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

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

**Background.** The major landscape in the hilly-gully region of the Loess Plateau is greatly affected by vegetation rehabilitation on abandoned cropland. 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 possibly due to the land type of vegetation or to the rehabilitation time. To close this gap, we conducted a long term experiment as follows.

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**Methods.** In this study, we analysed four land types of vegetation rehabilitation (shrub land, woodland, naturally revegetated grassland, and orchard land) with different rehabilitation times and investigated the mechanical composition and erodibility of the soil. Areas of slope cropland and natural forest were selected as controls.

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**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, naturally revegetated grassland and shrub land had lower fractal dimensions of particle size distribution (fractal dimensions of PSD), fractal dimensions of micro-aggregation, and erodibility (K factor) than did cropland. Compared to the positive effects of rehabilitation mainly happened in the topsoil layer at other rehabilitation land type, that of woodland happened in the deeper soil layer. Besides, the indispensable rehabilitation time for the significant improvement of soil condition was shorter at naturally revegetated grassland than that at shrub land and woodland.

**Discussion.** Although rehabilitation time was more influential than was rehabilitation land type or soil depth, the differences among the rehabilitation land types showed that naturally revegetated grassland is the most time-saving rehabilitation vegetation for the Loess Plateau in the conversion from slope cropland, 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 caused the degradation of soil quality but also the destruction of ecosystem function and safety (*Chen & Peng 2000; Zheng et al., 2010; Lian et al., 2013; Borrelli et al. 2017*). 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 to forest and grassland (*Uchida et al. 2005; Chen et al., 2007a; Uchida et al. 2009; Zhang et al., 2011a; Song et al., 2015*). This programme has greatly decreased soil loss (*Zheng & Fen 2006; Chen et al., 2007b*).

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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; Moora et al. 2014; 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; Alagöz & Yilmaz 2009; Xiao et al., 2014; Wang et al., 2016*). Many studies have reported positive impacts of vegetation rehabilitation of sloped cropland on soil conditions and soil resistance to erosion (*Xu et al., 2013; Ziadat & Taimeh 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 *(Bochet & García-Fayos 2004; Ghestem et al. 2014; Fu et al., 2015*). However, local precipitation, 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. Soil erosion, solution transformation and soil-moisture are influenced by soil particle size distribution (PSD) (*Mazaheri & Mahmoodabadi 2012; Yu et al., 2015*). Land use could influence soil structure and physical and biochemical activity through PSD affected by water erosion (*Basic et al., 2004; Su et al., 2004*). Therefore, its variation remains to be characterized for understanding and evaluating soil structure and dynamics and the effects of land use on soil structure. Fractal theory, an effective and reliable tool, can be used to characterize it (*Chen and Zhou, 2013*).

The Loess Plateau of China has been suffering serious soil erosion *(Liu et al., 2007)* mainly caused by the human irrational utilization *(Hu et al., 2017)*. The "Grain for Green" Programs (GGP) launched by Chinese government aimed at reducing soil erosion through replacing degraded cropland with forest and grassland. Since then, a sloped cropland was abandoned and restored naturally and artificially. 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 (Fig. 1) *(Sun et al., 2016a)*. This region has a typical semiarid continental climate with a mean annual temperature of 8.8°C, meaning that

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monthly temperature ranges from 22.5°C in July to 7℃ in January 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 in this area is mainly Huangmian soil, a Calcic Cambisol classified in the WRB reference system *(FAO/UNESCO/ISRIC, 1988)*, originating from wind-blown deposits and characterised by yellow color, absence of bedding, silty texture, looseness, macroporosity, and wetness-induced collapsibility (*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.

The vegetation cover of the Loess Plateau has changed greatly during the historical period; this area was generally occupied by forests and grassland. 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, the land use type in this region changed remarkably by the GGP, sloping cropland 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*). Much of barren lands and degraded croplands with slopes over 15° were rebuilt, accounting for about 14% of hilly Loess Plateau *(Xu et al., 2018)*. Artificially and naturally rebuilt grassland, shrub land, and planted woodland consist of the main land use types in the region.

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In this region, before restoration the soil is weakly cohesive and thus prone to erosion, with erosion modulus of 10,000-12,000 mg $km^{-2}$ $yr^{-1}$ *(Liu, 1999)*. Recently, some soil and water conservation measure such as revegetation have effectively reduced soil erosion and have successfully restored some degraded ecosystems in this area, where the representative vegetation includes woody plants such as *Robinia pseudoacacia*, shrubs as *Hippophae rhamnoides* and *Caragana microphylla* and herbaceous plants such as *Artemisia sacrorum* and *Stipa bungeana (Sun et al., 2016a)*. The wood land area has increased from <5% to >40% since 1980 *(Xu et al., 2018)* (SFig. 1).

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***Sampling and data collection***

Based on the investigation of the history of land use, we selected four types of vegetation rehabilitation of cropland abandoned between July 10 and September 10 in 2011 and 2012, the season in which plant community biomass peaks. The four types were naturally revegetated grassland (with rehabilitation times of 2yr, 5yr, 8yr, 11yr, 15yr, 18yr, 26yr and 30yr), planted shrubland (with rehabilitation times of 5yr, 10yr, 20yr, 30yr, 36yr, 47yr), planted woodland (with rehabilitation times of 5yr, 10yr, 20yr, 37yr and 56yr), and orchard land (with rehabilitation times of 5yr, 10yr and 20yr). All these sites suffering similar farming practices before conversion, and the farmlands had more than 200 years of cultivation history *(Deng et al., 2016)*. Thus, sloping cropland sites were selected as representative of the original condition for the rehabilitation chronosequences of the naturally revegetated grassland, revegetated shrub land, woodland and orchard land. In this area, the climax vegetation is the *Quercus liaotungensis Koidz (Zhang et al., 2011b),* which were naturally regenerated on abandoned land from grassland to shrub land and climax forest (*Q. liaotungensis*) over about 150 years, based on previous research of secondary forests in this area. So, we considered it 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.

The size of the plots were varied with the plant communities to match their spatial distribution: the replicated plots of 20 ×20m were established in each site of planted woodland (*Robinia pseudoacacia*), while the replicated plots of 10 ×10m were established in each shrub land site (*Caragana microphylla*, *Hippophae rhamnoides*) and in each orchard land site. The smaller replicate plots (2 ×2m) were randomly established in each naturally revegetated grassland site (including *Artemisia sacrorum, A. capillaries, A. giraldii, Aneurolepidium dasystachys, Bothriochloa ischaemum, Heteropappus altaicus, Lespedeza bicolor, Stipa bungeana, Setaria viridis*, and other grasses). The plots were separated by at least 50m.

We choose four random sampling to avoid the sampling error. At each sampling plot, after removing ground litter, five soil layers (0-10, 10-20, 20-30, 30-50, and 50-100cm) were separately collected with a soil drilling sampler (4cm diameter). The soil samples from the same layer of the same plot were mixed to form one sample. The samples were divided into two parts and were passed through 2mm screens for removing roots, gravel, and coarse fragments. Then each sample was brought to

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laboratory. 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 (Ding et al., 2019). 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*). There are some differences between the pretreatment methods for determining soil PSD and micro-aggregate. For soil PSD, soil samples were pretreated with 6% $H_2O_2$ and 10% HCL to remove organic matter and carbonates and oxides and were soaked in distilled water for 24 h, then mechanically dispersed with 0.4% Calgon by an ultrasonic bath for 5 min. For micro-aggregate determination, the soil samples were soaked in distilled water for 24 h and mechanically dispersed in ultrasonication for 5 min *(Xiao et al., 2014)*.

***Fractal features***

The fractal dimension of the PSD and micro-aggregation were 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 diameter, $R_i$ is the particle size of subinterval $i$ in the particle size grading, $V(r<R_i)$ is the total volume of soil particles with diameter less than $R_i$, $V_T$ is the sum volume 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:

$$K=\{0.2+0.3\exp[-0.0256SAN(1-0.01SIL)]\}\times\left(\frac{SIL}{CLA+SIL}\right)^{0.3}\times\left(1.0-\frac{0.25C}{C+\exp?(3.72-2.95C)}\right)\times\left(1.0-\frac{0.25C}{SN1+\exp?(-5.51+22.9SN1)}\right)$$

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 (naturally revegetated grassland, woodland, shrub land, orchard land), rehabilitation time (years since sloping cropland abandonment) and soil depth (0-10cm, 10-20cm, 20-30cm, 30-50cm, and 50-100cm) on soil mechanical composition and erodibility.

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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 types of 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.

# Results

Rehabilitation time, and rehabilitation land type had significant effects on the soil PSD fractal dimension and K factor, 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 cropland in all land types. However, PSD fractal dimension, micro-aggregate fractal dimension and erodibility varied among the land types (Figs. 2-4).

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***The rehabilitation pattern in naturally revegetated grassland***

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Fractal dimensions of PSD and K factor began to show greater decreases in naturally revegetated grassland than in cropland at $5^{th}$, $11^{th}$ years, respectively, since cropland 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 naturally revegetated grassland than for the other land types (Figs. 2-4) (STable 1-3). Naturally revegetated grassland did not differ from natural forest in fractal dimensions of micro-aggregation or K factor (20-100cm) over rehabilitation time (Figs. 5-7) (STable 1-3). Linear regression revealed that fractal dimensions of PSD decreased with the number of years since farmland conversion in the 0-50cm (except in 20-30cm) (Figs. 2-4) (STable 1-3).

***The rehabilitation pattern in Wood land***

Fractal dimensions of PSD, fractal dimensions of micro-aggregation and K factor began to show greater decrease in woodland than in cropland in the $10^{th}$,$10^{th}$ and $37^{th}$ respectively since cropland abandonment (Figs. 2-4) (STable 1-3). Over rehabilitation time, woodland did not differ from natural forest in fractal dimensions of PSD (30-100cm) and fractal dimensions of micro-aggregation (0-100cm), K factor in woodland did not differ from natural forest (0-30cm) and even was lower than that in natural forest (30-100cm) (Figs. 5-7) (STable 1-3). Compared to fractal dimensions of micro-aggregation and K factor, fractal dimensions of PSD in this site showed a clear decreasing tend at the all soil layers (Figs. 2-4) (STable 1-3).

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***The rehabilitation pattern in Shrub land***

Fractal dimensions of PSD, fractal dimensions of micro-aggregation and K factor began to show greater decreases in shrub land than in cropland in the $20^{th}$, $36^{th}$ and $30^{th}$ years, respectively, since cropland abandonment, and tended to have significant differences with cropland since then (Figs. 2-4) (STable 1-3). The decreasing trend of fractal dimensions of PSD and fractal dimensions of micro-aggregation occurred in 0-100cm, but it gradually weaken with increasing depth. After rehabilitation, naturally revegetated grassland were also higher than natural forest in fractal dimensions of PSD (0-50cm), fractal dimensions of micro-aggregation (0-30cm) and K factor (0-10cm) (Figs. 5-7) (STable 1-3), and had no difference with that of natural forest at the deep layer. Linear regression indicated that fractal dimensions of PSD decreased with the number of years since farmland conversion in the 0-100 cm (except 30-50cm) (Figs. 2-4) (STable 1-3).

***The rehabilitation pattern in Orchard land***

Fractal dimensions of PSD and fractal dimensions of micro-aggregation showed a trend of lower levels in orchard land than in cropland, but there are no significant differences between them (Figs. 2-4) (STable 1-3). However, K factor in this site didn't decrease after a long-term rehabilitation. Following rehabilitation, fractal dimensions of PSD, fractal dimensions of micro-aggregation, and K factor were significantly higher in orchard land than in natural forest at shallow soil layer (Figs. 5-7) (STable 1-3). Linear regression revealed that fractal dimensions of PSD decreased with the number of years since farmland conversion in the 0-10 cm soil layers (Figs. 2-4) (STable 1-3).

## 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 fractal dimensions of PSD, K factor of the soil in the various rehabilitation land types showed decreasing trends following rehabilitation (Figs. 2-4) (STable 1-3). These changes were mainly due to the large amounts of soil nutrients released by residues and decomposing dead roots, and they promote plant growth and rehabilitation succession (*Guo et al., 2013*). Fractal dimensions of PSD, K factor positively correlated with SOC, and the improvement of mechanical conditions were mainly explained by the soil nutrient levels (Table 3). *S*oil organic matter, as a binding agent, favoured soil structure stabilization and infiltration and protected it from erosion (*García-Orenes et al. 2012*). 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 (*Hodge et al. 2009; 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 (*Zuazo & Pleguezuelo 2009; Wang et al., 2008*).

**Comentario [GP6]:** Discuss in all the sections if there is a relative similitude of the species used in the rehabilitation to the original native vegetation present in the Loess Plateau, and the eventual effects of using other (?exotic) alternative species. Provide also a conclusion about this important point.

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### *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 of 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 naturally revegetated grassland 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 naturally revegetated grassland than for woodland and shrub land. 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, that effectiveness was different from various land types. In naturally revegetated grassland site, the lower vegetation layer was more effective in reducing the kinetic

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energy of rainfall striking the soil surface than the tall vegetation in shrub land and woodland. Owing to the lack of roots at deep soil layer, the naturally revegetated grassland only showed positive effect at the shallowest soil layer (0-10cm). However, due to the stronger stretching ability of the trees roots, woodland site also showed the potential of alleviate soil erosion at deeper layers. The soil loss in orchard land was continued over a long time owing to human disturbances (such as production management and tillage practices) and the absence of surface cover protection. This leads to the breakdown of shallow soil aggregates and the washing away of soil particles by raindrop energy and runoff (*Blanco-Canqui & Lal 2008*; *Wang et al., 2008*).

***Effects of soil depth on soil fractal dimension and erodibility***

In the analysed 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 fractal dimensions of PSD, fractal dimensions of micro-aggregation and K factor in the topsoil than in the subsoil (Figs. 2-4) (STable 1-3). 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 due to the decomposition of vegetation litter and by influence of the

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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 cropland to naturally revegetated grassland, shrub land or woodland, 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 cropland, the natural restoration process of grass represents a more efficient rehabilitation practice than does the planting of other vegetation types. Meanwhile, the woodland 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, but it strongly 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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