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*Original Research*

# Structural Stability and Erodibility of Soil in an Age Sequence of Artificial *Robinia pseudoacacia* on a Hilly Loess Plateau

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## Abstract

To assess the erosion resistance of soils beneath *Robinia pseudoacacia* (Robinia), soil anti-scouribility (AS) and its relevant structural properties in an age sequence of 4-, 11-, 24-, 37-, and 43-year-old *Robinia*, lands and one adjacent cropland (CK) were studied through a simulated flow scouring experiment on a hilly Loess Plateau. Soils from the six-stage *Robinia* planting were hypothesized to differ in their resistance to scouring, and these differences are believed to be related to differences in their soil physical properties. The results showed that:

1) *Robinia* planting significantly reduced sediment compared with CK. Changes in the sediment over scouring time were best described by a negatively exponential function.

2) Compared with CK, the average soil bulk density beneath *Robinia* significantly decreased by 14.5% in the surface (0-20 cm) soil layer and non-significantly by 5.7 and 3.3% in the middle (20-40 cm) and lower (40-60 cm) soil layers, respectively. Soil aggregate content and shear strength increased while soil disintegration rate decreased significantly in the three soil layers with *Robinia* stages. Mean 6.8, 1.6, and 0.2 times were increased in soil AS.

3) Linear regression equations between soil AS and the soil structural properties were well fitted in the surface and middle soil layers. Soil aggregate content and root biomass were the key factors, which contributed 71.0 and 90.8% to the reinforcement of soil AS beneath *Robinia* in the hilly Loess Plateau.

**Keywords**: *Robinia* planting, soil anti-scouribility, soil structural stability, root, hilly Loess Plateau

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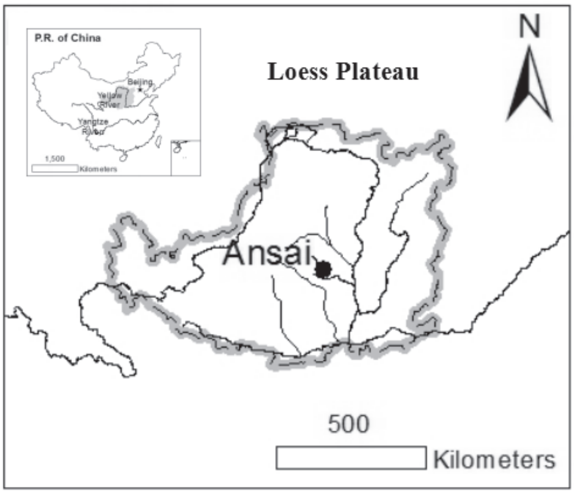

Fig. 1. Location of the study site.

## Introduction

Loess is a highly erosion-prone soil that is susceptible to water erosion, and the resulting environmental problems are far-reaching [1-2]. Vegetation is the main factor for improving the eroded environment on the plateau [3]. In the past two decades, great efforts have been made to restore degraded soil, including the "Grain for Green Project," which called for 14.67 million hectares of slope croplands and 17.33 million hectares of barren land to be replanted in the western part of China. Subsequently, the ecological consequences became a hot issue [3].

*Robinia pseudoacacia* (*Robinia*) planting is a very effective erosion control measure. It has been applied to mitigate soil erosion through restoration operations because of its easy adaptability, cost effectiveness, and reproductive capacities [4]. As such, some efforts have demonstrated that *Robinia* planting could ameliorate soil properties such as soil aggregate stability [5], nutrient content [6], and biological properties [7] – all of which affect or represent soil erodibility. However, many authors have argued that we are still far from a complete understanding of the implications of ecological restoration, in particular for water-induced eroded regions [2, 6]. In the concentrated flow erosion zones of the plateau, the erodibility of soils largely relies on soil anti-scouribility (AS). Therefore, soil AS was proposed for expressing soil erodibility, and higher soil AS indicates lower erodibility [8]. In this sense, soil AS and its relevant soil structural properties in an age sequence of 4-, 11-, 24-, 37-, and 43-year-old *Robinia* lands and one adjacent cropland were studied in Wu Liwan in a small watershed through a simulated flow scouring experiment on the plateau. This study aims to quantify the changes in soil AS and relevant soil structural properties following *Robinia* planting. The soil structural properties were also identified to evaluate the quality of *Robinia* planting and select the key indicators that best explain this ability. Such knowledge may improve the diagnosis of land vulnerability to erosion, and the evaluation of the soil environmental effect of ecological restoration [9].

## Material and Methods

### Study Area

The study was conducted in a small Wu Liwan watershed near the Ansai Ecosystem Research Station (36°31′-37°20′N, 108°52′-109°26′E) of the Chinese Academy of Sciences in the northern Loess Plateau, China (Fig. 1). The mean annual temperature and precipitation are 8.8ºC and 505 mm, respectively. The soils developed on wind-deposited loess parent material and are classified as calcic cambisols (FAO classification). This soil is highly erodible, with an erosion modulus of 10,000 to 12,000 t km$^{-2}$ a$^{-1}$ before the restoration efforts began in this region [4]. Five Robinia fields in an age sequence of 4-, 11-, 24-, 37- and 43-year-old and one adjacent cropland were selected through a simulated scouring experiment within the watershed. The six fields represent CK, RP4, RP11, RP24, RP37, and RP43, with the same aspect (northern aspect) in the same altitude zone and approximately in the same slope class (Table 1). Considering the strong influence of tillage history on succession, we selected a *Panicum miliaceum* land that had been planted for more than three years [10]. A portable GPS receiver (Magellan Explorist XL) was used to locate the sampling sites and geographic information.

Table 1. Description of the sampling plots.

| Site | Age | Aspect | Slope (°) | Elevation (m) | Canopy density (%) | SOM (g kg$^{-1}$) | Undergrowth vegetation |
|---|---|---|---|---|---|---|---|
| CK | 0 | N | 19 | 1201-1213 | — | 3.77 | Panicum miliaceum |
| RP4 | 4 | NW42° | 20 | 1253-1269 | 0.2 | 3.87 | Artemisia. capillaries |
| RP11 | 11 | NW35° | 24 | 1258-1273 | 0.4 | 8.03 | Stipa bungeana |
| RP24 | 24 | NE45° | 21 | 1267-1282 | 0.7 | 13.15 | Artemisia sacrorum-Stipa bungeana |
| RP37 | 37 | N | 18 | 1242-1268 | 0.8 | 13.61 | Artemisia sacrorum-Stipa bungeana |
| RP43 | 43 | N | 19 | 1288-1301 | 0.7 | 15.80 | Artemisia sacrorum-Stipa bungeana |

Mean values of soil organic matter (SOM) contents in the 0-20 cm soil layer.

### Soil Sample Collection and Flume Experiment

Once fields for sampling were decided, the surface residues were cleared approximately 1.5 m next to *Robinia* stem [11]. Two 80 cm deep soil profiles were excavated and a special rectangular device (20 × 10 × 10 cm) was used to obtain samples of undisturbed soil at intervals of 20 cm from the top to bottom in the soil profile. A total of 12 undisturbed soil samples (four replications × three soil layers) were taken in a field. Thereafter, the sampling box was packed using a membrane with a plastic plate attached to the bottom of the metal box to prevent soil loss during transport. The undisturbed soil samples were taken back to the laboratory and placed in a water bath for slow capillary rise for 12 h to obtain the same soil moisture content. Then the samples were taken out of water to drain eight hours before the experiment.

Laboratory experiments simulating scouring were conducted with a flume [12] (Fig. 2). The flume contained an opening at its lower base, which was equal to the size of a metal sampling box, so that the soil surface of the sample was at the same level of the flume surface. The space between the sample box and the flume edges was sealed with painter' mastic to prevent edge effects. The soil samples were exposed to a flow rate of 4.0 L min$^{-1}$ on a washing slope of 15º for 15 min. For each test, samples of runoff and detached soil were collected every one min in the first three minutes and every two minutes thereafter using 10-L buckets. After the suspended particles had settled, the clear water was siphoned off and the sediments were transferred into iron containers and oven-dried at 105ºC to determine sediment concentrations.

### Soil Analysis and Data Processing

After each experimental run, roots were separated from the soil samples by the wet hand washing method on a sieve [13]. Root biomass was measured by harvest method and dried in an oven. Soil bulk density was determined using a soil core (stainless steel cylinders with a diameter and a height of five cm each) with three replications in each soil layer. Soil aggregate content was determined by a conventional wet sieving method [14]. Soil mean weight diameter (MWD) was calculated as follows [15]:

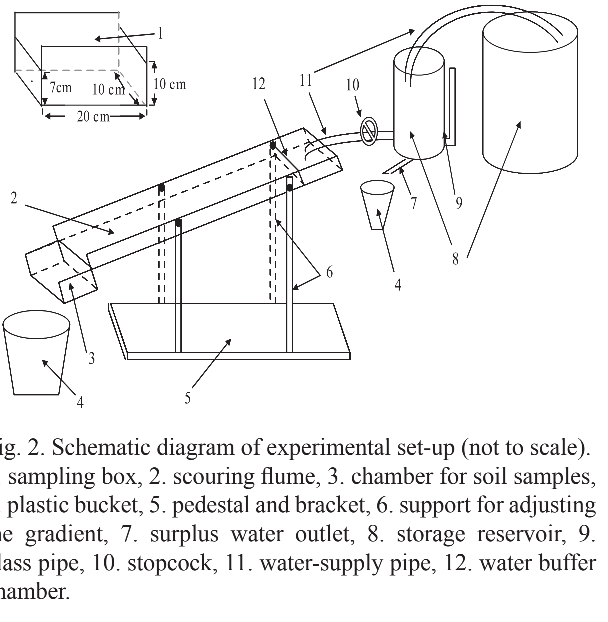

Fig. 2. Schematic diagram of experimental set-up (not to scale). 1. sampling box, 2. scouring flume, 3. chamber for soil samples, 4. plastic bucket, 5. pedestal and bracket, 6. support for adjusting the gradient, 7. surplus water outlet, 8. storage reservoir, 9. glass pipe, 10. stopcock, 11. water-supply pipe, 12. water buffer chamber.

$$MWD = \sum_{i=1}^{n} \left( \bar{R}_i w_i \right) \Big/ \sum_{i=1}^{n} w_i \tag{1}$$

…where $\bar{R}_i$ and $W_i$ are the average diameter of the class *i* soil aggregates and the percent of class *i* in the soil samples, respectively. Soil organic matter (SOM) was determined by the modified Walkey-Black wet oxidation procedure [16]. Direct shear strength samples were kept sealed at 4ºC after removal from the field. It was assumed that soil moisture content was similar to that in field conditions. Samples were placed in a shear testing device and four levels of loads (100, 200, 300, and 400 N) were applied as weights on separate samples. Lateral displacement was applied at a speed of 0.8 mm min$^{-1}$ until failure occurred and the peak shear force was recorded. The cohesion (C) and angle of internal friction (φ) were obtained using Mohr-Coulomb theory [17]. Soil disintegration rate was measured using the can buoy method [18]. Soil AS (L g$^{-1}$) was calculated as follows:

$$AS = \frac{f \times t}{W} \tag{2}$$

…where *f* is flow rate (L min$^{-1}$), *t* is scouring time (min), and *W* is the weight of oven-dried sediment (g).

### Statistical Analysis

Analysis of variance (ANOVA) was performed to investigate how soils of the six-stage *Robinia* planting differ in their structural properties and soil AS. SPSS15.0 software, the Pearson correlation coefficient, and least significant difference test ($p \leq 0.05$, two-tailed) were used to analyze the data.

## Results and Discussion

### Dynamics of Soil Loss in the Different Stages of *Robinia* Planting

As depicted in Fig. 3, a negatively exponential curve fit the process of soil loss over the scouring time in the three soil layers. Compared with CK, the soil loss was more stable in the soils beneath *Robinia*. The mean soil losses were 52.8, 53.6, and 28.6% – lower than that of the CK in the surface (0-20 cm), middle (20-40 cm), and lower (40-60 cm) soil layers, respectively. The reason may be that the root-permeated soil had larger soil cohesion, which could prevent runoff and reduce soil loss [19]. The

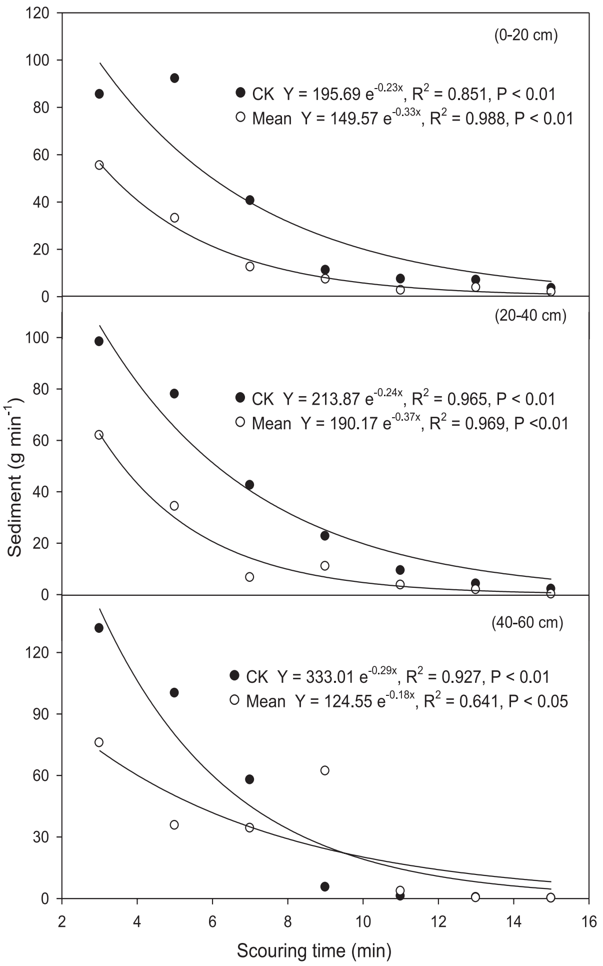

Fig. 3. Dynamics of soil loss following the scouring time (mean was the averaged sediments in the five stages of *Robinia* soils).

total soil losses in the middle and lower soil layers were 4.0 and 20.1%, which is 2.4 and 81.7% more than those in the surface soil layer beneath the CK and the *Robinia*, respectively (data not shown). This is because root biomass showed a decrease pattern from the top to bottom in a soil profile, and these roots in the surface soil layer could bind soil particles and provide a preferable soil structural condition, which was easier to retard scouring [20].

## Soil Structural Properties and Root Biomass in the Different Stages of *Robinia* Planting

Table 2 shows that the averaged soil bulk density beneath *Robinia* decreased significantly with a percentage of 14.5% in the surface soil layer and non-significantly with percentages of 5.7 and 3.3% in the middle and lower soil layers, respectively. It is notable that the soil bulk density in the RP4 stage showed a slight increase, ranging from 2.5 to 3.9%. This result may be attributed to the fact that strong human disturbance in the young stands [21]. Soil water-stable aggregate is one of the optimal indicators reflecting the capacity in the soil AS [22]. On average, the soil aggregate content increased by 34.7, 53.7, and 57.8%, respectively, in the surface, middle, and lower soil layers as compared to that in the CK. They reached the maximize values of 754.2, 463.8, and 396.2 g kg$^{-1}$, respectively, in the surface, middle, and lower soil layers at the RP43 stage. Meanwhile, 7.7, 58.1, and 30.6% increments were found in soil MWD compared with those of CK in the surface, middle, and lower soil layers, respectively. Soil shear strength – namely soil cohesion (C) and angle of inter friction (φ) – was a preferable indicator reflecting the capacity in soil AS. Higher soil shear strength indicates higher resistance to scouring. In the present study, about 0.28, 2.5, and 3.1 times were increased in the mean C in the surface, middle, and lower soil layers, respectively, compared with the value in the CK. The mean φ increased 11.1, 12.5, and 25.4% in the surface, middle, and lower soil layers, respectively. This observation concurs with previous studies, which showed that soil shear strength increased because roots enlaced and cohered soil particles around and more macro-aggregates were present in the root-permeated soils beneath *Robinia* [23]. Soil disintegration rate (cm$^3$ min$^{-1}$) is an important soil structural indicator in eroded regions. Compared with CK, the soil disintegration rate decreased significantly in the three soil layers. This result showed that the soils beneath *Robinia* were more stable under the condition of scouring. The major reason for this is that the increased root exudates and soil aggregate flocculation are prone to reduce soil disintegration [24]. Plant roots can contribute to soil cohesion and provide additional shear strength [25]. In this study, we assumed that no root was present in the CK. Table 2 showed that root biomass was steadily increased with *Robinia* stages. They approached the maximum values of 2.2, 2.0, and 0.8 kg m$^{-3}$ at the RP43 stage in the surface, middle, and lower soil layers. It is highly noted that, in the present study, the coarse roots (> 3 mm in diameter) were avoided in sampling, in which the root biomass accounted only for about 30 to 60% of the total roots within 60 cm soil depth [11, 26]. Thus, to a large extent this result may underestimate the contribution of root on soil AS. On the other hand, compared with the coarse root, the fine root (< 3 mm in diameter) has larger soil-contacting area of the roots and stronger enlacing and adherence of the root exudates to soil particles, which make the fine root easier to retard scouring [27-28].

Soil AS can be used to summarize the information given by the measured parameters as a whole. Higher soil AS values indicate higher resistance to scouring and therefore lower erodibility. Fig. 4 showed that a sharp increase was observed in the soil AS for the three soil layers with increasing *Robinia* stages. Compared with CK, mean 6.8, 1.6, and 0.2 times were increased in the soil AS. The soil AS in the surface soil layer increased rapidly from the RP11 stage and gradually approached a steady value. This finding may suggest that soil AS in the surface soil layer increases non-linearly with the *Robinia* stage going on. To the young stands, the effect of interactions between soil conditions and root was not so intensive, while clear differences in root biomass and soil structural properties were observed for mature stands [29]. Thus, the contribution of above-ground litter and biological

**Table 2.** Soil properties (mean ±SD) of the three soil layers in the different stages of *Robinia* planting

| Soil property | Soil layer | CK | RP4 | RP11 | RP24 | RP37 | RP43 | Mean |
|---|---|---|---|---|---|---|---|---|
| Bulk density (g kg$^{-1}$) | 0-20 cm | 1.19 ± **0.02** a | 1.22 ± **0.0**4 a | 1.05 ± 0.02 b | 0.98 ± **0.03** cd | 0.91 ± **0.04** d | 0.93 ± **0.02** d | 1.02 ± **0.02** bc |
| | 20-40 cm | 1.27 ± **0.04** ab | 1.31 ± **0.02** a | 1.23 ± **0.0**3 b | 1.13 ± **0.02** d | 1.14 ± **0.0**3 cd | 1.18 ± **0.01** c | 1.20 ± **0.0**3 bc |
| | 40-60 cm | 1.28 ± **0.03** ab | 1.33 ± **0.04** a | 1.32 ± **0.01** a | 1.23 ± **0.03** b | 1.12 ± **0.02** c | 1.19 ± **0.03** c | 1.24 ± **0.03** b |
| Aggregate (g kg$^{-1}$) | 0-20 cm | 384.8 ± 23.6 c | 357.2 ± 53.8 c | 433.2 ± 33.5 bc | 438.6 ± 28.2 bc | 608.4 ± 44.6 a | 754.2 ± **56.7** a | 518.4 ± 39.7 ab |
| | 20-40 cm | 192.1 ± 9.4 d | 178.4 ± 7.2 d | 259.3 ± 16.2 c | 241.8 ± 13.6 c | 332.4 ± 29.3 b | 463.8 ± 19.5 a | 295.2 ± 19.5 b |
| | 40-60 cm | 146.3 ± 8.2 c | 140.6 ± 3.2 c | 133.8 ± 17.4 c | 228.6 ± 23.2 b | 252.6 ± 10.8 b | 396.2 ± 13.8 a | 230.4 ± 13.8 b |
| MWD (mm) | 0-20 cm | 2.54 ± **0.**13 ab | 2.47 ± **0.08** b | 2.89 ± **0.18** a | 2.87 ± **0.**11 a | 2.66 ± **0.**12 ab | 2.79 ± **0.**13 a | 2.74 ± **0.**18 a |
| | 20-40 cm | 1.51 ± **0.18** c | 1.59 ± **0.18** c | 2.84 ± **0.**10 a | 2.53 ± **0.1**2 b | 2.54 ± **0.11** b | 2.43 ± **0.10** b | 2.39 ± **0.**13 b |
| | 40-60 cm | 1.30 ± **0.12** c | 1.19 ± **0.02** c | 1.62 ± **0.**16 b | 1.92 ± **0.04** a | 1.92 ± **0.**13 ab | 1.84 ± **0.**09 ab | 1.70 ± **0.14** b |
| C (kPa) | 0-20 cm | 2.3 ± 0.3 cd | 2.3 ± 0.2 d | 3.4 ± 0.3 a | 3.3 ± 0.2 a | 3.0 ± 0.3 ab | 2.8 ± 0.2 bc | 3.0 ± 0.2 ab |
| | 20-40 cm | 2.0 ± 0.2 d | 1.5 ± 0.2 e | 4.7 ± 0.4 c | 7.2 ± 0.4 b | 10 ± 0.9 a | 11.6 ± 0.8 a | 7.0 ± 0.5 b |
| | 40-60 cm | 1.0 ± 0.1 c | 1.1 ± 0.4 c | 1.8 ± 0.3 c | 6.5 ± 0.5 a | 5.5 ± 0.7 a | 5.7 ± 0.4 a | 4.1 ± 0.2 b |
| **φ** (°) | 0-20 cm | 25.5 ± 0.4 c | 25.5 ± 0.9 c | 25.3 ± 0.9 c | 32.2 ± 1.2 a | 26.7 ± 1.3 b | 28.8 ± 1.4 b | 27.8 ± 1.2 b |
| | 20-40 cm | 23.9 ± 1.1 c | 25.6 ± 0.7 bc | 26.8 ± 0.4 b | 26.0 ± 0.8 b | 28.4 ± 1.1 a | 27.7 ± 1.6 ab | 26.9 ± 0.9 a |
| | 40-60 cm | 22.4 ± 0.4 c | 27.7 ± 0.6 b | 30.0 ± 0.7 a | 27.1 ± 0.7 b | 28.6 ± 0.9 ab | 27.1 ± 0.8 b | 28.1 ± 0.7 b |
| Disintegration (cm$^3$ min$^{-1}$) | 0-20 cm | 0.95 ± 0.09 a | 0.85 ± 0.05 a | 0.68 ± 0.10 b | 0.69 ± 0.09 b | 0.48 ± 0.02 c | 0.32 ± 0.03 c | 0.60 ± 0.04 b |
| | 20-40 cm | 5.06 ± 1.03 a | 3.42 ± 0.48 b | 1.36 ± 0.08 d | 1.29 ± 0.04 de | 1.23 ± 0.03 e | 1.47 ± 0.04 d | 1.75 ± 0.22 c |
| | 40-60 cm | 2.46 ± 0.33 a | 2.87 ± 0.31 a | 2.66 ± 0.19 a | 2.04 ± 0.07 bc | 1.92 ± 0.07 c | 0.92 ± 0.02 d | 2.08 ± 0.06 b |
| Root biomass (kg m$^{-3}$) | 0-20 cm | — | 0.62 ± 0.07 e | 1.10 ± 0.05 d | 2.02 ± 0.13 b | 2.52 ± 0.27 a | 2.18 ± 0.15 ab | 1.69 ± 0.13 c |
| | 20-40 cm | — | 0.41 ± 0.04 d | 0.82 ± 0.03 c | 1.41 ± 0.11 b | 1.94 ± 0.21 a | 1.99 ± 0.14 a | 1.31 ± 0.11 b |
| | 40-60 cm | — | 0.33 ± 0.03 d | 0.47 ± 0.06 c | 0.73 ± 0.19 a | 0.70 ± 0.13 a | 0.83 ± 0.09 a | 0.61 ± 0.05 b |

Different small letters in the same row within the same soil layer means significance at $p \leq 0.05$. The mean was the average value of soil properties in five stages of *Robinia* planting.

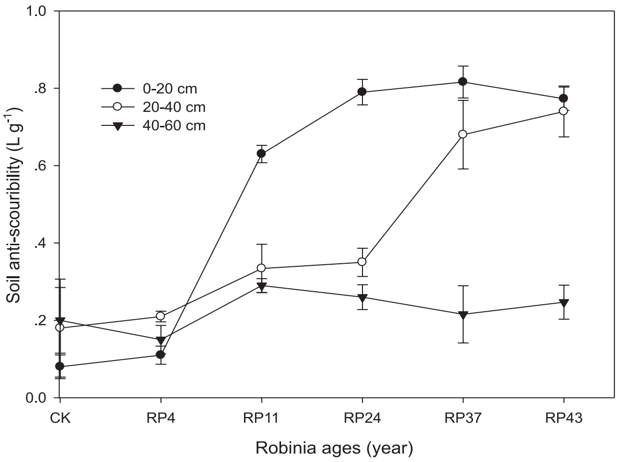

Fig. 4. Soil anti-scouribility in the different soil layers following *Robinia* planting.

crust in retarding scouring should be emphasized [30-31]. By contrast, soil AS showed a significant increase in the middle soil layer and a slight increase in the lower soil layer, which coincided with the increments of root biomass and aggregate content.

### Correlation between Soil AS and Soil Structural Properties with Root Biomass

Soil AS is a comprehensive indicator that depends on several factors such as soil aggregate content, soil shear strength, and plant roots. The linear regression equations between soil AS and soil bulk density $X_1$, soil aggregate content $X_2$, soil shear strength (cohesion $X_3$ and the angle of internal friction $X_4$), soil disintegration rate $X_5$, and root biomass $X_6$ are as follows:

Surface soil layer: $\hat{Y}_{sur} = 0.218\ X_2 + 0.\ 183\ X_3 + 0.231\ X_6 - 0.701$ ($R^2 = 0.926$, $n = 24$, $p \leq 0.05$)

Middle soil layer: $\hat{Y}_{mid} = 0.372\ X_2 + 0.055\ X_6 - 0.075\ X_5 - 0.043$ ($R^2 = 0.855$, $n = 24$, $p \leq 0.05$)

The results showed that both soil aggregate content and root biomass were the key indicators, contributing 71.0 and 90.8% to the reinforcement of soil AS in the surface and middle soil layers beneath *Robinia*. Moreover, soil cohesion and soil disintegration rates were identified as important indicators affecting soil AS in the surface and middle soil layers, respectively. These results were consistent with the findings of previous studies in West Bengal, India [32] and subtropical China [33-34]. However, in the lower soil layer, no statistical significance was found between soil AS and related properties, even though the soil AS has a positive correlation with soil aggregate content and root biomass (data not shown). Such results may be largely attributed to the disadvantage of the present sampling method (mentioned above) in which many roots accompanying numerous soil macro-aggregates were missed. However, it is unclear how much roots affect soil structural properties [35-36]. Therefore, additional studies are required to explore the contributions of physical enlacing and biochemistrical exudates of root in soil AS under both natural and laboratory conditions.

## Conclusions

The establishment of *Robinia* planting could effectively improve soil structural properties, and changes in the soil structural properties had a significant effect on soil AS. Compared with CK, the sediment beneath *Robinia* was less and showed a negatively exponential decreasing trend. Averaged soil bulk density reduced 14.5, 5.7, and 3.3% in the surface, middle, and lower soil layers, respectively. Soil aggregate content and shear strength were significantly increased, whereas soil disintegration rate decreased significantly in the three soil layers. Mean 6.8, 1.6, and 0.2 times were increased in soil AS in the surface, middle, and lower soil layers. Soil AS linearly correlated with the soil structural properties, and soil aggregate content and root biomass were key factors that respectively contributed 71.0 and 90.8% to the reinforcement of soil AS in the surface and middle soil layers. In addition, soil cohesion and soil disintegration rate were the important indicators affecting soil AS beneath *Robinia* in the hilly Loess Plateau.

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