Rehabilitation time has greater influences on soil mechanical composition and erodibility than does land type in the hilly-gully region of the Loess Plateau, China

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Background. The major landscape in the hilly-gully region of the Loess Plateau is greatly affected by vegetation rehabilitation on abandoned cropland (CL). Although many studies have shown that the rehabilitation have greatly improved soil conditions and protected them from erosion, these effectiveness were not always in consensus possibally due to the variation of vegetation or ehabilitation times. To close this gap, we conducted a long term experiment as follows.

Methods. In this study, we analysed four land types of vegetation rehabilitation (shrubland(SL), woodland (WL), natural grassland (NG), and orchard (OL)) with different rehabilitation times and investigated the mechanical composition and erodibility of the soil. Areas of slope CL and natural forest (NF)were selected as controls.

Results. The results showed that soil depth, rehabilitation time and rehabilitation land type had strong impacts on soil mechanical composition, micro-aggregation and erodibility. Following rehabilitation, NG and SL had lower fractal dimensions of particle size distribution (PD), micro-aggregation (MD), and erodibility (K) than did CL. Compared to the positive effects of rehabilitation mainly happened in the topsoil layer at other rehabilitation land type, that of WL happened in the deeper soil layer. Besides, the indispensable rehabilitation time for the significant improvement of soil condition was shorter at NG than that at SL and WL.

Discussion. Although rehabilitation time was more influential than was rehabilitation land type or soil depth, the differences among the rehabilitation land types showed that Natural grass is the most time-saving rehabilitation vegetation for the Loess Plateau in the conversion from slope CL, and the wood-land benefits to the rehabilitation of deeper soil layer. Based on the differences of rehabilitation effectiveness resulting from land type, we should be cautious to choose land types for the rehabilitation of soil conditions in the Loess Plateau.

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Key word: erosion; vegetation rehabilitation; fractal dimension; Loess Plateau

Introduction

Soil erosion initiated by either natural or human factors is a serious environmental problem in many parts of the world. It not only causedthe degradation of soil quality but also the destruction of ecosystem function and safety (*Chen & Peng 2000; Zheng et al., 2010; Lian et al., 2013*). Severe soil erosion is a serious challenge in the Loess Plateau of China (*Sun et al., 2016b*). To alleviate soil erosion and restore the local ecological environment, the Chinese government implemented the "Grain for Green" programme in 1999 to convert degraded cropland (CL) to forest and grassland (*Chen et al., 2007a; Zhang et al., 2011a; Song et al., 2015*). This programme has greatly decreased soil loss (*Zheng & Fen 2006; Chen et al., 2007b*).

Several studies had examined the effects of plant species changes, land preparation, rainfall intensity, anthropogenic disturbance, afforestation, and land abandonment on the mechanical composition and erodibility of the soil (*Koulouri & Giourga 2007; Keesstra et al., 2009; Xia et al., 2009; Zhang et al., 2011b; Yu et al., 2017*). Soil mechanical composition and micro-aggregate stability were shaped by complicated geophysical and environmental processes and responded to land-use changes, thereby affecting soil hydrological and mechanical functioning and soil erosion (*Wang et al., 2005; Xiao et al., 2014; Wang et al., 2016*). Many studies have reported positive impacts of vegetation rehabilitation of sloped CL on soil conditions and soil resistance to erosion (*Xu et al., 2013; Xiao et al., 2014; Fu et al., 2015; Sun et al., 2016b*). Different plant species, with differences in morphology, architecture and other biological characteristics, show variation in their effectiveness for vegetation rehabilitation (*Fu et al., 2015*). However, local precipitation of parent material, disturbance and their interaction and sampling time can influence vegetation rehabilitation and make interpretation of results challenging. Thus, long-term research on the dynamics of soil erosion is necessary to understand the effects of vegetation rehabilitation on soil physical condition while accounting for confounding factors. However, several studies have focused on the effects of different rehabilitation patterns or the dynamic changes following rehabilitation in a certain land type but have not clearly identified the impacts of the various rehabilitation land type on the soil mechanical composition and erodibility during a long-time scale.

In this study, we collected comprehensive and long-term data on historic vegetation (e.g., forest, shrubland and grassland) with different rehabilitation times (1) to elucidate the effects of rehabilitation land type, time and soil depth on soil mechanical condition and erodibility; (2) to clearly identify the key influencing factors.

Materials and methods

Experimental area

This study was conducted in Ansai County, Shanxi Province, China (36°31′-37°20′N, 108°52′-109°26′E; 1,012-1,731 m a.s.l.), which lies in the middle part of the Loess Plateau. This region has a typical semiarid continental climate with a mean annual temperature of 8.8°C and an annual precipitation of 549.1 mm, which mainly occurs between July and September. The landform is characterized by a deeply incised hilly-gully Loess landscape. The soil is mainly Huangmian soil (*Xiao et al., 2014*). This type of soil is characterized by weak cohesion (*Sun et al., 2016a*), which makes it highly susceptible to severe soil erosion.

Overgrazing, deforestation and other land-use patterns led to severe damage to the ecological environment and severe soil erosion by the middle of the last century. Since the late 1950s, sloping CL has been replanted with woodland (*Robinia pseudoacacia*), shrubland (*Caragana korshinskii, Hippophae rhamnoides*), artificial grassland *(Medicago sativa*) and naturally revegetated grassland to control soil erosion (*Sun et al., 2016b*).

Sampling and data collection

Based on our investigation of the history of land use, we selected four types of vegetation rehabilitation of CL abandoned between July 10 and September 10, the season in which plant community biomass peaks, in 2011 and 2012. The four types were natural grassland (NG) (with rehabilitation times of 2a, 5a, 8a, 11a, 15a, 18a, 26a and 30a), planted shrubland (SL) (with rehabilitation times of 5a, 10a, 20a, 30a, 36a, 47a), planted woodland (WL) (with rehabilitation times of 5a, 10a, 20a, 37a and 56a), and orchard (OL) (with rehabilitation times of 5a, 10a and

20a). Sloping CL sites were selected as representative of the origin condition for the rehabilitation chronosequences of the revegetated NG, SL, WL and OL. Additionally, we considered natural forest as representative of the soil-dominated climax community in vegetation rehabilitation to assess the effectiveness of vegetation rehabilitation. These selected sites offered representativeness, typicality and consistency and had similar slope gradients, slope aspects, and topography. The properties of the experimental sites are shown in Table 1.

Three replicated plots of 20 ×20 m were established in each site of planted WL (*Robinia pseudoacacia*) ensuring that all three plots within the site had the same rehabilitation time. Three replicated plots of 10 ×10 m were established in each SL site (*Caragana microphylla*, *Hippophae rhamnoides*) ensuring that all three plots within the site had the same rehabilitation time and in each OL site ensuring that all three plots within the site had the same rehabilitation time. Three smaller replicate plots (2 ×2 m) were randomly established in each revegetated NG site (including *Artemisia sacrorum, A. capillaries, A. giraldii, Aneurolepidium dasystachys, Bothriochloa ischaemum, Heteropappus altaicus, Lespedeza bicolor, Stipa bungeana, Setaria viridis*, and other grasses) ensuring that all three plots within the site had the same rehabilitation time. The plots were separated by at least 50 m.

After removing ground litter, soil samples were collected from each plot via random sampling with a soil drilling sampler (4 cm diameter) from five soil layers (0–10, 10–20, 20–30, 30–50, and 50–100 cm). The soil samples from the same layer of the same plot were mixed to form one sample. Each sample was air-dried and passed through 2 mm screens after removing roots, gravel, and coarse fragments. The samples were brought to the laboratory and divided into two parts. One part was naturally air-dried to measure the organic carbon and analyse soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) contents, particle size distributions and micro-aggregates. The other part was stored in a refrigerator at 4°C to analyse water-soluble amounts (carbon, nitrogen), microbial biomass (carbon, nitrogen), enzyme activity as well as other variables not reported in this paper.

Physical and chemical analyses

The soil bulk density (BD) of each soil layer was measured with the cutting ring method. SOC was determined using the dichromate oxidation method(*Nelson & Sommers, 1982*), and TN was determined using the Kjeldahl method (*Bremner, 1982*).For soil PSD (particle-size distribution) and micro-aggregate analysis, soil samples were analysed by a laser diffraction technique using a Longbench Mastersizer 2000 (Malvern Instruments, Malvern, England) (*Xiao et al., 2014*).

Fractal features

The fractal dimension of a PSD was calculated by the following formula (*Tyler & Wheatcraft 1992*):

$$V(r<R_i)/V_T=(R_i/R_{max})^{3-D}$$

where r is the particle size, R_i is the particle size of subinterval i in the particle size grading, V(r

$<R_i$) is the mass of soil particles with diameter less than R_i, V_T is the sum of soil particles, and *Rmax* is the maximum diameter of soil particles.

Erodibility (K)

Soil erodibility was measured by the K factor in the EPIC model using SOC content and soil PSD (*Williams et al., 1984*) and was calculated as follows:

$$K=\{0.2 + 0.3\exp[-0.0256SAN(1 - 0.01SIL)]\}$$

$$\times\left(\frac{SIL}{CLA + SIL}\right)^{0.3}\times\left(1.0 - \frac{0.25\,C}{C + exp?(3.72 - 2.95\,C)}\right)\times\left(1.0 - \frac{0.25\,C}{SN1 + exp?(-5.51 + 22.9\,SN1)}\right)$$

where SAN, SIL, and CLA are the sand (%), silt (%), and clay (%) fractions, respectively; C is the soil organic carbon content (%); and SNI = 1-SAN/100.

Statistical analysis

Three-way ANOVA was performed to test the effects of rehabilitation land type (NG, WL, SL, OL and MG), rehabilitation time (years since sloping CL abandonment) and soil depth (0-10 cm, 10-20 cm, 20-30 cm, 30-50 cm, and 50-100 cm) on soil mechanical composition and erodibility. Significance was evaluated at the 0.05 level ($P < 0.05$). Duncan's (D) post hoc test was used to perform multiple comparisons when significance of the ANOVA was observed. The differences between the natural forest and various vegetation rehabilitation at each last restoration year were examined by student's t test. Pearson correlation analysis was used to analyse the correlations among particle fractal dimension, micro-aggregate fractal dimension, erodibility and soil nutrients, soil texture, and recovery time. In addition, linear regression analysis was used to determine the relationships between each of particle fractal dimension, micro-aggregate fractal dimension, and erodibility and recovery time in each soil layer between 0 and 100 cm. All of the above statistical analyses were conducted using SPSS 17.0 (SPSS Inc., Chicago, IL, USA) and R version 3.4.4.we conducted the redundancy analysis (RDA) for the relationships between factors (rehabilitation land type, rehabilitation time, soil depth) and soil erosion properties by R version 3.4.4.

Results

Rehabilitation time, and rehabilitation land type had significant effects on the soil PSD fractal dimension and erodibility (K), only the rehabilitation land type had significant effects on the soil micro-aggregate fractal dimension (Table 2). PSD fractal dimension, micro-aggregate fractal dimension and erodibility showed trends of decline since CL in all land types. However, PSD fractal dimension, micro-aggregate fractal dimension and erodibility varied among the land types (Figs. 2-4).

The rehabilitation pattern in NG

PD and K began to show greater decreases in NG than in CL at 5^{th}, 11^{th}years, respectively, since CL abandonment. And these trends mainly occurred in 0-20cm, gradually weaken with depth . Overall, the minimum time before significant decreases appeared in the particle fractal dimension, soil micro-aggregate fractal dimension and erodibility varied among the different rehabilitation land types; in general, the times were shorter for NG than for the other land types

(Figs. 2-4). NG did not differ from NF in MD or K (20-100cm) over rehabilitation time (Figs. 5-7). Linear regression revealed that PD decreased with the number of years since farmland conversion in the 0-50 cm (except 20-30 cm)(Figs. 2-4).

The rehabilitation pattern in WL

PD, MD and K began to show greater decrease in WL than in CL in the 10th,10th and 37th respectively since CL abandonment (Figs. 2-4). Over rehabilitation time, WL did not differ from NF in PD (30-100com) and MD (0-100cm), K in WL did not differ from NF (0-30cm) and even was lower than that in NF (30-100cm) (Figs. 5-7). Compared to MD and K , PD in this site showed a clear decreasing tend at the all soil layers (Figs. 2-4).

The rehabilitation pattern in SL

PD, MD and K began to show greater decreases in SL than in CL in the 20th, 36th and 30th years, respectively, since CL abandonment, and tended to have significant differences with CL since then(Figs. 2-4). The decreasing trend of PD and MD occurred in 0-100cm, but gradually weaken with increasing depth. After rehabilitation, NG were also higher than NF in PD (0-50cm), MD (0-30cm) and K (0-10cm)(Figs. 5-7), and had no difference with that of NF at the deep layer. Linear regression indicated that PD decreased with the number of years since farmland conversion in the 0-100 cm (except 30-50cm)(Figs. 2-4).

The rehabilitation pattern in OL

PD and MD showed a trend of lower levels in OL than in CL, but there is no significant differences were observed between them(Figs. 2-4). However, K in this site didn’t decrease after a long-term rehabilitation. Following rehabilitation, PD, MD, and K were significantly higher in OL than in NF at shallow soil layer(Figs. 5-7). Linear regression revealed that PD decreased with the number of years since farmland conversion in the 0-10 cm soil layers(Figs. 2-4).

Discussion

Effects of rehabilitation time on soil mechanical composition and erodibility

In our study, rehabilitation time was a key factor in driving changes in soil mechanical condition, erodibility and properties (Table 2) (Fig. 8). The PSD fractal dimension (PD), erodibility (K) of the soil in the various rehabilitation land types showed decreasing trends following rehabilitation (Figs. 2-4). These changes were mainly due to the large amounts of soil nutrients eleased by residues and decomposing dead roots, and they promote plant growth and rehabilitation succession (*Guo et al., 2013*). PD, K positively correlated with SOC. And the improvement of mechanical conditions were mainly explained by the soil nutrient levels (Table 3). *Zhuang et al. (2008)* discovered that soil organic matter, as a binding agent, favoured soil structure stabilization and infiltration and protected it from erosion . In addition, well-developed root systems played a vital role in soil mechanical functioning and actively exude substrates, such as polysaccharides, phenolic compounds, and polygalacturonic acid, that affect soil particle cohesion and aggregation (*Sun et al., 2016b*). Furthermore, by directly binding soil particles in situ, plant roots prevented soil from being blown or washed away (*Reubens et al., 2007*). Dense canopies and ground litter following rehabilitation protected soil aggregates from breakdown and prevent particles from being washed away by raindrop energy and runoff (*Wang et al., 2008*).

Effects of rehabilitation land type on soil mechanical composition and erodibility

Vegetation rehabilitation type was the most influential factor in driving soil mechanical composition and erodibility (Table 2)(Fig. 8). Variation in vegetation recovery patterns and plant traits led to variation in the production and release of soil organic matter, which affect soil crusting, splash, aggregate size and stability. For example, high levels soil organic matter reduced soil vulnerability to detachment by surface flow, rain splash and other erosion-inducing phenomena (*Xiao et al., 2014; Fu et al., 2015*). Litters with different chemical composition among different plant species would impact decomposition rates and the release of soil organic matter(*Ayres et al., 2006*). Thus NG site dominated with high quality litter showed faster circulating rates than shrub and tree sites dominated with relative low quality litter. This phenomenon may explain why the recovery time needed to reach significant improvements of soil mechanical conditions and soil erosion was shorter for NG than for WL and SL. Our results are in accordance with the study of *Yu et al. (2015)*, which showed that high concentrations of soil organic matter greatly affected the fractal dimensions of PSD and generally facilitated the improvement of soil structure. In addition, vegetation alleviates erosion of soil by its canopy effectively reducing water-induced soil erosion (*Kutílek 1995; Mohammad & Adam 2010; Wei et al., 2010*). However, these effectiveness were different from various land type. In NG, the lower vegetation layer was more effective in reducing the kinetic energy of rainfall striking the soil surface than the tall vegetation in SL and WL. Owing to the lack of roots at deep soil layer, the NG only showed positive effect at the shallow soil layer(0-10cm). However, due to the stronger stretching ability of the trees roots, WL site also showed the potential of alleviate soil erosion at deep layer. The soil loss in OL was continued over a long time owing to human disturbances (such as production management and tillage practices) and the absence of surface cover protection, which leads to the breakdown of shallow soil aggregates and the washing away of soil particles by raindrop energy and runoff (*Wang et al., 2008*).

Effects of soil depth on soil fractal dimension and erodibility

In the four types of vegetation rehabilitation, soil depth had large influences on soil mechanical composition and erodibility (Table 2)(Figs. 8) being consistent with previous studies (*Xiao et al., 2014*). In our study, the positive effects of vegetation recovery mainly occurred in the topsoil with the higher reduction rates of PD, MD and K in the topsoil than in the subsoil (Figs. 2-4). This pattern was resulting from the variation in plant root distribution density decreasing along soil depth (*Reubens et al., 2007*); thus, the deeper soil layers were, the weaker the improvements of soil conditions were (*Sun et al., 2014*). In addition, soil nutrients accumulated near the soil surface also due to the decomposition of vegetation litter and biogeochemical cycling (*Wang et al., 2014*).

Conclusion

Our study suggested that vegetation rehabilitation time, type and soil depth significantly affects soil mechanical composition and erosion. Following the conversion of sloping CL to NG, SL or WL, the soil structure gradually recovered, and the resistance of the soil against erosive forces gradually increased, primarily within the topsoil. For the conversion of sloping CL, planting grass represents a more efficient rehabilitation practice than does the planting of other vegetation types. Meanwhile, the WL was the best type to improve soil mechanical condition and the erodibility of deep soil layer. Based on the differences of rehabilitation effectiveness among the rehabilitation land type, it is important to carefully select land types for the rehabilitation of soil conditions in the Loess Plateau. Our study, conducted at the regional scale, revealed the effects of vegetation rehabilitation on soil erosion in the Loess Plateau, China. This study contributes to our understanding of the mechanisms through which rehabilitation improves soil quality and provides a suggestion for ecosystem management in arid and semi-arid regions.

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Figure 1

Fig. 1. Location of the Loess Plateau China

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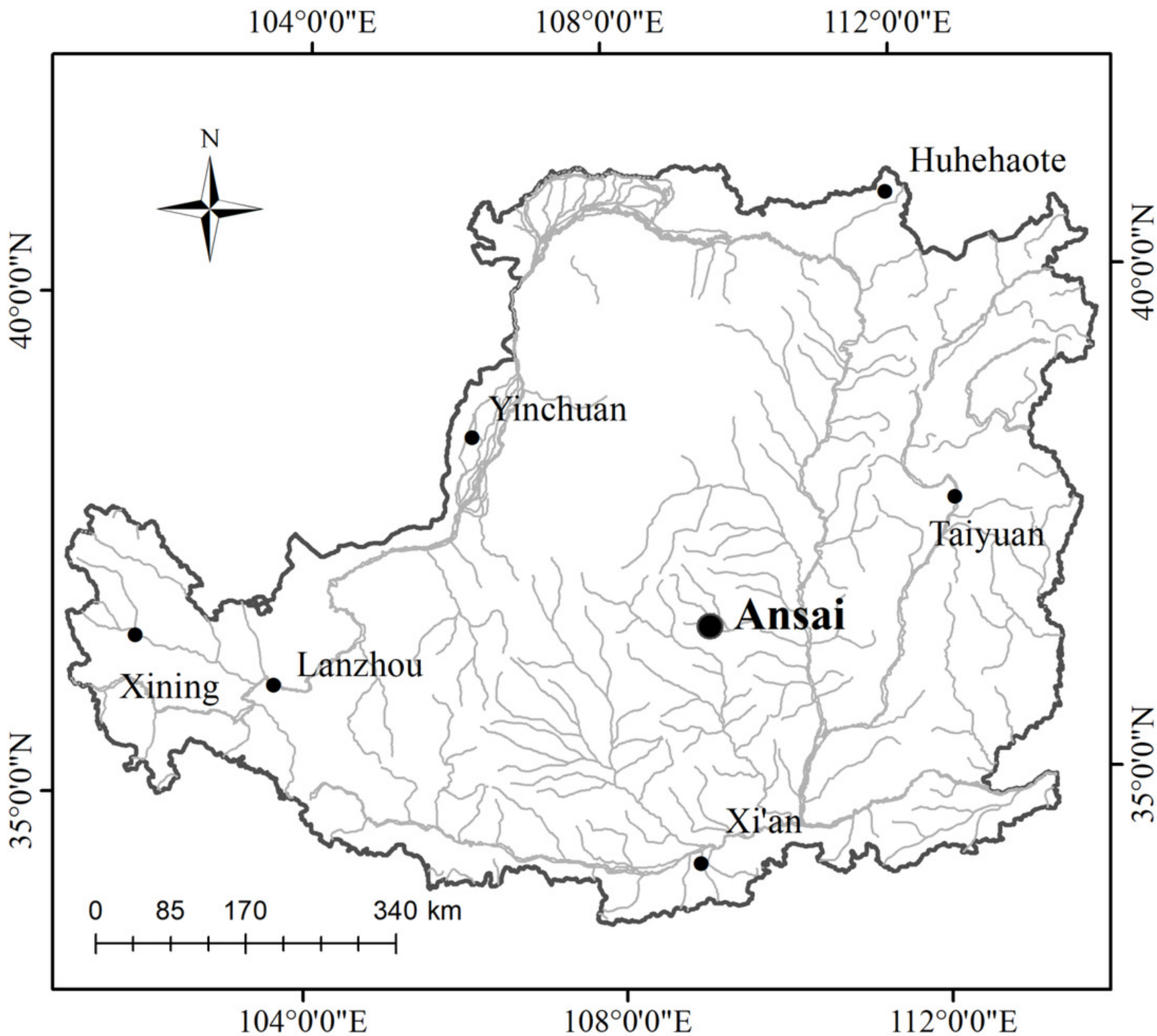


Figure 2 (on next page)

Fig. 2. Particle fractal dimension change with time since cropland abandonment in various vegetation restoration patterns.

Note: a: natural grassland, b: woodland, c: shrub land, d: orchard. 0: crop land. We set the CL as the initial stage of the rehabilitation process. Different lower-case letters above the bars mean significant differences among different ages within the same rehabilitation patterns ($P < 0.05$).

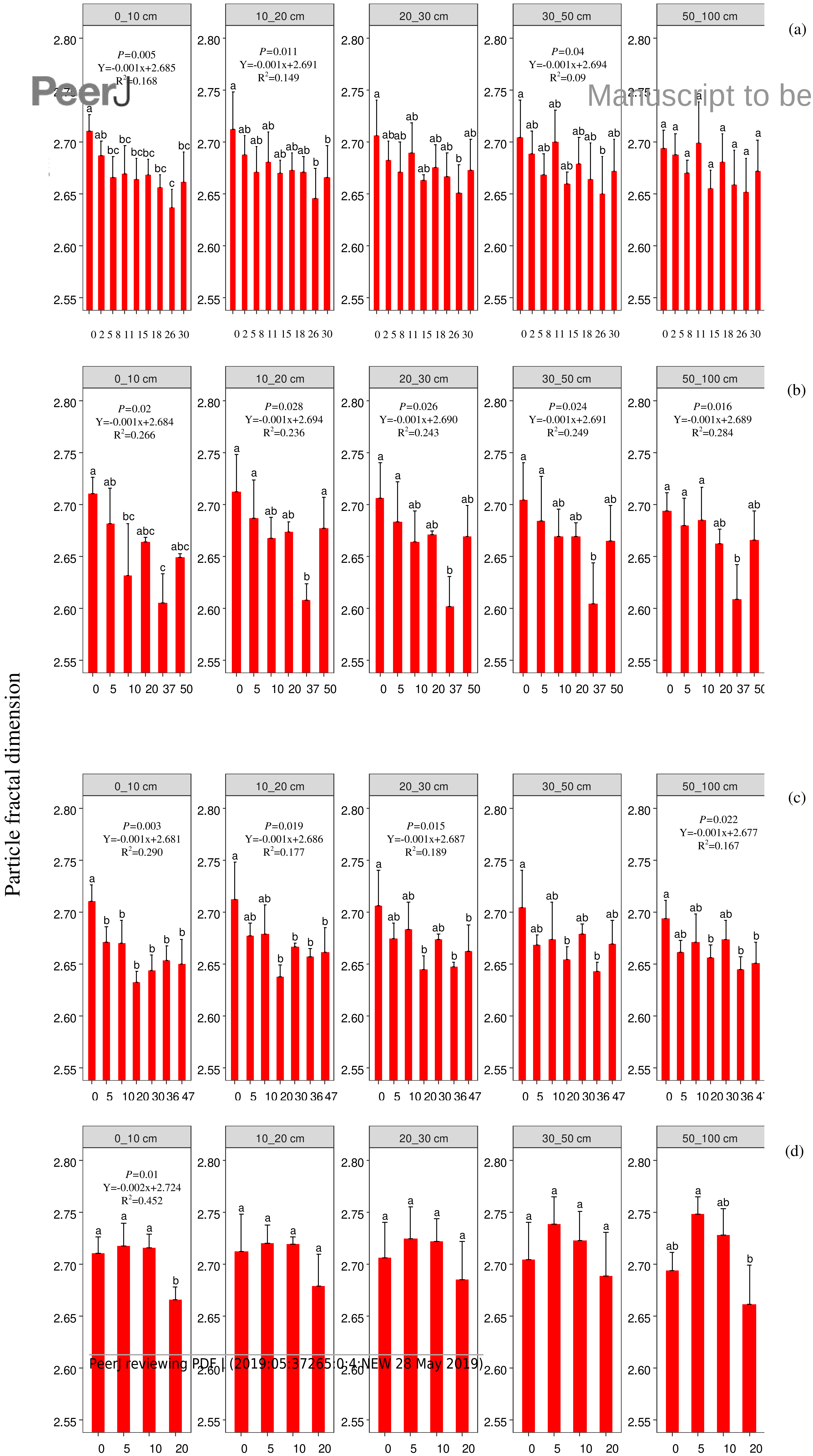

(a)
0_10 cm
P=0.005
Y=-0.001x+2.685
R²=0.168
10_20 cm
P=0.011
Y=-0.001x+2.691
R²=0.149
20_30 cm
30_50 cm
P=0.04
Y=-0.001x+2.694
R²=0.09
50_100 cm
0 2 5 8 11 15 18 26 30
(b)
0_10 cm
P=0.02
Y=-0.001x+2.684
R²=0.266
10_20 cm
P=0.028
Y=-0.001x+2.694
R²=0.236
20_30 cm
P=0.026
Y=-0.001x+2.690
R²=0.243
30_50 cm
P=0.024
Y=-0.001x+2.691
R²=0.249
50_100 cm
P=0.016
Y=-0.001x+2.689
R²=0.284
0 5 10 20 37 50
(c)
0_10 cm
P=0.003
Y=-0.001x+2.681
R²=0.290
10_20 cm
P=0.019
Y=-0.001x+2.686
R²=0.177
20_30 cm
P=0.015
Y=-0.001x+2.687
R²=0.189
30_50 cm
50_100 cm
P=0.022
Y=-0.001x+2.677
R²=0.167
0 5 10 20 30 36 47
(d)
0_10 cm
P=0.01
Y=-0.002x+2.724
R²=0.452
10_20 cm
20_30 cm
30_50 cm
50_100 cm
0 5 10 20
Particle fractal dimension

Figure 3 (on next page)

Fig. 3. Micro-aggregate fractal dimension change with time since cropland abandonment in various vegetation rehabilitation patterns.

Note: a: natural grassland, b: woodland, c: shrub land, d: orchard. 0: crop land. We set the CL as the initial stage of the rehabilitation process. Different lower-case letters above the bars mean significant differences among different ages within the same rehabilitation patterns ($P < 0.05$).

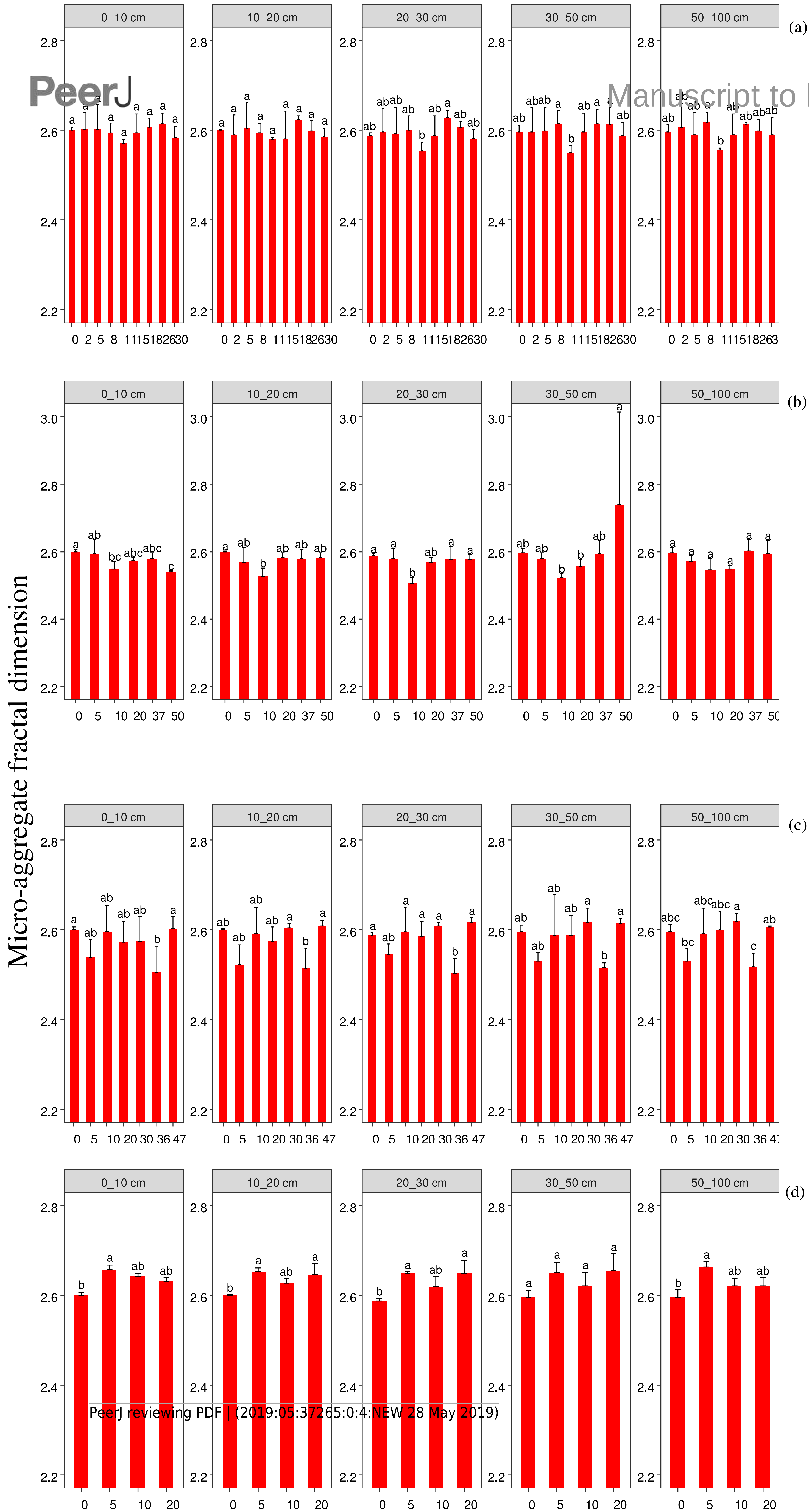

(a)
(b)
(c)
(d)
0_10 cm
10_20 cm
20_30 cm
30_50 cm
50_100 cm
Micro-aggregate fractal dimension

Figure 4(on next page)

Fig. 4. Erodibility change with time since cropland abandonment in various vegetation rehabilitation patterns.

Note: a: natural grassland, b: woodland, c: shrub land, d: orchard. 0: crop land. We set the CL as the initial stage of the rehabilitation process. Different lower-case letters above the bars mean significant differences among different ages within the same rehabilitation patterns ($P < 0.05$).

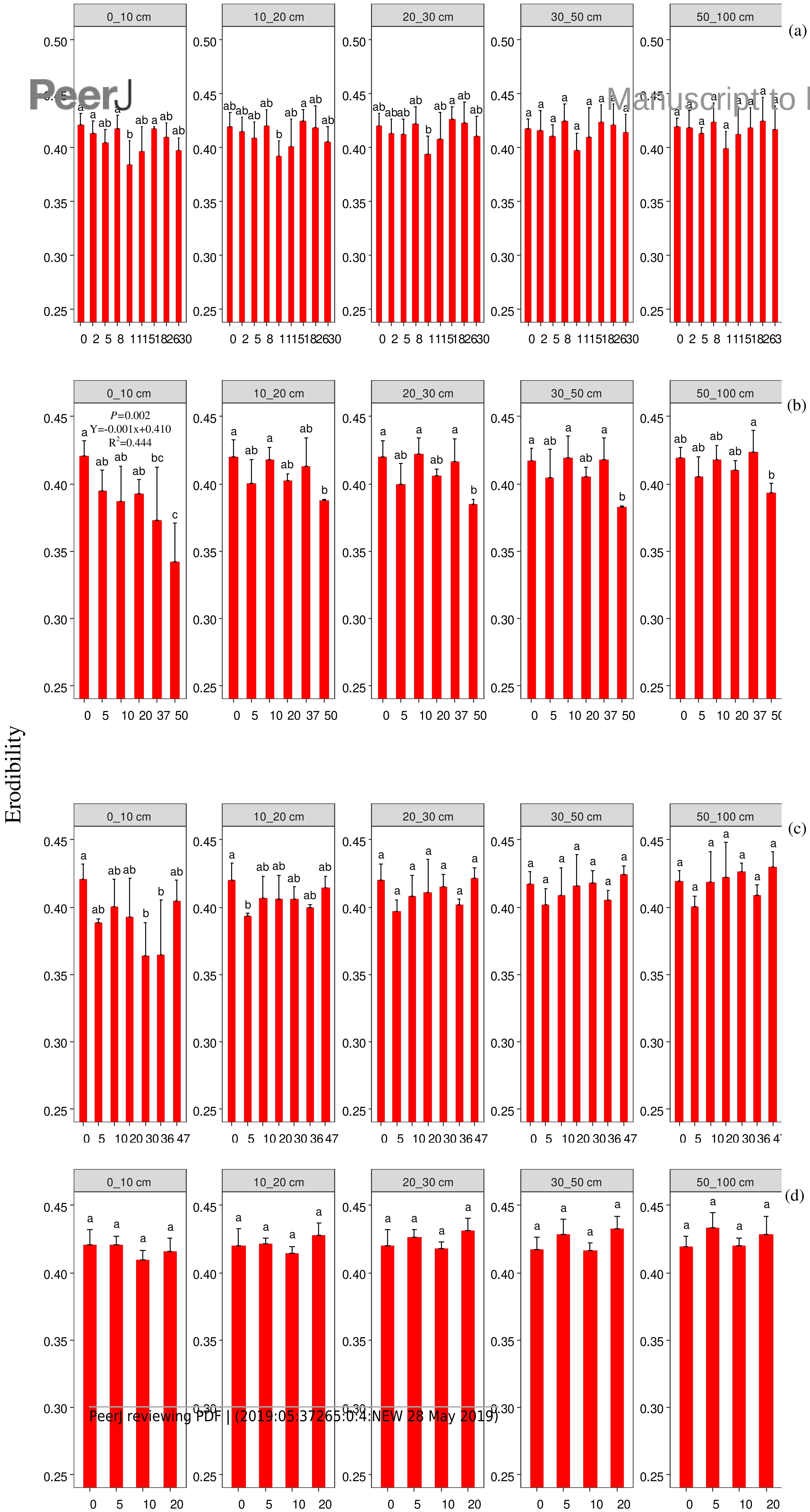

(a)
(b)
(c)
(d)
0_10 cm
10_20 cm
20_30 cm
30_50 cm
50_100 cm
Erodibility
P=0.002
Y=-0.001x+0.410
R2=0.444

Figure 5(on next page)

The differences of particle fractal dimension between the natural forest and various vegetation restoration patterns at each last restoration year.

Note: A: 0-10cm, B: 10-20cm , C: 20-30cm , D: 30-50cm ,E: 50-100cm. * means significant differences between the natural forest and various vegetation restoration patterns at each last restoration year (P < 0.05).

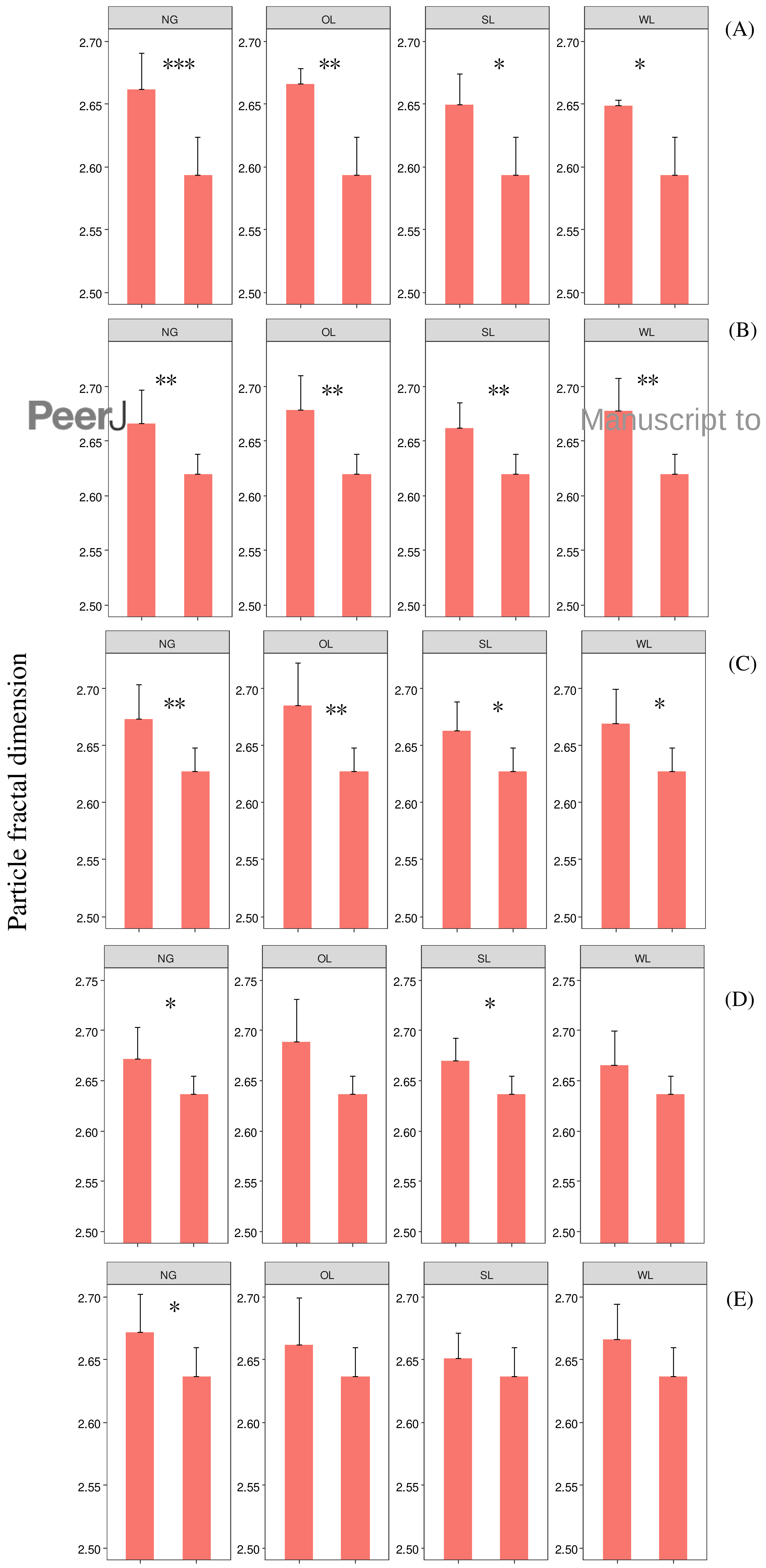

Particle fractal dimension
(A)
(B)
(C)
(D)
(E)
NG
OL
SL
WL
***
**
*
2.50
2.55
2.60
2.65
2.70
2.75

Figure 6(on next page)

The differences of micro-aggregate fractal dimension between the natural forest and various vegetation restoration patterns at each last restoration year.

Note: A: 0-10cm, B: 10-20cm , C: 20-30cm , D: 30-50cm ,E: 50-100cm. * means significant differences between the natural forest and various vegetation restoration patterns at each last restoration year (P < 0.05).

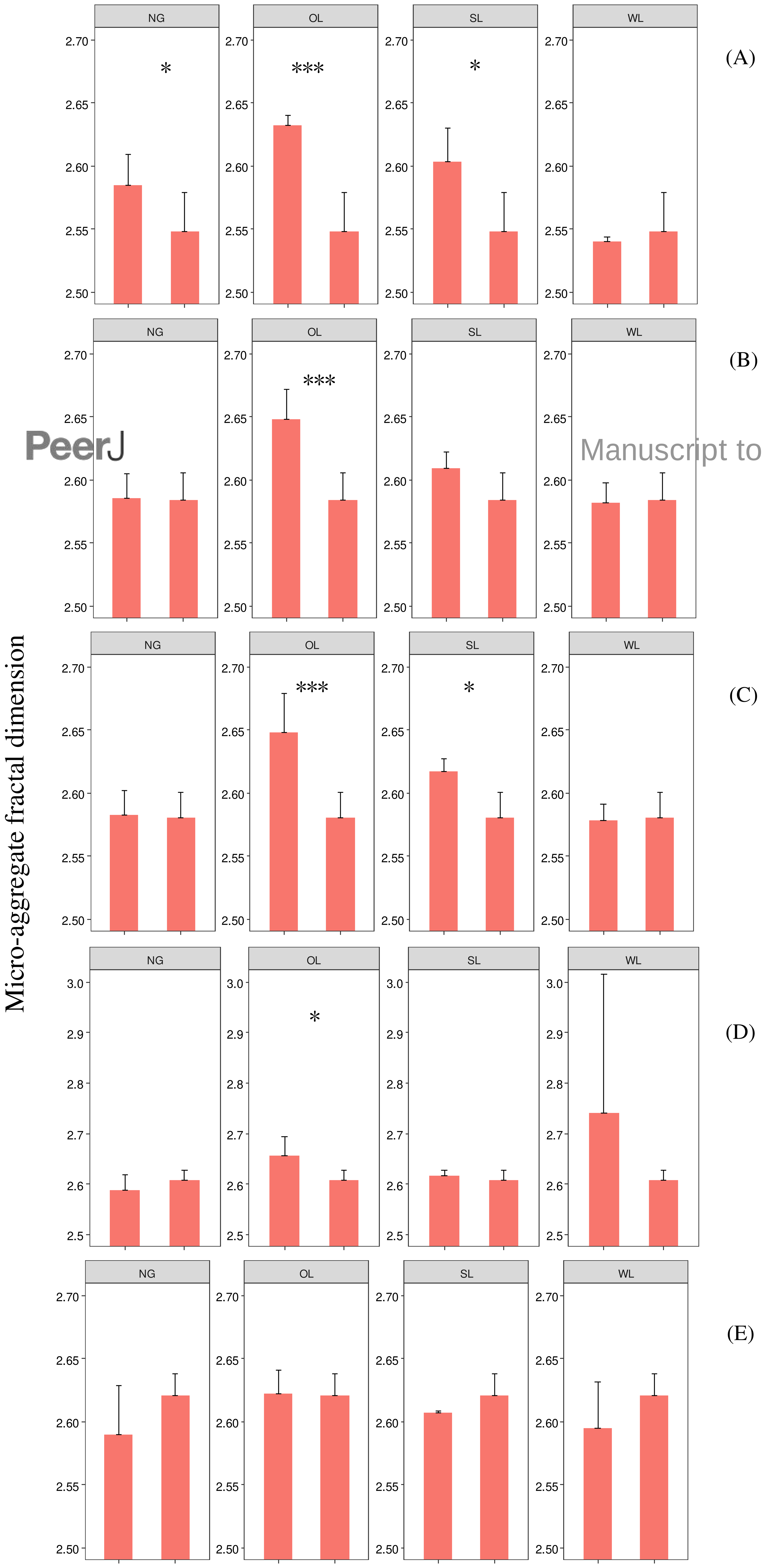
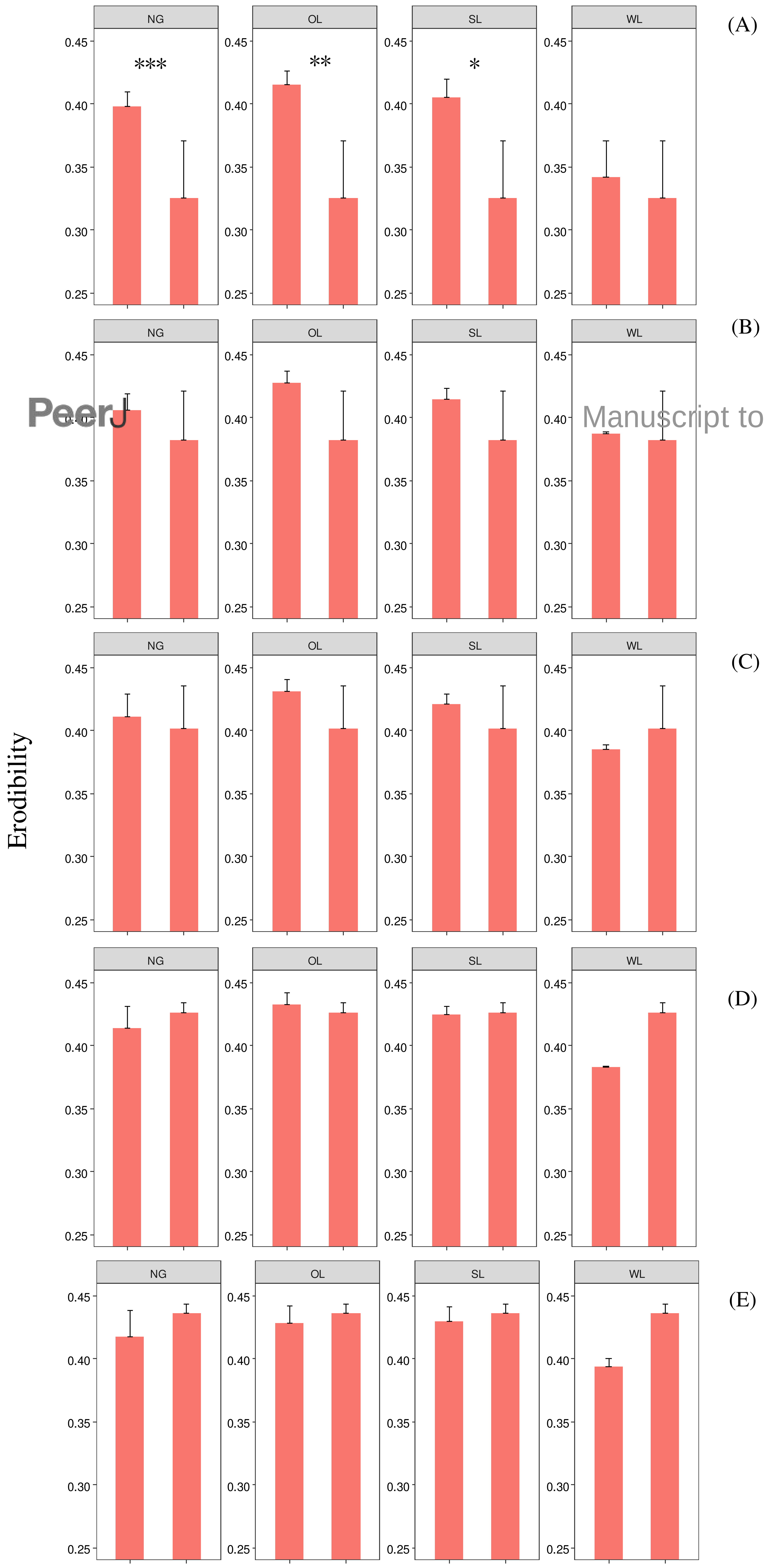

Micro-aggregate fractal dimension
(A)
(B)
(C)
(D)
(E)
NG
OL
SL
WL
*
***
2.70
2.65
2.60
2.55
2.50
3.0
2.9
2.8
2.7
2.6
2.5

Figure 7 (on next page)

The differences of erodibility between the natural forest and various vegetation restoration patterns at each last restoration year.

Note: A: 0-10cm, B: 10-20cm , C: 20-30cm , D: 30-50cm ,E: 50-100cm. * means significant differences between the natural forest and various vegetation restoration patterns at each last restoration year ($P < 0.05$).



(A)
(B)
(C)
(D)
(E)
NG
OL
SL
WL
***
**
*
Erodibility
0.45
0.40
0.35
0.30
0.25

Figure 8 (on next page)

Biplot of the first two RDA axes between the vegetation Rehabilitation patterns, soil depth, restoration time and fractal dimension, erodibility(K factor), TC, TOC, TN, each classes particles and micro-aggregate.

Biplot of the first two RDA axes between the vegetation Rehabilitation patterns, soil depth, restoration time and fractal dimension, erodibility(K factor), TC, TOC, TN, each classes particles and micro-aggregate.

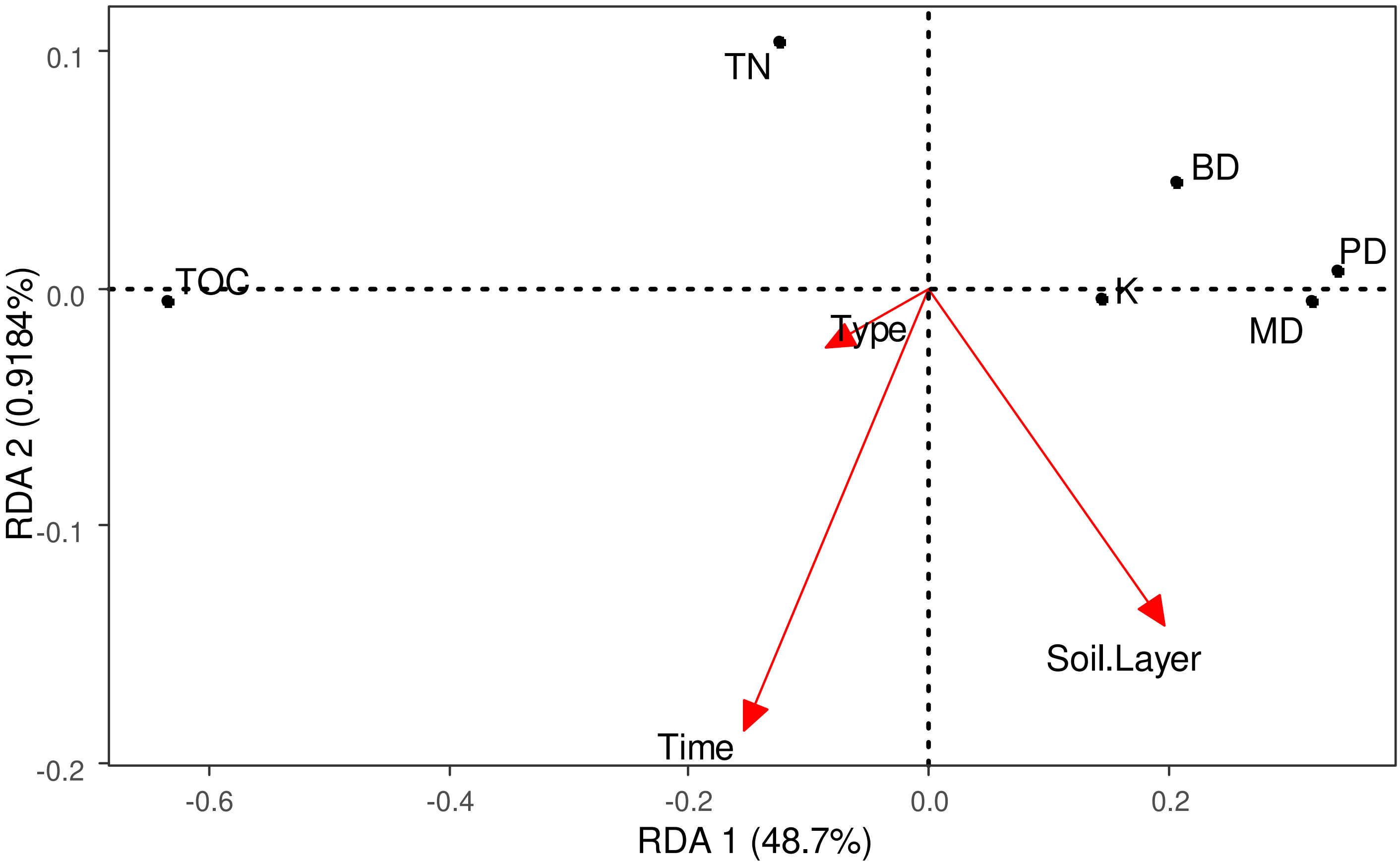

TN
BD
PD
TOC
K
Type
MD
Soil.Layer
Time
0.1
0.0
-0.1
-0.2
-0.6
-0.4
-0.2
0.0
0.2
RDA 2 (0.9184%)
RDA 1 (48.7%)

Table 1 (on next page)

Table 1 Basic information of sample plots

Table 1 Basic information of sample plots

Restoration pattern	Site code	Rehabilitation years (a)	Altitude (m)	Slop(°)	Vegetation coverage（%）	*Understory vegetation types*
CL	AS0	0	1270-1290	17-24	32	*Setaria italica*、*Glycine max*
	AS1	2	1101-1276	13-27	12.1-19.8	*Geranium wilfordii Maxim*，*Artemisia capillaris*，*Parthenocissus tricuspidata*，*Setaria viridis*
	AS2	5	1185-1262	17-19	30.7-57.3	*Artemisia leucophylla*，*Artemisia capillaris*，*Poa sphondylodes*，*Sonchus oleraceus L*，*Lespedeza bicolor Turcz*，*Heteropappus altaicus*
	AS3	8	1235-1276	12-40	18-60.4	*Lespedeza bicolor Turcz*，*Artemisia capillaris*，*Leymus secalinus*，*Potentilla bifurca* ，*Bothriochloa ischaemum*，*Stipa bungeana*，*Dendranthema indicum*
NG	AS4	11	1198-1292	23-37	24-76.3	*Artemisia leucophylla*，*Tripolium vulgare* ，*Lespedeza bicolor Turcz*，*Stipa bungeana*，*Cleistogenes hancei*，*Artemisia capillaris*，*Heteropappus altaicus*，*Setaria viridis*
	AS5	15	1291-1306	14-19	39.8-76	*Tripolium vulgare*，*Lespedeza bicolor Turcz*，*Stipa bungeana*，*Cleistogenes hancei*，*Stipa grandis*，*Heteropappus altaicus*，*Roegneria kamoji*
	AS6	18	1179-1189	22-30	16-49	*Artemisia leucophylla*，*Tripolium vulgare*，*Lespedeza bicolor Turcz*，*Stipa bungeana*，

						Cleistogenes hancei，*Stipa grandis*
	AS7	26	1144-1161	22-28	21.8-68.9	*Artemisia leucophylla*，*Tripolium vulgare*，*Lespedeza bicolor Turcz*，*Stipa bungeana*，*Cleistogenes hancei*
	AS8	30	1149-1293	14-29	33-79.7	*Artemisia leucophylla*，*Tripolium vulgare*，*Lespedeza bicolor Turcz*，*Stipa bungeana*，*Cleistogenes hancei*，*Stipa grandis*
SL	AS9	5	1281-1290	12-21	20-38	*Artemisia argyi*、*Artemisia giraldii*、*Lespedeza bicolor*
	AS10	10	1139-1161	29-32	53-78.4	*Bothriochloa ischaemum* 、*Stipa bungeana*、*Artemisia giraldii*
	AS11	10	1264-1281	14-27	36-57	*Artemisia argyi*
	AS12	20	1185	21	52	*Melica scabrosa*
	AS13	20	1203-1211	21-22	28-53	*Stipa bungeana*、*Artemisia argyi*、*Artemisia giraldii Lespedeza bicolor*
	AS14	30	1128-1139	14-25	21-46.3	*Artemisia argyi*
	AS15	36	1211-1253	20	46-65	*Stipa bungeana*、*Setaria viridis*、 *Artemisia argyi*、*Setaria viridis*、*Artemisia giraldii*
	AS16	47	1181-1241	18-24	49.3-89.6	*Stipa bungeana*、*Artemisia argyi*、*Artemisia*

						giraldii pamp.
WL	AS17	5	1259-1288	22-34	36-56	*Stipa bungeana*、*Artemisia argyi*、*Lespedeza bicolor*
	AS18	10	1161-1227	27.5-33	38-53	*Artemisia argyi*、*Setaria viridis*、*Leymus secalinus*
	AS19	20	1236-1259	17-26	32-42	*Artemisia argyi*、*Setaria viridis*
	AS20	37	1209-1259	30-33	53-65	*Artemisia gmelinii*、*Artemisia argyi*、*Stipa bungeana*
	AS21	56	1170-1175	21-22	49-90	*Stipa bungeana*、*Artemisia argyi*
OL	AS22	5	1207-1226	0		
	AS23	10	1220-1254	0		
	AS24	20	1206-1222	0		
NF	AS25	100	1332-1337	14-29	39-52	*Vittaria flexuosa*、*Syzygium aromaticum*
	AS26	100	1235-1283	23-38	35-70	*Artemisia gmelinii*，*Lespedeza bicolor*，*Vittaria flexuosa*
	AS27	100	1552-1570	28-45	10-28	*Rosa xanthina*，*Vittaria flexuosa*

2

Table 2(on next page)

Table 2 Tests of the soil particle fractal dimension, micro-aggregate fractal dimension, erodibility linkage with time(years since cropland abandonment), Rehabilitation pattern and soil depth

** Indicates a significant difference at the 0.01 level (*P* < 0.01).*** Indicates a significant difference at the 0.001 level (*P* < 0.001).

Source	Particles fractal dimension （PD）		Micro-aggregate fractal dimension （MD）		Erodibility （K）	
	F	*P*	F	*P*	F	*P*
Rehabilitation types	34.111	0.000***	4.901	0.002**	10.007	0.000**
Rehabilitation time	15.283	0.000***	0.943	0.508	5.491	0.000**
Soil depth	3.282	0.012*	0.108	0.98	25.056	0.000**
Rehabilitation time×Rehabilitation types	4.16	0.001***	0.628	0.678	2.127	0.06
Soil depth×Rehabilitation types	0.143	1	0.568	0.867	0.393	0.96
Soil depth×Rehabilitation time	0.278	1	0.321	1	0.379	
Rehabilitation time×Soil depth×Rehabilitation types	0.568	0.933	0.824	0.685	0.349	0.99

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Table 3(on next page)

Table 3 Relationships between particle fractal dimension, micro-aggregate fractal dimension, erodibility and soil nutrients and soil bulk density.

*Correlation is significant at the *P*0.05 level (2-tailed); **Correlation is significant at the *P* 0.01 level (2-tailed) ***

	BD	TOC	TN
particle fractal dimension fractal dimension	0.185**	-0.380**	-0.146**
micro-aggregate fractal dimension fractal dimension	0.018	-0.024	0.048
erodibility	0.410**	-0.658**	-0.399**