Ecological and hydrological response of farmlands abandoned for different lengths of time: Evidence from the Loess Hill Slope of China

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ABSTRACT

As a widely distributed land use type, abandoned farmland has become a research focus due to its complex ecological and hydrological responses. Most recent studies have focussed on the interactions between the ecological and hydrological responses in degradation processes, whilst little research has focussed on the recovery of the ecosystem. Moreover, some in-depth analyses are required to further elucidate their interactive on abandoned farmland. In addition, although runoff generation and soil erosion on abandoned farmland have been investigated, few reports have investigated nutrient transport in runoff and eroded sediments. This study investigated the vegetation and soil composition and carried out a 2 year monitoring experiment to monitor the runoff and soil erosion of farmlands abandoned for different lengths of time (4, 12, 22 and 50 years) on a mountain slope located in the Loess Plateau of China. It is found that after farmland abandonment, vegetation holds a positive succession. A two-phase mosaic structure forms, and the moss coverage increases on the inter-vascular plant. From 4 to 50 years in abandoned farmland, the average accumulated runoff increases from 9698.2 ml to 38,605.3 ml in a 5×2 m runoff plot. Additionally, the average accumulated sediment loss decreases from 2019.5 g to 387.7 g in a same plot. Furthermore, the wastage of soil organic matter and most nutrients also decreases on slopes after farmland abandonment because the nutrients are mainly lost in the eroded sediments.

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1. Introduction

Land use change has been the main characteristic of rural areas in many countries during recent years (Palang et al., 2005; Rounsevell et al., 2006; García-Ruiz, 2010). As a common process of inland use change, farmland abandonment (the cessation of ploughing and sowing) has become a focus of research because of the complex eco-hydrological responses involved. This response can be affected by the length of abandonment time, climatic conditions (resulting in different plant colonisation processes), geographical conditions (slope gradient, aspect, soil characteristics, etc.), and land management (García-Ruiz and Lana-Renault, 2011). To date, the ecological and hydrological processes on abandoned farmland and the relationship between them have been widely examined (García-Ruiz and Lana-Renault, 2011).

The ecological process on abandoned farmland mainly involves vegetation colonisation and succession, changes in the physical and chemical properties of soil, and the cycle of nutrients between the vegetation and soil. First, vegetation colonisation, as a secondary succession process (Pugnaire et al., 2006), is the most obvious consequence of farmland abandonment. A complex plant colonisation process depends

on soil fertility and depth, slope aspect, average annual precipitation, evapotranspiration (Teira and Peco, 2003), the distance from bordering vegetation, floristic composition, and the time since farmland abandonment (García-Ruiz and Lana-Renault, 2011). Second, soil properties tend to improve several years after farmland abandonment (Martínez-Fernández et al., 1995). Many studies have found that farmland undergoes a significant increase in soil organic matter (SOM) content (Holtkamp et al., 2008; Jin et al., 2008; Clark et al., 2011), total nitrogen (TN) or available nitrogen content (Arunachalam and Pandey, 2003; Raiesi, 2012; Zhang et al., 2013), aggregate stability (Li and Shao, 2006; Raiesi, 2011), and water holding capacity (Arunachalam and Pandey, 2003; Li and Shao, 2006) after a period of abandonment. Third, agricultural abandonment has some positive effects on the cycle of material (Arnaez et al., 2011), including greater CO_2 adsorption by the surface (Adams and Piovesan, 2002), increased vegetation cover and biodiversity (Benton et al., 2003), the increased biomass of bacterial communities (Holtkamp et al., 2008), enhanced soil nitrogen mineralisation (Raiesi, 2012), and improved hydrological cycles (García-Ruiz et al., 2008).

Various hydrological processes have been demonstrated by different studies in different environments. With respect to mountain areas, many studies in the Loess Plateau of China have shown that the abandonment of croplands resulted in a significant reduction in runoff

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generation (Huang et al., 2003; Wang et al., 2008; Zhang et al., 2010) and soil erosion (He et al., 2004; Zheng, 2006; Zhou et al., 2006). A study in the Central Spanish Pyrenees, a Mediterranean mountain area, found a marked reduction in runoff generation and sediment yield after farmland abandonment as a consequence of rapid plant colonisation (Nadal-Romero et al., 2013). A study of abandoned fields in the Estanque de Arriba catchment (Spanish Pre-Pyrenees) showed that as plant colonisation increased, the average soil erosion rate decreased (López-Vicente et al., 2013). A study in southern Ecuadorian tropical mountain regions found that abandoned farmland can generate more runoff than rangeland or arable land (Molina et al., 2007). With respect to terrace area, Meerkerk et al. (2009) reported that farmland abandonment in the Cárcavo basin (southeast Spain) resulted in an increase in soil erosion and in the sediment transported to the river system. Similarly, a study in terraced paddy fields in Taiwan found that abandoned cultivated land experiences more soil erosion than rice-planted terraced paddy fields (Chen et al., 2012). With respect to areas with rugged topography, Nunes et al. (2010) illustrated that abandoned farmland and pastureland that was converted from arable land as the result of abandonment showed a lower rate of soil erosion than arable land in the sub-humid Mediterranean area of Portugal.

The relationship between ecological and hydrological processes was mentioned in all of the above studies. Vegetation colonisation and succession are often used to explain the hydrological responses of abandoned farmland. Vegetation and litter can intercept rainfall, enhance water infiltration, and prevent soil crust formation (Cammeraat et al., 2005). Consequently, in a wide range of environments, both runoff generation and soil erosion decrease linearly or exponentially with increasing vegetation cover (García-Ruiz and Lana-Renault, 2011). In addition, the slope gradient is another important factor affecting hydrological processes on abandoned farmland that can negate the effect of vegetation on runoff generation and sediment losses (Koulouri and Giourga, 2007). Thus, it is expected that ecological and hydrological processes can differ in various environments of abandoned farmland. Most recent studies on the interactions between the ecological process and hydrological response have focussed on degradation processes (Turnbull et al., 2008). Notably, little research has focussed on the recovery of the ecosystem (Merino-Martín et al., 2012). Moreover, some in-depth analyses are required to further elucidate the relationship between the ecological process and hydrological response of abandoned farmland. Furthermore, few reports have mentioned nutrient loss with runoff and sediment transport on abandoned farmland.

By investigating and performing experiments on runoff plots on a mountain slope located in Loess Plateau of China, this research attempted to address the issues mentioned above. The aims of this research were to (1) investigate and explain the interaction between vegetation succession and changes of soil character with increasing farmland abandonment time; and (2) investigate the causes of runoff generation, soil erosion, and nutrient loss after farmland abandonment.

2. Materials and methods

2.1. Study area

The study area is in the Yangjuangou catchment (36°42' N, 109°31' E) in the Loess Plateau, Shaanxi Province, China (Fig. 1). This catchment holds a semi-arid continental climate, a mean annual precipitation of 531 mm, and a mean air temperature of 9.85 °C from 1952 to 2010 (Fig. 2). The elevation range of this catchment is from 1050 to 1298 m (Liu et al., 2012). The rainfall at this catchment is concentrated between June and September. The composition of the soil in the Yangjuangou catchment is generally more than 50% silt (0.002–0.05 mm) and less than 20% clay (<0.002 mm) and its porosity is nearly 50% (Liu et al., 2012). Farmland abandonment in sloping areas is a management policy in Loess Plateau (Jiao et al., 2007). Following this policy, from the 1980s to 1990s, vast farmland areas in mountainous regions were converted

into grassland or forestland in the gully and hilly zones of Loess Plateau (Liu et al., 2012). Due to a grazing ban after these farmlands were abandoned, there was little human impact on the vegetation succession, and there were no other disturbances to the land, such as fire or grazing.

2.2. Experimental design

The effect of farmland abandonment on eco-hydrological processes changes in relation to time over the course of decades (Koulouri and Giourga, 2007). Thus, a chronosequence approach has often been used to overcome the problem of diachronic studies under the presumption that there is not a significant difference between parent materials within the area of study (Cammeraat et al., 2005; Dana and Mota, 2006). After interviews with landowners and managers, four abandoned farmlands with abandonment times of 4, 12, 22, and 50 years were selected for this study. The environmental parameters of these four abandoned farmlands are similar except for their abandonment time (Table. 1). There is similar land use history on these four abandoned farmlands. After the interviews, we found that before farmland abandonment, millet (*Setaria italic*) has been cropped on these lands since the 1950s or earlier. Because of the similar ploughing techniques (artificial cultivation) and soil condition (*Calcaric Regosol*), it is suggested that soil nutrient levels can be similar on these four lands at the time of abandonment.

From June to October 2012, 15 randomly distributed quadrats (1 × 1 m) on each abandoned farmland were investigated. In each quadrat, the coverage area, location, and height of each vascular plant were recorded, and the moss area within each quadrat was also recorded. One soil sample was taken at a depth of 20 cm at the centre of each quadrat. Moreover, 3 closed runoff plots were established and randomly distributed on each abandoned farmland (Fig. 1). The width of the runoff plot was 2 m, and the length was 5 m. The runoff mixed with the sediment discharged from each plot was collected by a plastic tube and gauged by a plastic bucket (Fig. 1). During the study period, there was neither a runoff event that exceeded the storage capacity of the plastic buckets nor any significant losses from the buckets. After measuring the runoff volume and allowing the sediment to settle for 24 h, the sediment was separated from the water, dried in an oven at 105 °C for 8 h and weighed. This procedure was performed after each erosive rainfall from June 2011 to September 2012. For each erosive rainfall event, the rainfall depth and duration were measured, and a rainfall sample was analysed.

2.3. Laboratory analysis

Five parameters were determined for each soil sample and sediment: SOM, TN, total phosphorus (TP), total potassium (TK), and total sulphur (TS). The SOM was determined by the potassium dichromate volumetric method. TN and TS were measured using an element analyser (Vario EL III). Morgan's extraction solution (10% sodium acetate in a 3% acetic acid solution buffered at pH 4.8) was used to determine the TP and TK.

Three parameters were determined for each runoff and rainfall water sample: P, K, and S. N was not determined because of its instability in water. All of these three parameters were determined using anion chromatograph (Dionex ICP-1000).

2.4. Data analysis

Five vegetation indices were calculated for each quadrat. The first index determined was the degree of succession (DS), which is a quantitative index to describe the succession degree of the vegetation community. The algorithm of this index was obtained from Kitazawa and Ohsawa (2002). According to Numata (1969), the higher the DS value, the more vegetation community development has occurred (Numata, 1969). The second index was the aggregation index of vascular plant patches (AI) (He et al., 2000). To evaluate the vascular plant pattern

Fig. 1. Locations of experimental lands and a schematic diagram to explain the runoff plot process.

within each quadrat, the coverage area of each vascular plant was simulated by a circle with the plant located in the centre. Meanwhile, the overlaps within each circle were combined. Following this method, AI, a commonly used plant patch pattern index, can be calculated within each quadrat. AI was computed as an area-weighted mean class aggregation index. Each class is weighted by its proportional area in the landscape. The AI is scaled to account for the maximum possible number of like adjacencies given any landscape composition. According to He et al., the higher the AI value, the greater the number of

aggregation plant patches (He et al., 2000). The third and fourth indices were the total coverage area of vascular plant (VA) and the total moss coverage area (MA) in the quadrat. The fifth index, total coverage area of vegetation (TA), equals the summation of VA and MA in the quadrat.

The least significant difference test (LSD-test) was used to compare the value of the indices (DS, AI, TA, VA and MA) and soil parameters (SOM, TN, TP, TK, and TS) on farmlands abandoned for different lengths of time.

For the data achieved from the runoff plots, the LSD-test was also used to compare the monitoring results of the different abandoned farmlands. First, the runoff volume and sediment loss caused by every erosive rainfall event were accumulated for each plot during the study period. Then, the LSD-test was used to compare the value of the runoff volume and sediment loss of different abandoned farmlands. Second, for every runoff event, the nutrient concentrations (P, K, and S) of the runoff water were compared for different abandoned farmlands using the LSD-test. The accumulated nutrient loss caused by runoff during the study period was also compared for different abandoned farmlands, after multiplying the nutrient concentration with the runoff volume. Third, similar to the runoff water analysis, for every runoff event, the SOM and nutrient concentrations (TN, TP, TK, and TS) of the sediments were compared for different abandoned farmlands using the LSD-test. The accumulated nutrient loss caused by soil erosion during the study period was also compared for the different abandoned farmlands, after multiplying the nutrient concentration with the sediment loss.

The DS and LSD-tests were calculated by R 2.15.2, with the packages “agricolae.” The AI was calculated by ArcGIS 10.0 and Fragstats 4.1. Plant species were determined according to the Chinese Flora mentioned in “Chinese Vegetation” (Wu, 1980).

Fig. 2. Walter–Lieth diagram of Yangjuangou catchment.

Table 1

The environmental parameters of abandoned farmlands (experimental lands).

Abandoned time	Vegetation community ^a	Slope	Aspect	Slope position	Soil type
4 years	<i>Artemisia scoparia</i> + <i>Sonchus brachyotus</i>	25°	West–South	Middle slope	Calcaric Regosol
12 years	<i>Carex korshinskii</i> + <i>Cleistogenes squarrosa</i>	24°	West–South	Middle slope	Calcaric Regosol
22 years	<i>Bothriochloa ischaemum</i> + <i>Cleistogenes squarrosa</i>	23°	West–South	Middle slope	Calcaric Regosol
50 years	<i>Stipa grandis</i> + <i>Silene gallica</i>	25°	West–South	Middle slope	Calcaric Regosol

^a The nomenclature of vegetation community is dominant-species nomenclature (*Chinese Flora*). Vegetation community is defined by two plant species that have the biggest importance values in the vegetation community.

3. Results

3.1. Change of vegetation and soil parameters

Vegetation positive succession after farmland abandonment was confirmed by comparing the DS value on different abandoned farmlands. The DS value significantly increased from nearly 100 in farmland abandoned for 4 years to nearly 350 in farmland abandoned for 50 years (Fig. 3). During this developing process, though the VA was basically unchanged, the AI value significantly increased from 98.3 in farmland abandoned for 4 years to 99.6 in farmland abandoned for 50 years (Fig. 3). The data suggests that during the vegetation succession process, more and more vascular plants grow in aggregation. Moreover, the MA increases from nearly 0 in farmland abandoned for 4 years to nearly 0.9 m² in farmland abandoned for 50 years, and the TA increases from 0.6 in farmland abandoned for 4 years to 1.7 m² in farmland abandoned for 50 years in the quadrat (Fig. 3). It is suggested that during the vegetation positive succession process, although VA is unchanged, increasing vascular plants grow in aggregation. A two-phase mosaic structure with vascular plant patches and inter-vascular plant patches forms on the abandoned farmlands.

Amongst the five soil parameters analysed (SOM, TN, TP, TK, and TS), only the contents of SOM and TN in farmland abandoned for 12 years showed a significant difference from the farmlands abandoned for the other lengths of time studied (Fig. 4).

3.2. Rainfall event selection

From June 2011 to September 2012, there were 16 erosive rainfall events that caused runoff. The rainfall durations of these events were from 25.39 to 2375.18 min. The maximum rainfall depth was 65 mm

during August 24–25, 2011. The minimum rainfall depth was 6.4 mm on September 17, 2012. However, runoff was not found in all of these runoff plots during erosive rainfall events due to the low rainfall intensity of the events. To compare the results of runoff and sediment loss in different runoff plots, 10 available erosive rainfall events that caused runoff in all of the runoff plots were selected (Fig. 5).

3.3. Runoff and sediment loss

The average accumulated runoff within one plot significantly increased from 9698.2 ml in farmland abandoned for 4 years to 38,605.3 ml in farmland abandoned for 50 years. In comparison, the average accumulated sediment loss within one plot significantly decreased from 2019.5 g in farmland abandoned for 4 years to 387.7 g in farmland abandoned for 50 years (Fig. 6). It is suggested that after farmland abandonment, as the farmland abandonment time increases, rainfall can cause increasing runoff, but the sediment loss decreases.

3.4. Nutrient contents of runoff and sediments

In terms of nutrient concentrations in the runoff water, the most significant finding was that the P and K contents of the runoff were significantly lower in farmland abandoned for 50 years than in farmland abandoned for 4 years (Fig. 7). For example, from August 31 to September 1, 2012, the concentrations of P and K in the runoff water decreased from 10.4 ppm and 14.4 ppm in farmland abandoned for 4 years to 6.4 ppm and 4.9 ppm in farmland abandoned for 50 years, respectively (Fig. 7). However, an obvious trend in the content of S in the runoff in farmland abandoned for different lengths of time was not determined (Fig. 7).

Fig. 3. LSD-tests for degree of succession (DS), aggregation index (AI), total vegetation coverage area (TA), vascular plant total coverage area (VA), and total moss coverage area (MA) of quadrats of farmlands abandoned for different lengths of time.

Fig. 4. LSD-tests for the contents of soil parameters (soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), total potassium (TK), and total sulphur (TS)) on farmlands abandoned for different lengths of time.

In terms of the nutrient concentrations in the sediments collected mostly by erosive rainfall events, the content of TP in the lost sediment significantly decreased as the abandonment time of the farmland increased from 4 to 50 years. For example, during August 17–19, 2011, the concentration of TP in the sediment decreased from nearly 0.1% in farmland abandoned for 4 years to nearly 0.07% in farmland abandoned for 50 years. However, there was not an obvious trend for the content of TK and TS in the sediments as the abandonment time of the farmland increased from 4 to 50 years. The concentration of TK remained near 1.6%, and the concentration of TS remained near 0.01% for all the abandoned farmlands analysed. Moreover, the contents of SOM and TN in the sediments of farmland abandoned for 12 years were significantly different than almost all the other farmlands that were abandoned for different lengths of time; some values of these were not found to be significantly different between the farmland abandoned for 22 years and the other abandoned farmlands (Fig. 8). This suggests that the contents of SOM

and TN in sediments of farmland abandoned for 12 years are generally higher than on farmlands abandoned for other lengths of time.

3.5. Accumulated nutrient loss during the monitoring period on slopes

Soil erosion and runoff are the main avenues of nutrient export. In this study, the average contents of P, K, and S in the rainfall were 0.31 ppm, 0.30 ppm, and 0.72 ppm, respectively. These values are much lower than the content values of the nutrients in the runoff (Fig. 7), suggesting that the rainfall has little effect on the nutrient contents of the runoff. As shown in Fig. 9, there was not a significant difference between the loss of P caused by runoff on the different abandoned farmlands during the study period. Significant differences in the loss of K and S caused by runoff between the farmland abandoned for 50 years and the other abandoned farmlands were observed. The average losses of K and S on runoff plots of farmland abandoned for 50 years were more than 0.2 g, whilst the loss of K and S on runoff plots of farmland abandoned for 4 years was less than 0.12 g during the study period.

The nutrient changes caused by soil erosion have an obvious trend after farmland abandonment. Although the losses of some nutrients were not significantly different between the farmlands abandoned for different lengths of time (for example: the loss of SOM and TN on farmlands abandoned for 4 and 12 years and the loss of TP and TK

Fig. 5. Selection and features of available erosive rainfall events that caused runoff in all of the runoff plots. Available: erosive rainfall event that caused runoff in all of the runoff plots. Unavailable: erosive rainfall event that did not cause runoff in all of the runoff plots.

Fig. 6. LSD-tests for runoff and soil loss generated from runoff plots during the study period on farmlands abandoned for different lengths of time.

Fig. 7. For every available erosive rainfall event, LSD-tests were carried out for the nutrient contents of runoff from runoff plots on farmlands abandoned for different lengths of time.

on farmlands abandoned for 12, 22, and 50 years), the nutrients lost by soil erosion decreased during the study period as the abandonment time of the farmland increased from 4 to 50 years (Fig. 10). For example, the average lost amount of TP, TK, and TS on runoff plots decreased from nearly 1.35 g, 32 g, and 0.26 g on farmland abandoned for 4 years to nearly 0.2 g, 5 g, and 0.05 g, respectively, on farmland abandoned for 50 years.

4. Discussions

4.1. Vegetation development with farmland abandonment

In arid and semi-arid areas, because of the limited water, vegetation distribution often changes from a homogeneous to heterogeneous pattern to hold high water availability (Aguilar and Sala, 1999). This two-phase mosaic structure of high (plant patches) and low plant cover patches (inter-plant patches) has been reported in arid and semi-arid areas of the world (Imeson and Prinsen, 2004; Ludwig et al., 2005; Moreno-de las Heras et al., 2010; Espigares et al., 2011). Generally, during the formation of this heterogeneous plant pattern, the cycling of nutrients is progressively confined to the plant patches that can intercept runoff and sediments, whilst inter-plant patches become increasingly nutrient poor. This process can be described as the development of resource islands (Reynolds et al., 1999).

Plant and inter-plant patches have different effects on slope. Plant patches can obstruct runoff and store run-on (Segoli et al., 2008), enhance soil infiltrability (Stavi et al., 2008), and enhance plant growth by storing water that carries more soil particles with nutrients (Hodgkinson and Freudenberger, 1997). Inter-plant patches can be a major source of water and sediment, and these resources are trapped by plant patches or lost from a slope (Bartley et al., 2006). Due to the absence of protective plant cover, the soil surface often generates a

Fig. 8. For every available erosive rainfall event, LSD-tests were carried out for SOM and nutrient contents of sediments from runoff plots on farmlands abandoned for different lengths of time.

clay-rich seal (Molina et al., 2007) or biological crust (Segoli et al., 2008). These seals and crusts can bind the soil particles and create a tightly structured soil, thereby limiting water storage and infiltration (Oumarou et al., 1999). Different crusts were found in inter-plant patches of different abandoned farmlands in this research. In farmlands abandoned for 4 and 12 years, little moss or lichen was found in the inter-plant patches (Fig. 11). In farmland abandoned for 22 years, more litter covered the surface than in farmlands abandoned for 4 and 12 years (Fig. 11). Because litter can prevent rain from falling directly on the soil surface and prevent soil crust formation (Cammaraat et al., 2005), it is suggested that litter accumulation on the inter-plant patches can be beneficial for moss development. The most moss cover was found in the farmland abandoned for 50 years (Figs. 3 and 11). So, generally, the moss coverage increased as the abandonment time of the farmland increased from 4 to 50 years (Fig. 3). The different cover features of inter-plant patches have different hydrological responses, which may explain the difference in moss cover in the farmlands abandoned for different lengths of time.

4.2. The change of soil nutrient contents after farmland abandonment

Many studies have reported that soil nutrient contents increase with positive vegetative succession after farmland abandonment (Liu et al., 2012). However, in this study, only the contents of SOM and TN in

Fig. 9. LSD-tests for accumulated nutrient loss by runoff from runoff plots on farmlands abandoned for different lengths of time from June 2011 to September 2012.

farmland abandoned for 12 years showed a significant difference from the other farmlands analysed. After farmland abandonment, the changing trend of soil nutrients can be understood by investigating the ecosystem development on the slope. In general, the cycle of soil nutrients can be affected by vegetation development or geochemical processes, which are the origins of nutrients (Gallardo and Paramá, 2007). TN is mainly cycled through organic matter (Gallardo, 2003). Because SOM is mainly from litter, vegetation development greatly affects the SOM and has a similar effect on TN. It is suggested that from 4 to 12 years after farmland abandonment, the contents of SOM and TN increase because of vegetation development and an increase in litter. Furthermore, after farmland abandonment for 12 years, increasing soil nutrients have been transported from inter-plant patches to plant

patches, causing the development of a two-phase mosaic structure. Although plant patches accumulate nutrients by the positive nutrient cycle, there were many inter-plant patches that were increasingly nutrient poor around them. The average content of SOM and TN decreased on the farmlands after 12 years of abandonment; however, this study did not find a gradual decrease of SOM and TN after 12 years of abandonment. This suggests that an acute decrease in SOM and TN arises between 12 and 22 years of abandonment; however, there were no farmlands in the Yangjuangou catchment that were abandoned for 13 to 21 years at the time of this study. With regards to TP, TK, and TS, as P, K, and S are important components of soil minerals and rocks, their cycles can be greatly affected by geochemical processes (Gallardo and Paramá, 2007). For example, the presence of Fe and Al oxides in soil may have a great influence on the P and S availability in ecosystems (Guadalix and Pardo, 1991). There is a limited effect of vegetation development on these three nutrients. Though these nutrients are continuously transported from inter-plant patches to plant patches to form the two-phase mosaic structure, the content of these nutrients is maintained at a similar level on the whole slope after land abandonment. No changes in the content of TP, TK or TS were found.

4.3. The changing trend of runoff and sediment following farmland abandonment

The changing trend of runoff and sediment can be explained by the development of vegetation on abandoned farmlands. With the formation of a two-phase mosaic structure after farmland abandonment, the coverage of moss increases in inter-plant patches (Fig. 3). This biological crust can limit water storage and infiltration (Li et al., 2004; Zhang et al., 2011). Therefore, as the abandoned time increases, so does the runoff. Due to the protection of the biological crust and plant cover on the soil surface, with the increase in total vegetation coverage after farmland abandonment (Fig. 3), the loss of sediment from the plots decreases.

Some other findings about hydrological response on abandoned farmlands in semi-arid areas of the world can be different with our research, because of various environments of abandoned farmland.

Fig. 10. LSD-tests for accumulated SOM and nutrients loss by sediments from runoff plots on farmlands abandoned for different lengths of time from June 2011 to September 2012.

Fig. 11. A schematic diagram to show the development process of biological crust in inter-plant patches. When farmland was abandoned for 4 or 12 years, there was little moss cover in the inter-plant patches. When farmland was abandoned for 22 years, it is suggested that much litter accumulated on the inter-plant patches, which was beneficial for moss development. When farmland was abandoned for 50 years, it is obvious that moss coverage had developed in the inter-plant patches.

However, due to the similar climate condition, our findings still can be the valuable references for the researches on these areas.

4.4. Characteristics of nutrient loss on farmlands abandoned for different lengths of time

The changing trend of SOM and nutrients in runoff and eroded sediments can also be explained by the development of the ecosystem on abandoned farmlands. Due to the interception of runoff and sediments by plant patches, the runoff and sediment loss are mainly from connective inter-plant patches on the farmlands. The effective transport of runoff and sediments is often called the hydrological connectivity (Bracken and Croke, 2007; Merino-Martín et al., 2012).

In terms of SOM and TN, from 4 to 12 years after farmland abandonment, the content of SOM and TN increased on the slope (Fig. 4). So, it has been found that the contents of SOM and TN in sediment increased (Fig. 8). Similarly, after 12 years of abandonment, with the decrease of the content of SOM and TN on the slope (Fig. 4), the contents of SOM and TN in sediment decreased (Fig. 8).

In relation to P and K, because the origin of P and K is parent material weathering, there is a limited effect of vegetation development on TP and TK. After farmland abandonment, an increasing loss of TP and TK in inter-plant patch is caused by soil erosion. This suggests that runoff and sediment loss are mainly from connective inter-plant patches on the farmlands. Whilst TP and TK decrease in the inter-plant patches as the abandonment time of the farmland increases from 4 to 50 years,

the content of P in the runoff and eroded sediments and K in the runoff generally decreases.

However, overall, there was not a significant trend for the change in TK in sediment and S in runoff and sediments. Compared with P and K, S in the soil surface is not only formed from parent material weathering but also from atmospheric deposition. This suggests that although the increasing amount of S from atmospheric deposition cannot lead to an increasing trend of S on the whole slope after farmland abandonment (Fig. 4), this increase of S can prevent the decrease in the S on the inter-plant patches. In terms of TK in the sediment, a change was not obvious, and this needs to be further researched.

During the entire monitoring period, the nutrient loss caused by soil erosion generally decreased as the abandonment time of the farmland increased from 4 to 50 years (Fig. 9), but there was not a unified trend in the changes in nutrient loss caused by runoff after farmland abandonment (Fig. 8). However, it has been found that the nutrient loss caused by runoff is so much less than that caused by soil erosion that most nutrients, except for S, are lost from the slope by soil erosion. In terms of S, although there was a decrease in the loss caused by soil erosion after farmland abandonment during the monitoring period, there was an increase of loss by runoff. Additionally, the lost amounts of S by these two avenues were similar. Thus, there was not an obvious trend in the change in the loss of S from the slope after farmland abandonment during the monitoring period. All results of nutrient loss were calculated as the volume of sediments or runoff multiplied by the content of the nutrient. Increasing abandonment time decreases the sediment erosion on slopes and, thus, significantly influences nutrient loss.

5. Conclusions

Farmland abandonment greatly affects the eco-hydrological process. First, following farmland abandonment, there is a positive vegetation succession. During this process, although the vascular plant coverage is unchanged, increasing vascular plants grow in aggregation. A two-phase mosaic structure with plant patches and inter-plant patches forms. Moreover, the soil on farmland abandoned for 12 years had significantly higher contents of SOM and TN than the other farmlands (abandoned for 4, 12, and 50 years). Second, with the formation of a two-phase mosaic structure, the moss coverage increases in inter-plant patches. Because the biological crust can limit water storage and infiltration, the runoff increases with the abandonment time. Third, as the biological crust in inter-plant patches increased and the total vegetation coverage area increased after farmland abandonment, the loss of sediment from plots decreased. With decreasing sediment loss after farmland abandonment, the wastage of SOM and nutrients (N, P, and K) decreased on the slopes because the lost SOM and nutrients primarily originate from the sediments.

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