Accepted: 11 September 2014 – Published: 24 September 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

Soil erosion of the Pisha Sandstone area of Loess Plateau is extremely severe in China. The Pisha Sandstone is very hard when it is dry, while it is very frail when wet. The seabuckthorn flexible dam (SFD), a type of ecological engineering, was proposed to control soil erosion and meliorate soil within the Pisha Sandstone area. To assess its effectiveness and the ecological restoration and soil improvement performance, a field experiment was conducted in this area. We found the strong sediment retention capacity of the SFD is the basis of using it to restore the ecosystem. We compared some certain ecological factors and soil quality between a gully with the SFD and a gully without the SFD, including soil moisture, soil organic matter (SOM), soil nutrients (including Ammonia Nitrogen, available phosphorus and Potassium), vegetation coverage and biodiversity. The results showed that the SFD exhibits excellent performance for ecological restoration and soil improvement of this area. The results are as follows: (i) by the sediment retention action, the deposition commonly occurred in the SFD gully, and the deposition patterns are obviously different from upper to lower gully, (ii) more surprisingly, unlike trees or other shrubs, the seabuckthorn has good horizontal extending capacity by its root system, (iii) soil moisture, SOM, soil nutrients, vegetation coverage and biodiversity in the vegetated gully with the SFD are all markedly increased. The results showed the SFD is both effective and novel biological measure for ecological restoration and soil improvement within the Pisha Sandstone area.

1 Introduction

The Pisha Sandstone area is located in the Loess Plateau of China, which is a major source of coarse sediment entering the upper and middle reaches of Yellow River. The Pisha Sandstone covers an area of 17 500 km^2, with a considerable sediment yield of 0.214 billion tons per year (Jin, 2003; Ran, 2006). Coarse sediment (> 0.05 mm) (Qian et al., 1980) derived from the Pisha Sandstone area accounts for 71.1 % of the

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total coarse sediment yield (0.301 billion tons per year) in the middle reaches of Yellow River (Zheng, 2005; Xu and Gao, 2007). The Pisha Sandstone is extremely hard like stone when it is dry, but very soft and friable when wet. Therefore, erosion commonly occurred in many gullies during and after rainfall events (Ziadat and Taimeh, 2013). The large amount of soil and water loss leads to soil nutrients loss (Zhao et al., 2013). Undoubtedly, this further worsened environment of this area, which makes many types of vegetation hardly live in this area. The threat of the Pisha Sandstone to vegetation is often compared with the toxin of arsenic as a metaphor and local people conventionally call it as Pisha (Chinese Pinyin of arsenic) Sandstone.

The Pisha Sandstone belongs to the continent fragment bedrock, which is composed of thick layer Sandstone, arenaceous shale and mudstone (Bazhenov et al., 1993; Mark et al., 1999), thereby easily being eroded by wind and water due to the diagenesis. The maximal erosion module of this area is up to 3×10^4 t km^{-2} year^{-1}, by which this area was often compared to "the cancer of the earth" or "the most severe soil and water loss in the world" (Bi, 1998, 2003). At present, the engineering measure, such as the check dam and some small-scale sediment retention reservoirs, was mainly applied to this area to control soil and water loss. However, rare vegetation measures are there used to restore the ecosystem of the area. Due to the special topography and extremely poor soil, some measures used successively to the other regions of Loess Plateau, including terrace or bench terrace, hedge fence, forest shelter belt, grass protective strip, etc. (Cao et al., 2007a, b; Zhao et al., 2013), are not suitable to this area. Current studies showed that soil and water conservation measures are different in various regions, including some man-made ones, which is mainly associated with local climate condition, soil physical property, autochthonous types of vegetation and their coverage, agricultural farming system structure, land use change, hydro-mulching, and etc. (Fernández et al., 2012; Prats et al., 2013; Prokop and Poreba, 2012; Cerdà, 1999). In fact, with the lapse of time, the negative effects of the engineering measure are gradually exposed due to the emergence of some new environmental problems. Therefore, people have recognized that vegetation is still the fundamental measure for soil erosion control and ecosystem rehabilitation in most regions of the world. Thus, seeking a type of vegetation, which can adapt the Pisha Sandstone area well, becomes the key to control soil erosion and restore the ecosystem of the area.

"*Hippophae* is commonly known as seabuckthorn, a multi-use plant which can be used to control soil erosion, biological nitrogen fixation and medicinal purposes" (Rongsen, 1992). There are two common species of seabuckthorn in China, namely, *Hippophae salicifolia* D. Don and *Hippophae rhamnoides* L.. *H. salicifolia* has a shrub-to-tree habit and is restricted to the Himalaya region, whereas *H. rhamnoides* is bushy, mainly growing at high altitude in China. Additionally, it is also widely distributed in Asia and Europe (Rousi, 1965, 1971). The seabuckthorn is a native plant of Loess Plateau in northwestern China, and has excellent biological features such as drought tolerance, barren soil tolerance and rapidly cloning capacity by its root nodule. To control soil erosion and restore the ecosystem of the Pisha Sandstone area, based on the ancient Chinese LaoZi's general philosophical viewpoints of "using soft to overcome hard" and "using flexibility to dissipate energy", the concept of the seabuckthorn flexible dam (SFD) was proposed by Bi and Li (1998, 2003) and Li et al. (2009). Actually, this is an active response to the call of "using the seabuckthorn to control Loess Plateau of China" put forward earlier by Qian (1986). The SFD is composed of the preferentially selected 2–3a seabuckthorn seedlings, and the seabuckthorn seedlings are grown, in an interlaced way, in the transects of certain large or small gully within the Pisha Sandstone area, according to specific row spacing and plant spacing within a row. The SFD can effectively slow flow velocity and dissipate flow energy by large numbers of branches and leaves of the seabuckthorn thus being able to efficiently trap coarse sediment transported by flood. Studies using different kinds of vegetation to control soil erosion or to prevent soil and water loss have been made for a long time in arid and semi-arid or tropical areas (Fang et al., 2012; Hussein et al., 2007; Mishra et al., 2006; Zhang et al., 2004; Yu, 2002; Yu et al., 2003; Gomi et al., 2006; Sidle, 2006). Great attention has been paid to vegetation reducing soil loss by decreasing runoff volume or by changing runoff-sediment yield relationship (Slattery and Phillips,

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2011; Kumar et al., 2008; Pan et al., 2011; Li et al., 2008; Ide et al., 2009; Hartanto et al., 2003). The measures include vegetation barriers, vegetation filter strips, and riparian forest buffer system, tree/grass hedge system and etc. Kiepe (1995) studied effects of the hedge barrier system on trapping soil and retarding slope runoff and found that little runoff and soil loss occurred. Tree/grass hedges had also obvious effect on soil erosion control in the Central Kenyan highland and other regions (Angima et al., 2000). Rao et al. (1991) managed *Leucaena leucocephala* as hedgerows for trapping soil and sediment in semiarid area of India. Detailed studies of vegetation and erosion process interactions were undertaken within an ephemeral channel in SE Spain at three scales (channel network, reach and patch) by repeat surveys and mapping after floods by Sandercock and Hooke (Sandercock and Hooke, 2011). Moskalski and Sommerfield (2012) examined sediment deposition and retention in a section of salt marsh in the St. Jones River estuary in Delaware. Spaan et al. (2005) studied vegetation barrier by using the *Andropogon gayanus* (a species of dense grass) with remarkable effectiveness in diminishing soil loss in the Africa sub-Saharan semi-arid area and found that hedgerow intercropping was beneficial in terms of soil richness and water conservation. These vegetation barriers offer a direction for researchers in the management of erosion control (Oteroa et al., 2011; Reeder et al., 2005; Dorioz et al., 2006; A. B. P. Rasmussen et al., 2011; J. J. Rasmussen et al., 2011). Current studies showed that vegetation barriers have good soil and water conservation, ecological restoration and pollution control effects (Udawatta et al., 2010; Ghebremichael et al., 2008; Lee et al., 2003; Arorak et al., 1996; Lowrance et al., 1985). Chen (2010) pointed out that landscape restoration has many positive effects on soil water storage and effective water use. Further, forest ecosystem can saliently increase soil nutrients, thus being beneficial to the growth of forest and vegetation community (Amazonas et al., 2011; Mohammad and Alseekh, 2012). Another study also showed forest restoration has strong improvement effect on soil physical properties and the growth of seedlings on steep slopes after coal surface mining (Fields-Johnson et al., 2012). Related studies indicated vegetation structure and density, species diversity, and ecosystem processes

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were the main impacting factors for ecological restoration (Ruiz-Jaen and Aide, 2005; Cao et al., 2008). All the vegetation measures or treatments and good forest management mentioned above have better soil and water conservation and ecological effects in the entire watershed (Lu et al., 2001).

Compared to the check dam or concrete dam, the SFD has many advantages. On the one hand, storage capacity of the check dam or concrete dam is gradually reducing with sediment deposition. Eventually, they become death or no use. On the other hand, the habitat and the migration pathway of flora and fauna in the gully were completely blocked off by the check or concrete dam, which is rather adverse to the restoration of regional ecological environment. However, the SFD is composed of the seabuckthorn, which can create a migration passage for flora and fauna thus being able to improve local ecological environment.

As mentioned above, the ecological environment of the Pisha Sandstone area is extremely poor. To restore ecology and improve soil of this area, the SFD-a novel vegetation measure and its concept was proposed. Subsequently, in order to examine the effectiveness and performance of the SFD on the ecological restoration and soil improvement within the Pisha Sandstone area, a field prototype experiment has been systematically conducted since 1996. In this paper, we analyzed the sediment retention capacity, the ecological restoration and soil melioration effects of the SFD within the Pisha Sandstone area in many aspects. This study has an important value for understanding the SFD efficacy and can provide the theoretical evidence for widespread planting of the SFD within the Pisha Sandstone area or even in other similar regions of the world.

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2 Materials and methods

2.1 Study area

The Pisha Sandstone area is close to Shaanxi Province, Inner Mongolia Autonomous Region and Shanxi Province (39°37′2″–40°41′48″ N, 109°4′30″–110°15′40″ E) (Fig. 1). Due to the special hilly topography and poor vegetation cover, the Pisha Sandstone was eroded into many deep gullies and hummocks, resulting in the present barely hilly landscape (Fig. 2). The study area is located 5 km west of Jungar county, Ordos city, Inner Mongolia, China, at 39°37′ N, 110°9′ E (Fig. 1). The research was mainly conducted in the east gully one (EG1), a tributary of the xi-zhao gully in Jungar County. The xi-zhao gully covers an area of 15 km^2, and it is a tributary of ku-ye River, a second-order tributary of Yellow River. Investigation was also conducted in the other several gullies such as EG2, EG3, EG4, (west gully 6) WG6. Jungar County situated south-east of Erdos plateau, typical of Pisha Sandstone area of Loess Plateau of China, is one of the most serious sand-dust storm sources. Also, it is one of the most dominant coarse sediment sources into the upper and middle reaches of Yellow River in China. Jungar County belongs to the typical low hilly zone of Loess Plateau. The study area has a continental and monsoon climate. Mean annual rainfall is 390 mm and mean annual potential evaporation is 2265 mm. Rainfall in July and August accounts for approximately 70–80 % of the whole year. Average annual temperature is 7.4 °C. The mean elevation is around 1400 m a.s.l. The soil belongs to the Aeolian sandy soil of Loess, which is mainly dominated by the Pisha Sandstone. The EG1 where the experiment was mainly conducted, with a 1628 m length and average 6.8 m width, covers an area of 1.67 km^2. Mean slope of main gully channel is 0.04 (4 m vertical: 100 m horizontal) and the average gully side slope is 0.74. The EG1 has two tributary gullies. The left tributary gully is approximately 294 m long and averagely 2.66 m wide, with a mean channel slope of 0.066 and an average side slope of 0.83. The right tributary gully is approximately 246 m long and averagely 2.45 m wide, with a mean channel slope of 0.058 and an average side slope of 1.16. The bare gully similar to the EG1, ap-

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proximately 100 m below the EG1, was selected as the contrast gully (non-vegetated), which is located downstream of the Xi-zhao gully. The contrast gully has a length of 400 m, an average width of 4.5 m, a mean channel slope of 0.039, and a mean side slope of 0.72. Nine monitoring sections were designed in the contrast gully from down- to up-stream, with a 50 m interval between each other. It should be mentioned that during the course of comparison, the few SFDs within the WG6 are also selected. However, the topography of the WG6 is nearly similar to the EG1, here no specific description was done on it. On average, soils in the investigated EG1 and WG6 had 8.3 g kg^{-1} gravel (2.0 > size > 1.0 mm), 800 g kg^{-1} coarse sand (1.0 > size > 0.25 mm), 178 g kg^{-1} fine sand (0.25 > size > 0.05 mm), 13.7 g kg^{-1} including coarse silt, middle silt, fine silt, coarse clay and fine clay (size < 0.05 mm), 0.5 g kg^{-1} organic C, and 8.8 pH_W.

2.2 The seabuckthorn flexible dam system

The diagram of single seabuckthorn flexible dam is presented in Fig. 3. The SFD is substantially a small-scale man-made seabuckthorn forest (Fig. 4). The seabuckthorn flexible dam system (SFD system) (Fig. 5) composed of a series of seven dams was vegetated in the upper EG1 in spring 1996. Some SFD systems were also sparsely vegetated in the other branch gullies of the Xi-zhao gully. The seven seabuckthorn flexible dams (SFDs) were named as No.0-6. Four SFDs were planted in the major gully while three were vegetated in the left and right tributary gullies of the EG1. Each of the SFDs was planted in the gully at 0.4 m depth, with 2.0 m spacing between rows and 0.3 m spacing within a row. There are some shrub and herbaceous plants including *Festuca arundinacea Schreb*, *Clinelymus dahurcus Turcz*, *Youngia japonica, Artemisia arenaria DC*, *Salsola collina*, *Heteropappus altaicus*, etc. in the gully.

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2.3 Sampling locations and measurement methods

2.3.1 Plant growth

The recorded growth parameters on the SFD include basic diameter, height and canopy. These were measured in specific sampling plots designed in the upper, middle and lower sections of each SFD within the EG1, respectively. Each sampling plot is approximately 5.0 m by 3.0 m. In addition, the other nine sampling plots are located in the three SFDs at the mouth of the EG4. The total number of the sampling plots is 30. The basic diameter was measured at 10 cm height aboveground; the height was measured using normal method by leveling rod. As for canopy, the mean in north-south direction and that in west-east direction were respectively recorded.

2.3.2 Sediment deposition and grain size distribution

The deposition elevation in different sections was measured within the SFD in EG1 in 2005. Six cross-sections (C_d, C_m, C_u, C_3, C_2, C_1, respectively) (Fig. 5) were marked by concrete stakes, and the relative channel elevation was measured to compare the changes of sediment deposition from 1997 to 2005. The grain size distribution of deposited sediment within the SFD was measured by sieving method (Lao, 1988), because the deposited sediment is coarser and the grain size is commonly greater than 0.05 mm.

2.3.3 Soil moisture contents

Soil moisture data are collected from the several major flexible dams located in the EG1. Sampling sections were generally distributed in the front, upper, middle and lower location of the SFD during the period 1996 to 2010. The soil moisture measurements of the 2#, 4# and 5# SFDs as well as the contrast gully were conducted on 8 August 1998, 10 August 1999 and 24 August 2000, five days later after rainfall event; those of the 6# SFD and the contrast gully are only conducted on 16 August 2005, five

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days later after rainfall event; and those of the 0#, 1#, 2#, 5# and 6# SFDs together with the contrast gully were performed on 9 October 2006, five days later after rainfall event. The first section is located at the first row of the SFD, the second section at the middle, and the third section at the last row. For each section within the SFD, we firstly dig a hole with a diameter of 20 cm and a total depth of 100 cm at the centre of each section within the entire deposition body caused by the SFD, then samples were collected every 10 or 20 cm interval from the surface downwards along the inner profile of the hole (10 cm interval at the 0–40 cm depth; 20 cm interval at the 40–100 cm depth), nonetheless, the surface sample was taken at 5 cm depth. The weight of each soil sample is approximately 0.5 kg. All soil samples (the total number of 240) were preserved in a sealed plastic bag and rapidly taken back to the laboratory. All data are of volumetric soil moisture (here always expressed as % m^3 water m^{-3} soil) in the top 100 cm of soil profile, which represents the majority of the active root zone of these sites. The soil moisture contents were measured after each sample was oven dried at 105 °C for 8 h. For each sample, we measured three replicates, and then the mean is as the value of the sample. In the following measurements of SOM and nutrients, the replicates are the same.

2.3.4 Soil organic matter and nutrients

The collected samples were gently broken by hand, air dried and passed through a 2 mm sieve. Then, the large pieces of stubble and root that passed through the sieve were removed by hand. In the laboratory, a 0.5-g sub-sample was removed to determine organic matter using the standard oil bath heating and potassium dichromate method. Soil nutrients here were only included ammonium nitrogen, Available phosphorus, Available potassium (K_{avail}), which were measured in 2010. Ammonium nitrogen (N_{amm}) was measured according to indophenol blue colorimetric method. Available phosphorus (P_{avail}) was extracted with sodium bicarbonate and measured with colorimetry. Available potassium (K_{avail}) in each soil sample was extracted with ammonium acetate (Lao, 1988).

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2.3.5 Determining of species diversity and vegetation coverage

A vegetation investigation was conducted at five different sites in the EG1 and contrast gully (without the SFD) on 10 August 2005, respectively, to assess the species diversity and vegetation coverage of the SFD. We selected a sampling grid of 4 m × 2 m at certain location near each chosen section. These locations are as follows: (1) the monitoring sections within the SFD in the EG1 (at the upper and lower sections, two quadrats), (2) the depositional section at the tail of the SFD at the gully outlet (one quadrat), (3) within the No. 2 SFD in the EG1 (at the upper and lower sections, two quadrats), (4) the corresponding sections of the contrast gully (five quadrats), named as S1–S5, which are spaced 100 m apart from each other from downstream towards upstream.

3 Results and discussion

3.1 General growth characteristics of the SFD

The statistical soft of Minitab 16.0 was used to analyze the data for the descriptive statistics. Growth differences were evident in all these SFDs due to some undetermined factors such as topography, soil property, soil moisture, soil organic matter, soil nutrients, and etc. Growth parameters of the SFD were summarized in Table 1. As it can be seen from Table 1, a marked change in growth is found in the 2#, 3# and 5# SFDs from 1998 through 1999 to 2005, that is, all the SFDs grow rapidly in different ages. Among them, the change in growth of 2# SFD is greater than those of 3# and 5# SFDs, whatever the period from 1998 to 1999 or from 1999 to 2005. This is related to the radiations exposure and topography factors such as slope, indigenous soil property, the vegetation photosynthesis and transpiration, and etc, which is a complicated mechanism. Based on field observation, the topography of the gully reach with the 2# SFD is beneficial to the seabuckthorn growth, where the slope is gentle, sunshine radiation exposure is much, the understory coverage is better and thus the soil moisture is

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sufficient. In sum, these parameters describe the good growth of the SFDs. As shown in Table 2, the extending capacity of the typical SFDs was summarized. We clearly found the SFD has a very good horizontal extending capacity due mainly to its rapidly self-reproduction ability by developed nodules. From Table 2, we found that the mean length extension rate of the 1# and 3# SFDs within WG6 is about 1.24 $m\,yr^{-1}$, indicating that they have more rapid extension rate as compared to the 0# and 2# SFDs in the EG1. However, the area extension rate of the SFDs in the EG1 is greater than that of those in the WG6. Overall, the mean length extension rate of the surveyed SFDs is 1.09 $m\,yr^{-1}$ and the average area extension rate is 5.61 $m^2\,yr^{-1}$. From the case of the 1# and 3# SFDs in the WG6, we found that although the length extension rate is rapid, the area extension rate is not necessarily rapid, which is mainly subject to the complicated vegetation growth mechanism. However, the developed root system and its strong extending capacity are also helpful for stabilizing the slope toe to prevent collapse.

3.2 The sediment trapping effect of the SFD

Based on the field observed data in 1997–2005, we found that deposition commonly occurred in all the SFDs in the EG1, and the deposited sediment showed different patterns characterized by different slopes and forms. The field investigation also demonstrated that the coarse and fine sediment from upper gully and side slopes were effectively separated through the joint use of the SFD system and lower rigid check dam. We called the phenomena as "trapping coarse sediment and silting fine sediment", that is, the coarse sediment can be just trapped in the gully but the finer sediment silted in the lower check dam thus greatly trapping sediment from the gully.

3.2.1 The SFD impacts on sediment distribution

Figure 6 presented the grain size distributions of deposition sediment of the typical SFDs (0#, 1#, 2# and 5#) and the 1# check dam. As can be seen from Fig. 6, the mass percents of coarse sediment greater than 0.05 mm of 2# and 5# SFDs are smaller than the 0# and 1# SFDs due mainly to sediment retention effect of the SFD system. The mass percent of the coarse sediment decreased from 99.7 % of 1# SFD to 86.6 % of 0# SFD, and the sediment reduction rate is approximately 1/7, which showed the reduction in sediment is quite remarkable because of the trapping effect of the whole SFD system. Furthermore, the finer sediment was almost deposited into the lower 1# check dam. The field data showed that the mass percent of coarse sediment is about 37 % in the upper section of 1# check dam and that of the lower section is approximately 11 %, which demonstrated that the coarse and fine sediment were well separated. In addition, the flood filtered by the SFD system can be stored in the lower rigid check dam. Thus, a small reservoir was formed providing irrigation water for local agriculture. The field investigation fully showed that the SFD system can not only trap sediment but also store a large proportion of surface runoff by the joint use of the SFD and lower check dam. Due to the strong sediment retention capacity by the SFD, the soil and sediment loss in the gully would be greatly controlled. First of all, the sediment was trapped and would thus form the deposition body, which is able to lift the erosion benchmark level of the gully. This can allow the gully bed slope to become gentle or flat so as to lessen the gully erosion and protect gully bed, thus being helpful for the restoration of vegetation community as well as soil improvement. The most main reason for the SFD trapping sediment is the SFD can greatly increased the roughness of the gully together with understory and other subordinate or attendant vegetation community.

3.2.2 The various deposition slopes and forms by the SFD

Based on our field observation, the coarser sediment deposited commonly occurred within the SFDs in the gully during flood season of every year. According to the reservoir and general riverbed deposition theory, the deposition patterns consist of the delta and parallel deposition forms. In general, the delta deposition has three segments of front slope, top slope and tail slope. The deposition forms of 1#, 2#, 5# and 0# SFD were showed in Fig. 7. The deposition forms of 1#, 2# and 0# SFD are roughly the delta deposition, but that of the 5# SFD belongs to the parallel deposition. Here, as a case of 0# SFD, the front segment is steep with slope 4.1 %, the top segment is more flat with slope 0.6 %, and the tail segment is slightly steep with slope 1.5 %, so the two slopes of top and tail segments of the deposition were smaller than the initial slope of 2.8 % of the gully except for the front slope. The deposition form of 5# SFD presents a little parallel deposition. This is because the 5# SFD is just located in the confluence of the left branch gully into the EG1. Thus, the flood flowing into the EG1 is easily resisted by that occurred in the EG1 (i.e. the main gully), that is, the resistance action can simultaneously slow velocity of flood flowing into the EG1 and even result in local reverse flow, which made the back water rapidly occur in the 5# SFD. Thus, the parallel deposition form is eventually produced.

As aforementioned, the SFD can greatly increase the roughness of the gully bed, and thus slow down the velocity of the flood to compel the sediment to deposit within the gully. Gradually, with the rising of the deposition level, the gully channel slope is becoming more and more gentle, which keeps the gully bed not be easily eroded and therefore protect the surface soil nutrients in the gully. In addition, the litters under the SFD also contribute to the conservation of the nutrients. The humus, produced by the senescence, death, secretion of the roots of the understory vegetation, can improve the soil quality as well. Moreover, the decomposition of the litters can accrue the humus too. Hence, the soil was improved greatly in the gully, which is definitely beneficial to the growth and restoration of the understory vegetation. Like that, a benignant circle of the interaction of between the SFD and the soil quality improvement was naturally developed within the SFD gully. These discussed above powerfully indicated that the strong sediment retention capacity of the SFD is the basis of using it to restore the ecosystem and improve soil quality.

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3.3 Soil moisture

As shown in Fig. 8a–c, the comparison of soil moisture of 2#, 4#, 5# SFDs with the contrast gully is evident in August 1998, 1999 and 2000. As can be seen from Fig. 8d, the variations of soil moisture between the 0#, 1#, 2#, 5# and 6# SFDs (respectively) and the contrast gully were also obvious in October 2006. Compared to the contrast gully, the change in soil moisture of the 6# SFD is also marked in August 2005. Soil moisture of each typical SFD is obviously greater than the contrast gully (Fig. 8). Moreover, soil moisture variations in profile are also quite striking. Basically, soil moisture in top 0–40 cm depth is rapidly decreased with an increase of depth, and the mean soil moisture in this depth is approximately 9 %, while the mean soil moisture of the contrast gully is only 4 %. However, the soil moisture in top 40–100 cm depth of each SFD has roughly the same variation as the contrast gully. Based on our field investigation, this is attributed to the process of the seabuckthorn roots distributed in 0–60 cm soil depth using soil moisture. According to our field observation, the depth of major rhizosphere of the seabuckthorn is not over 60 cm because of the strong horizontal extending and developing capacity of its root system. The interaction of the horizontally developed roots and soil moisture of 0–60 cm depth leads to the variation. However, no variation is evidently found in the contrast gully due to no the SFD in the gully bed. Another reason is the much litter covered in the SFD gully can greatly reduce evaporation of soil moisture.

As presented in Fig. 8a–c, soil moisture of the three SFDs of 2#, 4# and 5# was respectively greater than the contrast gully, especially in 1998 and 2000. The soil moisture in profile is sharply increased in top 0–10 cm depth, however, soil moisture variation in 10–80 cm depth is slight. It is no doubt that the mean soil moisture in 0–100 cm depth in the SFD gully was also greater than the contrast gully. Only the average soil moisture in profile in the SFD gully in 1999 is slightly smaller than that in 1998 and 2000. This is because of different rainfall and climate condition during the same period.

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The soil moisture comparison in profile between the SFD gully and the contrast gully showed that the seabuckthorn plant can strikingly increase the mean soil moisture of the Pisha Sandstone gully, particularly in 0–40 cm soil layer. Thus this can relatively increase the water storage of soil reservoir, adjust soil water resource in the gully, and be beneficial to the growth and restoration of vegetation. Increase of soil moisture in the gully has a significant effect on the restoration of the ecological environment within the Pisha Sandstone area.

3.4 Soil organic matter

Soil organic matter is the most important component of soil fertility. And SOM is often used to assess the soil melioration. The seabuckthorn growth has an important effect on SOM which can improve the gully soil quality. The comparison of SOM in the upper and middle sections of the typical SFD and that of the contrast gully was shown in Fig. 9a. It was clear that SOM of the gully with the SFD is greater than that of the corresponding sections in the contrast gully. For example, the average SOM of the 2# SFD increased by 96 % compared to the contrast gully, the average SOM of the 6# SFD increased by 145 %, and the average SOM of the 0# SFD increased by 148 %. Obviously, the SFD can improve SOM of the Pisha Sandstone gully, which can promote the vegetation growth and increase the roughness of the gully bed. In terms of the investigation in August 2005, many kinds of plants grow quite well in the gully (see Table 4 hereinafter).

As shown in Fig. 9b, the SOM distributions in profile at various sections of the typical SFDs were quite different from those of the contrast gully. The contrast section the 0# dam is located at the inlet of it. We found that SOM of all typical SFDs (1#, 2#, 5#, 6# and 0#) is greater than the contrast gully. And the surface SOM of the contrast gully is minimal while the SOM of bottom soil layer is rather greater, but that of the middle soil layer is relatively smaller, which is in accordance with the evolution of SOM in the course of vegetation community restoration. Based on the statistical results, the mean SOM of each SFD is greatly higher than the contrast gully. Furthermore, the

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SOM variations in profile of the typical SFDs are relatively smaller than the contrast gully. These results showed that the SFD indeed helps increase SOM and meliorate the Pisha Sandstone gully soil.

3.5 Soil nutrients

Soil nutrients have a close relationship with the soil organic matter. The SFD can also increase the content of soil nutrients and further improve soil fertility by improving soil organic matter. The distributions and variations of ammonium nitrogen, available phosphorus and potassium in soil profile in the EG1 with the SFD and the contrast gully are shown in Fig. 10. It is evident that soil nutrients in the EG1 with the SFD were greater than the contrast gully. In addition, in top soil layer of 0–30 cm, ammonium nitrogen and available potassium rapidly became small with an increase of soil depth, but the change in soil layer of 30–100 cm is relatively slight, which was consistent with the SOM variations mentioned above. We also found available phosphorus in the SFD gully varied little in the whole profile of 0–100 cm, not only the ammonium nitrogen in the contrast gully is smaller, but also the available phosphorus is even smaller, and the variation of the available phosphorus is much slighter in profile.

In total, the soil nutrients of the gully with the SFD are much higher than the contrast gully. The soil nutrients comparison of the SFD gully and the contrast gully is shown in Table 3. In the soil layer of 0–30 cm, ammonium nitrogen content of the SFD gully is 2.5 times of the contrast gully, available phosphorus content of the SFD gully is 5.73 times of the contrast gully, and the available potassium of the SFD gully is 1.5 times of the contrast gully. Moreover, in the soil layer of 30–100 cm, soil nutrient content of the SFD gully is still higher than the contrast gully. The above comparison indicated that the SFD can effectively improve soil fertility. It is well known that the litter and some dead roots can provide or supply nutrients for the soil, which is beneficial to the vegetation growth. Certainly, the interaction of the seabuckthorn plant and soil nutrients may bring about those variations in profile, which is mainly related to soil physical and chemical properties.

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Above these variations and comparisons of soil nutrients between the SFD gully and the contrast gully showed that the SFD can strikingly improve soil fertility of the gully, which is helpful for the growth and restoration of vegetation community as well as the ecosystem rehabilitation within the Pisha Sandstone area.

3.6 Changes in species diversity and vegetation coverage

3.6.1 Species diversity

Species diversity is an index describing richness extent of species in some ecological community. There are 18 species of vegetation within the SFD in the EG1 gully (Table 4), and the cover of 88 % is *Clinelymus dahurcus Turcz*. However, there are only 5 plant species in the corresponding study locations. Plant species richness meant the number of total species per area, and the difference of the understory should be taken into consideration. The species richness of the understory within the SFD is obviously higher than the contrast gully. It can be inferred that the SFD can greatly improve the growth of other species.

3.6.2 Vegetation coverage

Development of the forest ecology of different areas at certain period is widely evaluated by the forest thickness (FT) (Fan et al., 2008). The index is usually expressed as FT (mm) = total forest storage volume (m^3)/total land area (m^2) × 1000 ($mm\,m^{-1}$) = forest storage volume per unit area ($m^3\,ha^{-1}$) × forest coverage × 1000 ($mm\,m^{-1}$). According to the calculation formula of FT, the mean thickness coverage is often used to evaluate the vegetation cover and health state of the ecological environment of some area. The mean thickness coverage is usually expressed as:

$$VC = \frac{A \times C_U \times \sum_{j=1}^{n} P_j \times H_j}{A} \quad (1)$$

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Where VC denotes the mean thickness coverage, n is the total species of understory vegetation, A is the square of study area, C_U is the understory coverage of study area, P_j is the proportion of the ith species, and H_j is the mean height of the ith species. The higher the value of the mean thickness coverage is, the better the growth of vegetation. As shown in Table 4, the mean thickness coverage of the SFD in the EG1 is 0.376, and the corresponding value of the contrast gully is only 0.056. It is very clear that the mean thickness coverage of understory vegetation community within the SFD is 6.76 times of the contrast gully (non-vegetated gully). This indicated that the other kinds of vegetation within the SFD also grow better.

3.6.3 Shannon–Weaver diversity index

The Shannon–Weaver diversity index is commonly used to evaluate the diversity of plant species (Begon et al., 1986; Colin, 1986). The greater the species diversity is, the better the stability of the plant community is. The Shannon–Weaver diversity index (Eq. 2) is expressed as:

$$H = -\sum_{i=1}^{n} P_i(\log_2 P_i) \quad (2)$$

where n is the number of individuals of the ith species, P_i is the proportion of the ith species number to the total species number of plant community.

H is usually less than 1, and the H is proportional to the biodiversity. The H within the SFD is 0.817, however, H value of the contrast gully is only 0.267. The comparison between the two H values showed that the seabuckthorn plant can indeed increase the number of plant species, thus being beneficial to the vegetation community restoration.

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4 Conclusions

The results showed that the SFD plays a predominant role in the ecological restoration and soil improvement within the Pisha Sandstone area, and exhibits good performance. As discussed above, on the one hand, the SFD has a strong sediment retention capacity, particularly for the coarse sediment greater than 0.05 mm from the gully head and side slope, which provides a good basis for using it to restore the ecosystem and improve soil quality within the Pisha Sandstone area. On the other hand, the SFD is able to stabilize the slope toe to prevent collapse. Water stored in the deposition is helpful for the vegetation growth in the gully and usable for local agricultural irrigation. Moreover, the soil moisture distribution in profile within the SFD gully was quite different from the contrast gully (i.e. non-vegetated gully). This may be attributed to the interaction of the seabuckthorn and the other species of vegetation. The SFD can greatly improve SOM and the other nutrients, which is clearly demonstrated by the comparison of the SFD gully and the contrast gully. In addition, based on the field investigation and our analysis, the SFD is obviously capable of increasing the species diversity and taxa richness of the Pisha Sandstone gully, while that of the contrast gully was quite low. These findings provide the important theoretical proof for widespread planting of the SFD. Up to now, the SFD has been planted about 1 500 000 ha within the Pisha Sandstone area by Chinese government. This action has made a great success in improving the ecological environment of this area.

As a whole, the SFD plays a significant role in local ecological restoration and soil melioration by soil erosion control, soil moisture storage, soil nutrients increase, and improvement of species diversity as well as vegetation coverage, which indicates it is very effective. By virtue of the SFD and its planting convenience, the SFD is progressively spread to many other similar severe soil erosion areas in northwest of China.

Although we have achieved some research results on the ecological restoration and local soil improvement by examining the ecological effects of the SFD, more complicated issues still need to be further studied, such as the intrinsic interaction of certain

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ecological processes, impacts on the local climate, and etc. Moreover, the studies on these issues will have a significant value for development of the ecology discipline and flexible vegetation engineering. Currently, based on our previously accumulated data, the authors set out to study the intrinsic interaction mechanism between the SFD and the soil in the gully from the biological viewpoint. Thus, the study on the SFD is very interesting, and the authors hope more researchers to focus on the SFD.

The Supplement related to this article is available online at doi:10.5194/sed-6-2803-2014-supplement.

Acknowledgements. This study is supported by both National Natural Science Foundation (Grant No: 51279163) and Postdoctoral Science Foundation of China (Grant No: 2012M512022), and is also financed by Humanities & Social Science Foundation for young scholars of Education Ministry of China (Grant No: 09XJC910001) and Natural Science Foundation for young scholars of Shaan'Xi Province (Grant No: 2010JQ5003). In the course of writing this manuscript, Liu Kang, Bai Hong-ying and Ma June-jie give us many good advices and suggestions for improving this paper. And Doctor Ross from Australia, being as a visiting Professor of college of foreign language of Northwest University, revised initial manuscript. And Doctor Smith from America, being as an exchange scholar of Northwest University, also revised this manuscript. We really thank all of them for their cordial help very much.

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Ecological restoration and soil improvement of the seabuckthorn flexible dam

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Table 1. Growth parameters of the selected seabuckthorn flexible dams.

Parameters	No. 5# SFD			No. 2# SFD			No. 3# SFD		
Age (a)	12	5*	6**	14	7*	8**	12	5*	6**
Height (m)	2.75	1.58*	2.06**	2.98	1.53*	2.05**	2.04	1.48*	1.69**
Canopy (m)	1.86	1.40*	1.72**	2.41	1.36*	1.69**	1.61	1.33*	1.69**
Basic diameter (cm)	–	5.00*	–	–	5.39*	–	3.72	–	–

Notes: survey time of the No. 5#, No. 2# and No. 3# SFD is on 6 August 2005. The sign "*" denotes the survey time is on 30 October 1998. The sign "**" denotes the survey time is on 20 November 1999. The SFD denotes the seabuckthorn flexible dam.

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Table 2. Outline of extension of the selected SFDs via self-reproduction along gully length.

Survey sites		Plant time	Seedling age at planting	Survey width of dam (m)	extension (m)	Extension per year ($m\,yr^{-1}$)	Extension area (m^2)	Extension area per year ($m^2\,yr^{-1}$)
No.2# dam at EG1	upper	1997.5	2 year	5.85	9.10	1.14	53.24	6.65
	lower			7.55	9.50	1.19	71.73	8.97
No.0# dam at EG1	lower	1996.5	3 year	9.90	5.70	0.63	56.43	6.27
No.1# dam at WG6	lower	2002.5	2 year	1.89	3.75	1.25	7.07	2.36
No.3# dam at WG6	upper	2002.5	2 year	3.64	3.65	1.22	13.27	4.42
	lower			4.41	3.40	1.13	14.99	5.00
average				5.54	5.85	1.09	36.12	5.61

Note: survey time is on 8 May 2005.

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Table 3. Comparison of nutrients at 0–30 cm and 30–100 cm soil layers between the SFD gully and the contrast gully.

Locations	Soil layer (cm)	Ammonia nitrogen (mg kg^{-1})	Available phosphorus (mg kg^{-1})	Available potassium (mg kg^{-1})
The gully with SFD	0–30	7.78	30.13	104.63
	30–100	5.13	37.43	52.88
The contrast gully	0–30	3.13	5.26	70.13
	30–100	3.45	4.16	37.85

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Table 4. Vegetation investigation in the EG1.

Sites	Area (m^2)	Understory Coverage	Species richness and proportion		Mean height (m)	Mean species richness (m^2)	Mean thickness Coverage (m)	Shannon–Weaver index
			Understory community	Proportion				
Under the seabuckthorn shrub	8	96 %	*Clinelymus dahurcus*	88 %	0.4	2.3	0.376	0.817
			Turcz	2 %	0.2			
			Artemisia arenaria DC	4 %	0.3			
			Milulotus officinalis-(Madnle) Len	3 %	0.4			
			Youngia japonica	2 %	0.5			
			Artemisia gmelinii	1 %	0.2			
			Salsola collina					
			Echinops latifolius-Tausch					
			Heteropappus altaicus					
			Stipa capillata					
			Paris tetraphylla A. Gray					
			Setaria					
			Artemisina arayi					
			Others[a]					
			Total species: **18**	**100 %**	**0.33**	**2.3**	**0.376**	**0.817**
The contrast gully	8	35 %	*Heteropappus altaicus*	90 %	0.15	0.63	0.056	0.267
			Stipa capillata	3 %	0.26			
			Medicago sativa	2 %	0.12			
			Setaria	3 %	0.18			
			Paris tetraphylla A. Gray	2 %	0.42			
			Total species: **5**	**100 %**	**0.23**	**0.63**	**0.056**	**0.267**

Note: [a] contains 5 species.

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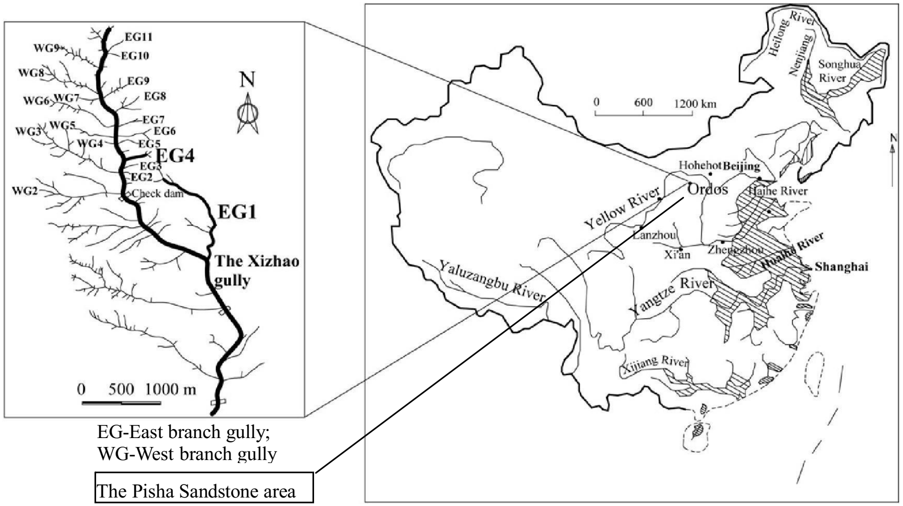

Figure 1. Location map of the Pisha Sandstone area, xi-zhao gully and EG1 (i.e., East branch Gully one).

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EG-East branch gully;
WG-West branch gully

The Pisha Sandstone area

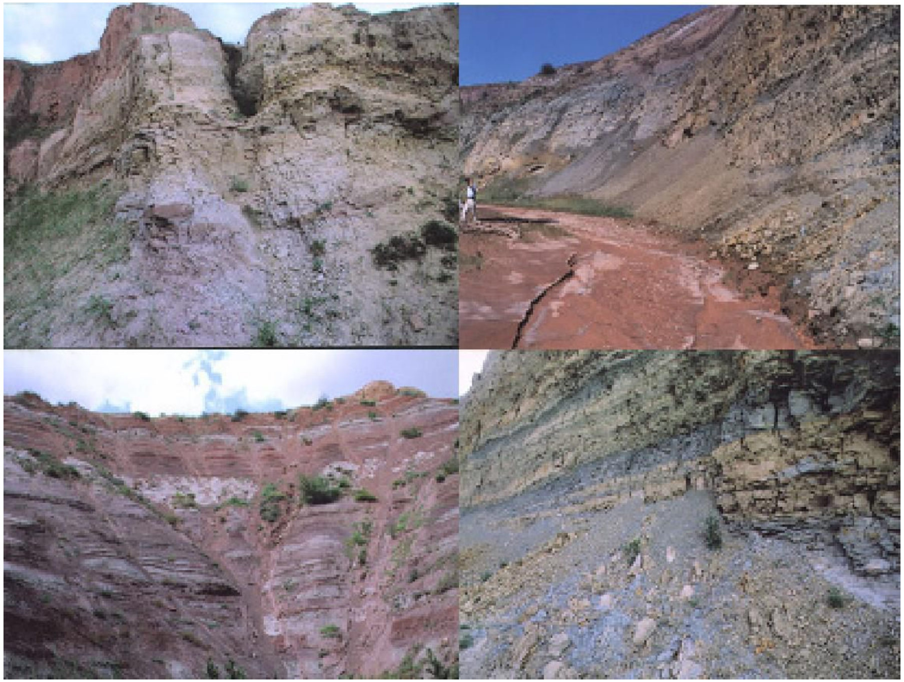

Figure 2. Easily eroded bare Pisha Sandstone.

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The Pisha Sandstone area

WG-West branch gully
EG-East branch gully;

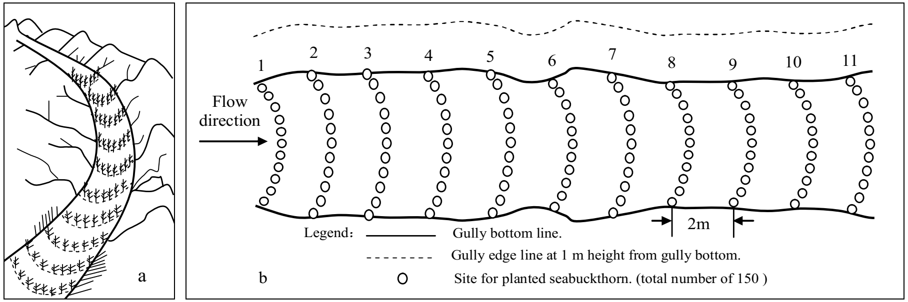

Figure 3. Schematic diagram of the SFD. **(a)** Sketch map of the SFD and **(b)** layout diagram of the SFD.

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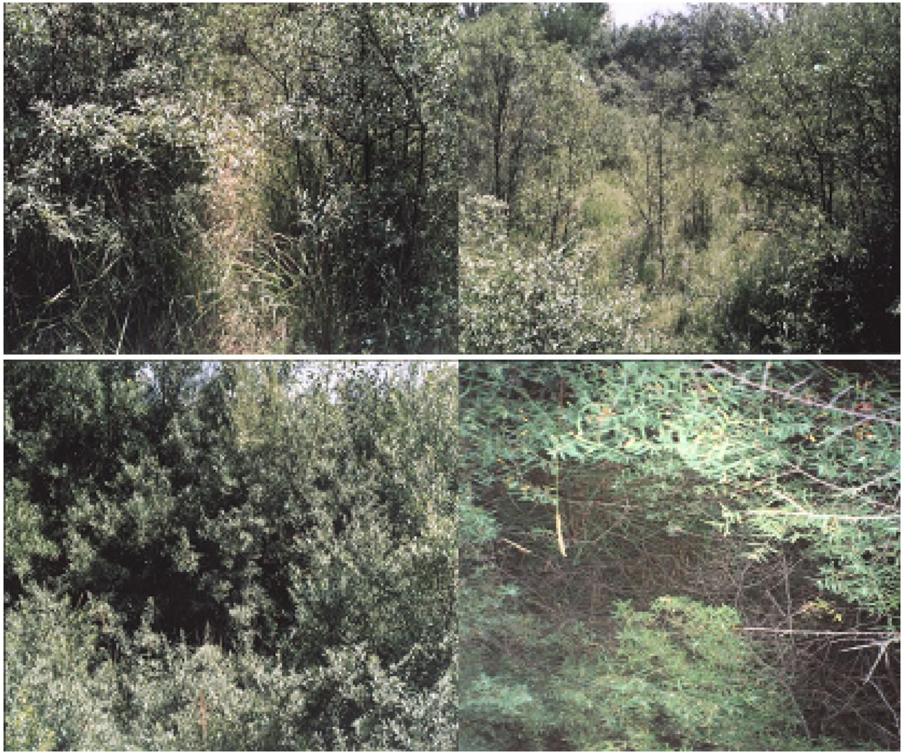

Figure 4. Growth state of several SFDs in 2005 (planted in 1996).

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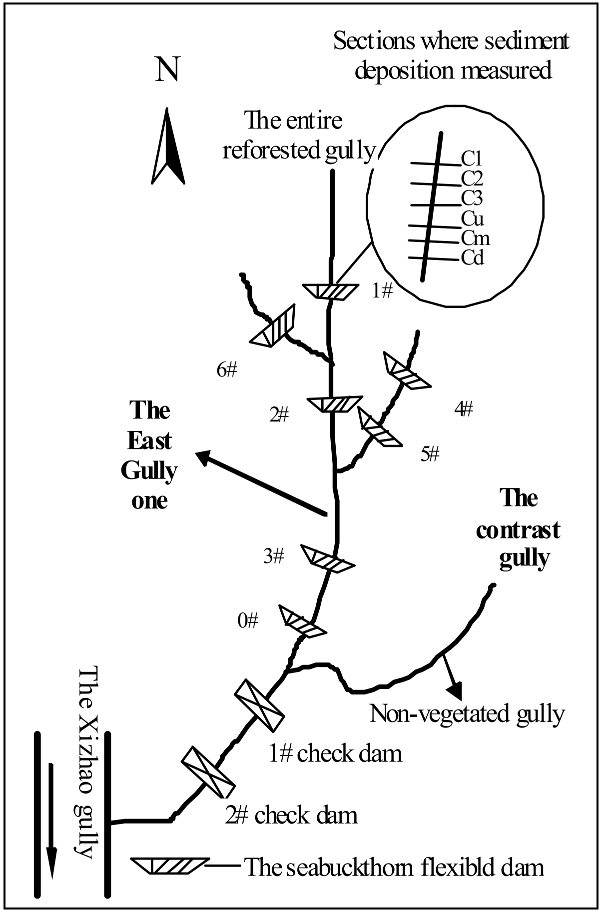

Figure 5. Sketch map of the SFD system in the EG1.

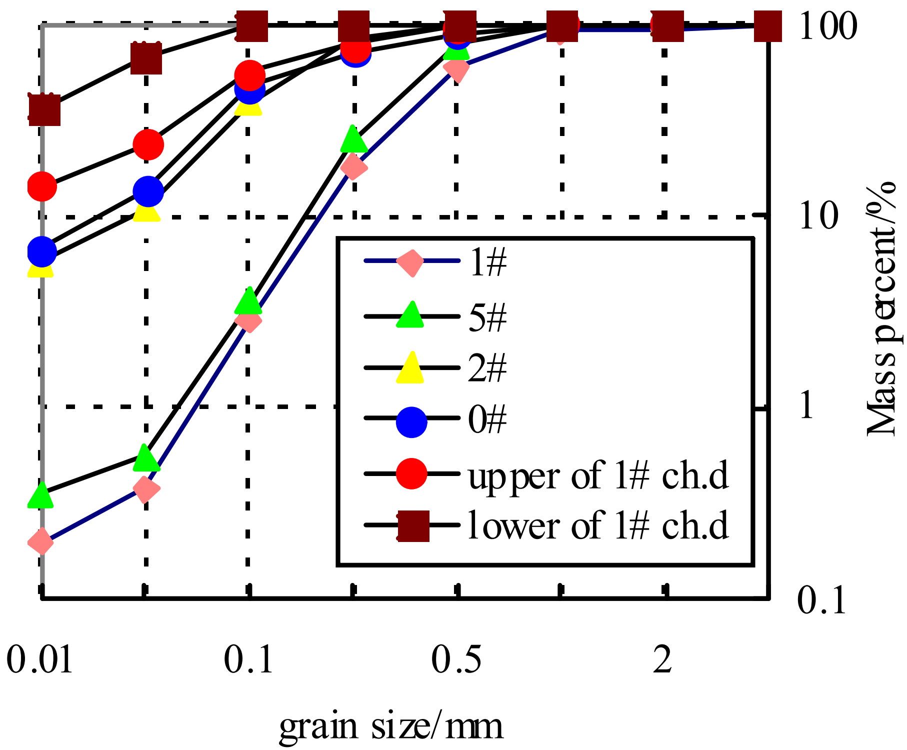

Figure 6. Distributions of sediment grain sizes in the typical SFDs. Note: the ch. d. – the check dam.

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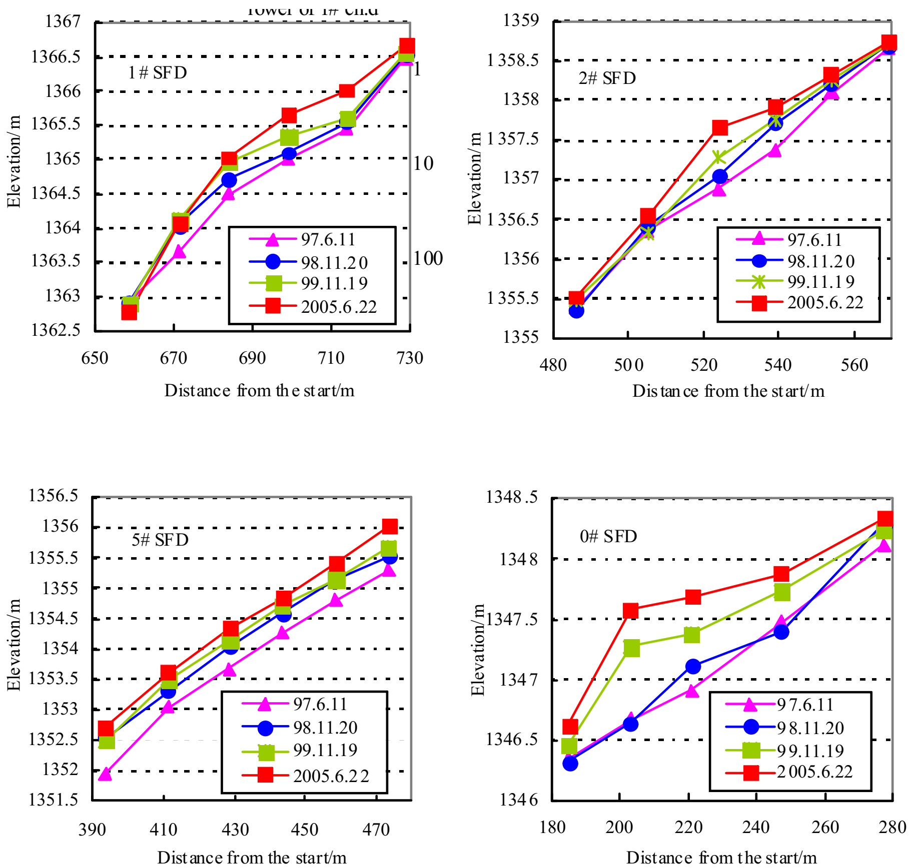

Figure 7. Various deposition forms within the typical SFDs.

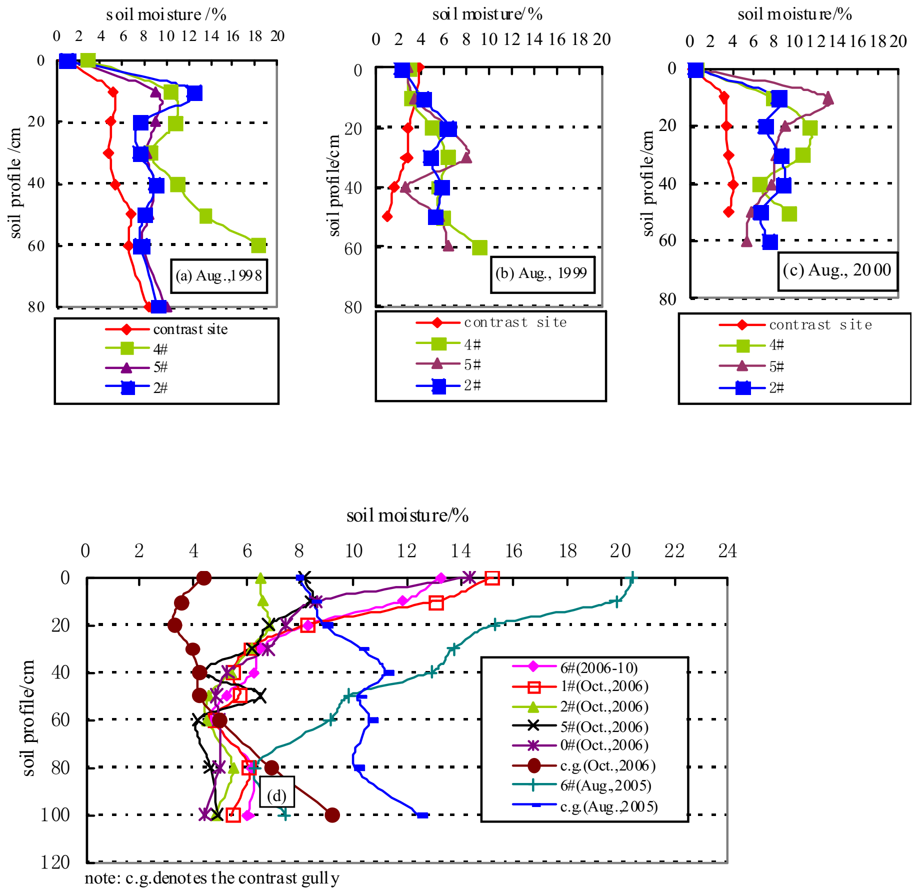

Figure 8. Comparison of soil moisture profile distribution between typical SFDs and the contrast gully.

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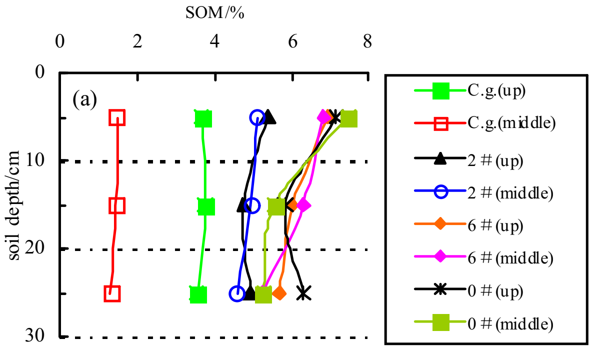

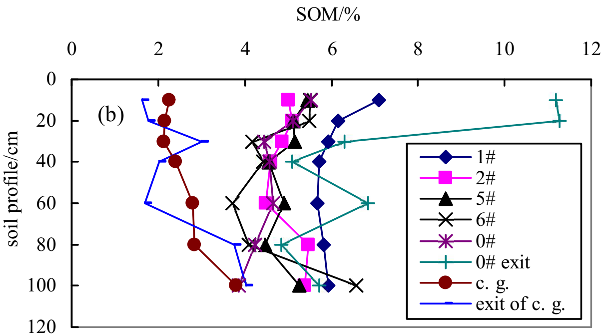

Figure 9. Comparison of soil organic matter of typical SFDs. **(a)** SOM comparison between typical SFDs and the contrast gully (August 2005) and **(b)** layer-averaged organic matter distribution in profile of each typical SFD and the contrast gully (October 2006). (Notes: up–upper section; middle–middle section; c. g. – the contrast gully.)

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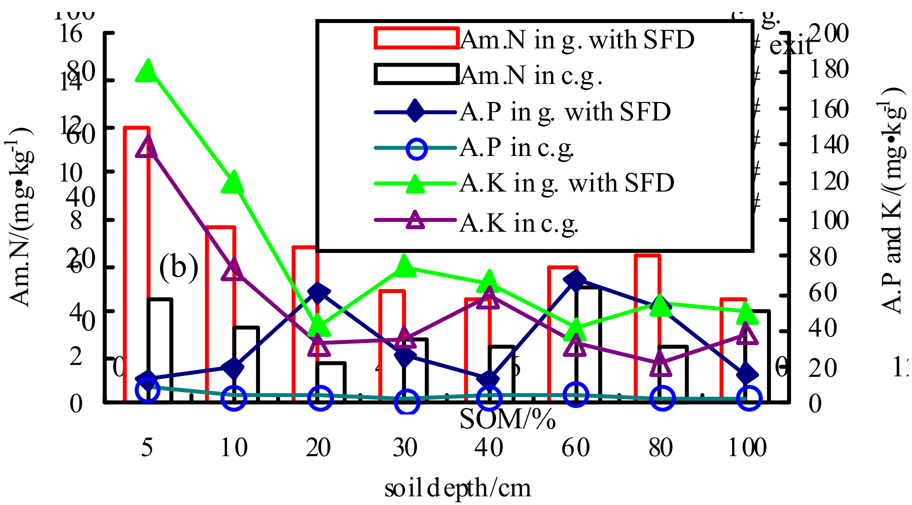

Figure 10. Comparison of ammonia nitrogen, available phosphorus and Potassium between the SFD gully and the contrast gully (August 2010). (Notes: Am. N – Ammonia Nitrogen; A. P – Available Phosphorus; A. K – Available Potassium; c. g. – the contrast gully.)