The effects of different land uses on soil hydraulic properties in the Loess Plateau, Northern China

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Funding information
National Natural Science Foundation China (NSFC), Grant/Award Numbers: 41701025 and 41471439

Abstract
Some agriculture practices are unsuitable in the northern hilly region of the Chinese Loess Plateau and have resulted in the degradation of the native vegetation ecosystems and unfavorable soil hydraulic properties, which cause serious soil losses. The objective of this study was to ascertain the influence of land use changes on soil infiltration rate and other related soil properties in this region. A total of 90 infiltration tests were run on six different land uses (natural grassland, apple orchard, abandoned apple orchard, farmland wheat, farmland maize, and scrub grassland). For studying the infiltration rate, a triplicate of infiltration tests had been taken using a disc permeameter with different pressure heads. Infiltration rate was high in abandoned apple orchard (10 mm min⁻¹) whereas very low in apple orchard (0.6 mm min⁻¹). The statistical analysis showed that the main soil properties were affected by changes of land use types or vegetation cover. Compared with that in the natural grassland and abandoned apple orchard sites, a notable reduction of soil root biomass, infiltration, and bulk density in apple orchard was recorded. The root image analysis showed that the natural grassland and abandoned apple orchard have strong root systems, that is, root length density 6.97 ± 0.344 cm cm⁻³, root surface area 1.56 ± 0.24 cm² cm⁻³, and average root diameter 0.814 ± 0.24 mm, in comparison with other sites. The limited root length density, root surface area, and average diameter were recorded in apple orchard 0.51 ± 0.03 cm cm⁻³, 0.49 ± 0.12 cm² cm⁻³, and 1.88 ± 0.24 mm. Conclusively, our study suggests that converting farmland apple orchard into grassland or scrubland may change soil hydraulic properties, which may help to reduce soil losses in the Loess Plateau.

KEYWORDS
root image analysis, soil infiltration, soil water characteristic curve, Win-Rhizo

1 | INTRODUCTION

Land use systems and land degradation are a global issue in the 21st century because the degradation of land quality has an adverse influence on agriculture production, agriculture ecosystems, and the quality of human life (Kumar, Huang, Cai, & Miklavcic, 2014). The effects of land degradation on agriculture production lie on the negative changes of the land use systems on-site, where degradation...
occurs (e.g., erosion) and off-site, where sediments are deposited (Kumar et al., 2014). The alteration of land use, primarily through conversion of natural vegetation, may exert a great impact on the various natural phenomenons and environmental processes, and unsustainable agriculture practices may result in degradation of naturally restored plant ecosystems (Yu et al., 2015). Vegetation restoration practice has been carried on the Chinese Loess Plateau from 1999, with the starting project entitled ‘grain for green’ (Kalhoro et al., 2017; Y. Li et al., 2016).

The soil is a heterogeneous mixture of soil particles, soil pores (macro, micro, and meso), dead plant material, soil fauna, and flora. All these factors control changes in the soil characteristics solute transportation (Jarvis & Messing, 1995; Wahl, Bens, Schafer, & Huttl, 2003) and soil loss through erosion (Lavelle, Rouland, Binet, Diouf, & Kersante, 2004). The impact of the different types of plant communities and vegetation restoration on soil are important and active indicators to improve permeability and reduce soil losses (Huang, Tian, Wu, Liu, & Dang, 2016).

Rainfall and infiltration are important sources of water generally in the arid and semiarid parts of the world, particularly in the present study area (X. Y. Li et al., 2011). Accumulative infiltration is needed for agriculture crop cultivation, vegetation restoration, conservation, and sustainable development (Leung, Garg, Coo, Ng, & Hau, 2015). ‘Accumulative infiltration’ has become synonymous with the decreasing of runoff and soil losses (wind and water erosion; X. Zhao, Wu, Gao, Tian, & Li, 2014). Type of vegetation could effect on soil hydraulic properties especially on infiltration rate and soil water characteristic curve (SWCC; Gonzalez-Sosa et al., 2010). Degradation of soil is the indication of soil and vegetation loss, which in turn aggravate soil erosion (Mchunu & Chaplot, 2012). In grassland, root distribution could recover soil physicochemical properties and that is in favor of infiltration rate (Kodesova, Jirk, Kodes, Muhlhanselova, & Zigova, 2011). Indeed, from the last few decades, Chinese government pay more attention to reduce soil losses and initiate many projects (Zhou, Zhao, & Zhu, 2012).

The available published evidence and experiences have shown that the plant restoration has a direct effect on soil losses and affects the soil infiltration rate (Y. Y. Li & Shao, 2006). Soil hydraulic conductivity had a significant effect on water budget (B. Wang, Liu, Xue, & Zhu, 2010), surface and subsurface runoff of water (Ren, Zhu, Wang, & Cheng, 2016), and that associated with soil erosion (Chartier, Rostagno, & Pazos, 2011; Michaelides, Lister, Wainwright, & Parsons, 2009). However, in the field study, unsaturated soil hydraulic conductivity is key component to estimate the flow of solute transportation in soil (Y. Zhao, Wu, Zhao, & Feng, 2013). The number of procedures and methods has been used in measuring infiltration rates and unsaturated hydraulic conductivity, among which disc permeameter (DP) is more common due to being easy to handle, cheap, and less time consuming. DP was designed by Commonwealth Scientific and Industrial Research. It contains a nylon mesh to supply membrane, the water reservoir, and bubble tower, the reservoir connecting each other, which have an open and closed system (Huang et al., 2016). SWCC also play a key role in soil hydraulic function and meanwhile for sustainable agriculture production (Shwetha & Varija, 2015) that showed the interlink between soil water potential and volumetric content. In the forest restored area such as the Loess Plateau, the flow of water is key parameter in terms of management of water resources (Fisher & Binkley, 2013).

Root is also an essential driver of soil structure and soil pore formations (Scholl et al., 2014). The properties of roots (root area, root length density, and average root diameter) were directly correlated with soil pore and structure formations (Jegou, Schrader, Dieselt, & Cluzeau, 2001; Scholl et al., 2014). Many procedure and methods were used to calculate the root characteristics, and among them, computer tomography scanning is more common and is used for the calculation of the distributed roots and also for the evaluation of different root parameters (Himmelbauer, Loisikandl, & Kastanek, 2004).

Chinese Loess Plateau has experienced extensive vegetation restoration. Former studies paid great attention to soil properties (Zhi, Liu, Zhang, & Zhang, 2009), water storage (Chen, Wang, Wei, Fu, & Wu, 2010), plant nutrition, soil quality (Jiao, Wen, & An, 2011), soil aggregation, and plant restoration (Kalhoro et al., 2017), whereas limited research has been conducted to estimate the effect of different land uses on soil hydraulic properties such as infiltration rate, SWCC, root biomass, and related characteristic of roots. Therefore, the present study has been carried out on six different land use systems that are traditionally used as natural grassland, apple orchard, abandoned apple orchard, farmland maize, farmland wheat, and scrub grassland. The main objectives of this study were (a) to provide valuable information on the flow of water as infiltration rate into the soil, (b) to estimate the effect of land use on water holding capacity, soil porosity, and impact on the plant, and (c) to estimate the effect of root biomass of different plant communities on different land uses.

2 MATERIALS AND METHODS

2.1 Research study area

Field experiments were conducted in the Agriculture Ecological Experimental Research Station of Chinese Academy of Science. Changwu County of the Chinese Loess Plateau is located in the southern part of the Loess Plateau (107° 40′–107° 42′ E and 35° 12′–35° 16′ N) and covering an area of 525 km² with altitude between 946 and 1,226 m (Figure 1), whereas mean annual rainfall 582 mm occurred between May and September. The mean annual temperature was 9.20°C. Before the start of the field experiment, field survey visits were conducted to generate basic data that are related with land uses, and finally, six types of different land uses were selected, and the study sites were labeled as natural grassland (NGL), scrub grassland (SGL), apple orchard (AO), abandoned apple orchard (AAO), farmland wheat (Fw), and farmland maize (Fm), which were distributed within 2-km radius. The historical information was collected from the local farmers at the time of soil sampling, detail of which is described as follows: NGL, before the year 2000, the land was used as apple orchard; however, during 2000, all the standing apple plants were removed from the field, and it is natural grassland since the last 15 years. SGL, it is situated on the high slope
and with high water erosion particularly during monsoon; therefore, the land was not in use since the last 20 years. AO, in 2006, apple tree plant was established since then as an apple orchard, but before, this land was used as crop cultivation (wheat, maize, and millet). AAO, before 1999, the land was utilized as apple orchard; however, since the last 16 years, the apple utilization has been abandoned. Flw, presently, the land has been used for the cultivation of wheat, but 4–5 years ago, the land was utilized as an apple orchard. Fim, for the last 20 years, the land has not been recycled and used as the cultivation of maize crop. Overall, the allocated sites had been utilized for more than 15 years except for AO, which became a newly established apple orchard 8 years ago.

2.2 | Field experiment and soil sampling

Three plots were selected in each site with 108 soil core sample collected at 0–10, 10–20, 20–30, 30–40, 40–50, and 50–60 cm of the soil layer. Stainless auger and steel rings (5 cm in diameter and height) were used to calculate soil physicochemical properties, such as soil particle size distribution (sand, silt, and clay), soil organic matter (SOM), SWCC, soil total porosity (STP), and soil bulk density (BD). Collected soil samples were transported to the laboratory for further analysis. After being placed in water for 12 hr, the wet and dry weight of the soil samples were noted to calculate the STP (%). After 24 hr of oven drying at 105°C, soil BD was determined (Goossens & Buck, 2009; Himmelbauer et al., 2004; Shwetha & Varija, 2015). STP and SOM were determined by international procedures and calculated by the following formulas George, Rolf, and John (2013).

\[
\text{Soil Total Porosity (STP)} = \left(1 - \frac{BD}{ds}\right) \times 10, \tag{1}
\]

\[
\text{Bulk Density (BD)} = \frac{W}{V}, \tag{2}
\]

where BD is the bulk density Mg m\(^{-3}\), ds is the soil particle density (equal to 2.56, in this study), W is the oven dry weight of sample, and V is the sample volume cm\(^2\).

\[
\text{Oxidizable Organic Carbon (\%)} = \frac{V_b - V_s \times 0.3 \times M}{W_t}, \tag{3}
\]

\[
\text{Total Organic Carbon (\%)} = 1.334 \times \text{Oxidizable Carbon}, \tag{4}
\]

\[
\text{Organic Matter (\%)} = 1.724 \times \text{Total Organic Carbon}, \tag{5}
\]

where \(V_b\) and \(V_s\) are the volume of blank sample and volume of soil sample, 0.5 M is the molarity of \((\text{NH}_4)_2\text{SO}_4\) and FeSO\(_4\)\(\cdot\)6H\(_2\)O, used titration of \(V_b\) and \(V_s\), and \(W_t\) is the soil sample weight.

2.2.1 | Sampling procedure for root image analysis

Intact soil core sample was collected using steel ring of 10 cm in diameter of length and height at six different soil layers 0–10, 10–20, 20–30, 30–40, 40–50, and 50–60 cm in depth. Carefully, plant roots were separated from attached soil particles. Roots were washed and surface dried with blotting paper. Finally, root images were taken by using the Epson Perfection V700 Photo Scanner (Seiko Epson Corporation, Nagano, Japan) preceded by the computer software Win-Rhizo, 2009, to measure the root diameter (root length density, root surface area, and average root diameter; Himmelbauer et al., 2004).

2.2.2 | Measurement of infiltration rate from different land use

On each site triplicate infiltration, experiments were carried by using the DP (Figure 2). Before the experiment, soil surface was cleaned and covered with fine sand; standing plants were trimmed with scissors, and then infiltration was tested using different pressure
heads of 0.53, 0.63, 0.82, 1.12, and 1.17 kPa, and the flow of water was recorded in the time intervals of 10, 20, 30, 40, 50, 60, 70, 80, 90, 120, and 150 s and then intervals of 3, 4, 6, 9, 12, 15, 18, 21, 24, and 27 min under stable conditions and calculated in the following formula after the observation of three continual tests in similar infiltrated flow in soil (Huang et al., 2016).

\[
f_s = \frac{\Delta h D_1^2 \times 10^{-4}}{\Delta t D_2 (0.7 + 0.03T)}.
\]  

where \( f_s \) = 10°C standard water temperature infiltrations rate (m s\(^{-1}\)), \( D_1 \) is the effective diameter of infiltrated disc (cm), \( D_2 \) is the water storage pipe diameter (cm), \( \Delta h \) is the difference between the readings of water, \( \Delta t \) is time period (min), and \( T \) is the average water temperature (°C) for a given period of time.

### 2.2.3 Soil water characteristic curve

The Hitachi CR21G, a high-speed centrifuge, was used to analyze SWCC with pressure heads ranged from 10.2 to 10,200 cm. Hitachi CR21G automatic maintained the air temperature at 20°C. The high-speed centrifugal force was applied to the saturated sample. The pressure head consecutively increased with rotation speed. The pressure head (cm), rotation speed (r s\(^{-1}\)), and time period (min) were measured and recorded at the same time. Furthermore, Table 1 showed the tested pressure heads, with equilibrium to rotation speed and time period.

### 2.3 Data analysis

Analysis of variance was used to estimate the effect of the different land uses on infiltration rate, SWCC, root biomass, and related soil properties, with mean and standard errors. The significant difference between the data was calculated at \( p \leq 0.05 \) probability using STAT 8.1 version.

### 3 RESULTS

#### 3.1 Characteristics of basic soil properties

Triplicate data of the soil particle size (sand, silt, and clay) distribution for different land uses are presented in Table 2. The observation results show that soil textures were silty-loam at the different depth of layer through the whole soil profile of 0–60 cm for different land uses (Table 2). The BD of surface soil is lower than that of subsurface soil layers, with an average of 1.2 Mg m\(^{-3}\) across all study sites and throughout the whole soil profile of 0–60 cm but except for Flw 1.48 ± 0.18 at 20–30 cm of soil depth (Table 2). The RB of NGL at depth of 0–10 cm is higher than in other study sites, whereas RB is higher in Flw than Flm (Table 2), and the lowest RB was recorded in AO with comparison of all other sites (NGL, SGL, AAO, Flw, Flm, and AO) in a decreasing order (Table 2). The result is different in soil layers, although this is statistically nonsignificant (\( p \leq 0.05 \)). STP was ranging from 42% to 65% and decreased with soil depth (Table 2). Mostly, the maximum STP was observed in AAO at 0–10 cm of the soil layer. Overall, the ascending order of STP under different land uses was Flm, AO, Flw, SGL, NGL, and AAO respectively at 0–10 cm of soil layer. BD and SOM are the most important soil physicochemical properties and have an effect on soil hydraulic properties, mainly on soil permeability and SWCC. The maximum SOM was recorded in NGL, about 3.2 ± 0.09% at 0–10 cm of soil. The SOM content of Flw was higher than that of Flm, and AAO was higher than that of AO in every layer of soil (Table 2); the results were different and varied with soil layers (0–60 cm), though this was not found statistically significant (\( p \leq 0.05 \)).

#### 3.2 Infiltration rate in different land uses

The infiltration rate for different land uses showed that it was significantly different among land uses (Figure 3). Increasing pressure caused a decrease in the infiltration rate with the lowest infiltration rate recorded in AO at 1.71 kPa and the maximum infiltration rate in NGL and AAO at 0.53 kPa among all applied pressures, that is, 0.53, 0.63, 0.82, 1.12, and 1.71 kPa and in all study sites (Figure 3).
infiltration rates recorded in NGL, AAO, and SGL were more noticeable than all others whereas an ascending order was recorded as AAO, SGL, NGL, Flm, Flw, and AO (Figure 3).

### 3.3 Root image analysis

The analysis result of root images is presented in Figure 4 with the root images categorized as root length density cm$^{-3}$ (RLD), root surface area cm$^2$ cm$^{-3}$ (RSA), and average root diameter mm (ARD; Stokes, Atger, Bengough, Fourcaud, & Sidle, 2009). The maximum root RLD, RSA, and ARD were recorded in NGL $69.7 \pm 0.344$ cm$^{-3}$, $1.56 \pm 0.24$ cm$^2$ cm$^{-3}$, and $0.814 \pm 0.24$ mm in comparison with other land use at 0–10 cm depth in the soil profile (Figure 4). The minimum results were recorded in AO $0.51 \pm 0.03$ cm$^{-3}$, $0.49 \pm 0.12$ cm$^2$ cm$^{-3}$, and $1.88 \pm 0.24$ mm among Flm, Flw, and SGL at 0–10 cm depth in the soil profile. The results of root parameters were decreased with increase in the depth of soil layers. So different land uses and the depth of soil layers may have different root characters (Figure 4), though not statistically significant ($p \leq 0.05$).

### 3.4 Soil water characteristic curve

The result of SWCC is presented in Figure 5 and showed that the maximum soil water content ($\theta_r$) at 0–10 cm of soil depth were recorded in SGL $0.45 \pm 0.01$ (at 0 pressure head and 240 min for saturation period), and at the same soil depth, the minimum of soil water content was recorded in Flm $(0.04 \pm 0.001)$ with the time interval of 90 min under the pressure head of 10,200 cm (Figure 5). Furthermore, the water content ($\theta_r$) decreases with an increase of pressure head and time period. In comparing Flm and Flw, Flw has greater water content under the same pressure head (Figure 5). The results also indicated that SWCC at different depths of layers 0–10, 10–20, 20–30, 30–40, 40–50, and 50–60 cm are impartially similar. The results are also different in soil layers under different land use systems (Figure 5).

### 4 DISCUSSION

The degradation of soil leads to the loss of vegetation, which in turn worsens the soil erosion (wind and water). The change in land use...
systems, primarily through conversion of natural vegetation, may employ a great influence on various natural environmental processes, and unsuitable agriculture practices may result in the degradation of the naturally restored plant ecosystems. The study showed that soil hydraulic properties were considerably improved on slopes in NGL, SGL, and AAO after the land was abandoned for 15–18 years. This has also been realized in many studies (Kalhoro et al., 2017; Y. Zhao et al., 2013). The changes of the infiltration rate are directly correlated with vegetation feature and soil property (Neris, Jimenez, Fuentes, Morillas, & Tejedor, 2012). The changes could increase the percentage of SOM in the soil, which develop soil structure and soil porosity. The same type of experiments have been conducted and revealed that grassland had a higher infiltration rate than cropland (Huang et al., 2016). Similar findings were observed in NGL, AAO, and SGL that the higher amounts of SOM play a major role in improving infiltration status (Yuksek & Yuksek, 2011). Furthermore, the formation of macropores, root channels, and preferential flow paths could reduce the runoff water and water erosion (Bargues et al., 2014). Such kind of changes was also observed in some studies (King & Bjorneberg, 2012) partially in line with our findings (Liu, Fu, Lu, Wang, & Gao, 2012) that the BD is slightly higher in farmland as compared with NGL, AAO, and SGL (Table 2). We assume that soil hydraulic conductivity and mainly soil infiltration rate play a major role in the soil physicochemical properties, due to much variations of vegetation cover for different land uses with more vegetation in NGL, AAO, and SGL and less in AO, Flm, and Flw.

SWCC shows the connection between water suction and water content of an unsaturated field. It is an important factor for analysis and soil behavior (Gens, 2010; Nuth & Laloui, 2008). The observation of this study shows that water retention curves of different land uses are fairly similar in terms of soil depths. The results are slightly significant with regard to different land uses, that is, NGL, SGL, AO, AAO, Flm, and Flw at the high-pressure head (Figure 5). The similarity may be due to the similar weather and environmental conditions (at least in the present study period) for different land uses, but the main cause might be that soil structure and texture are the leading aspects of the water suction controlling the water retention (Manoli et al., 2014). Many researchers have observed that NGL, SGL, and abandoned lands had more macropores than cultivated land (Tarantino, 2010), which is consistent with our findings that the NGL and SGL is in favor of the formation of macropores and root channels by the activity of soil fauna and decayed plant roots (Moore, Burch, & Wallbrink, 1986) and that they had more air capacity whereas farmland had less macropore (Schwarzel et al., 2011), mainly due to tillage operations that possibly destroyed the root channels and mainly caused the formation of macropores (Cai et al., 2015; Y. Wang, Fan, Cao, & Liang, 2015).

Root image analysis is an important and commonly used method for examining roots. Computerized root image analysis provides more data such as RLD, RSA, and ARD at different angles and compared with other methodologies. The diameter of roots is important for agricultural ecosystems (Sadeghi, Vangah, & Safaeeian, 2007). The growth
of roots is important for soil porosity (Banger, Kukal, Toor, Sudhir, & Hanumanthraju, 2009). Being used for soil microorganisms and their populations (Loranger, Ponge, Blanchart, & Lavelle, 1998), the root growth and its distribution play a key role for enhancement of soil physicochemical properties (Goss, 1991). The results of RLD, RSA, and ARD were recorded in a descending order as NGL, AAO, Flw, Flm, SGL, and AO. The decayed and growing roots are the primary pool for SOM in the soil. The diameters of roots and SOM are taken as the primary supporting factors playing a major role in the soil hydraulic properties, particularly for soil infiltration rate and SWCC (Poeplau et al., 2011). Better infiltration rate and SWCC recorded in NGL and SGL compared with other land uses (Figures 4 and 5) were associated with more SOM and root biomass (Table 2) as revealed by other researchers (Huang et al., 2016; Mamedov, Huang, Aliev, & Levy, 2017; Poeplau et al., 2011; Y. Wang et al., 2015; Yu et al., 2015). There are limited RLD, RSA, and ARD in AO compared with

**FIGURE 4** Infiltration rate of different land uses of NGL, AO, AAO, Flm, Flw, and SGL, the mean results in triplicate with standard errors and with applied different pressures (0.53, 0.63, 0.82, and 1.12 kpa). AAO: abandoned apple orchard; AO: apple orchard; Flm: farmland maize; Flw: farmland wheat; NGL: natural grassland; SGL: scrub grassland [Colour figure can be viewed at wileyonlinelibrary.com]
NGL, AAO, SGL, FLm, and Flw, which we assumed is due to farmers practice during crop growth as all types of vegetation have been removed from the soil surface to maintain a clean field. All land use system showed different correlate relationships with root parameters. Generally, SOM has significantly ($p \leq 0.05$) positive correlation with root parameters such as RB, RLD, RSA, and ARD in all land use systems except in scrub grassland followed by apple orchard. Similarly, STP has a positive correlation with root parameters in apple orchard, abandoned apple orchard, and scrub grassland. However, it has a nonsignificant and negative impact on root parameters in farmland maize and farmland wheat, respectively. Likewise, soil texture (silt, clay, and sand) has no any significant correlation with natural grassland and apple orchard land use. But in case of an abandoned apple orchard, farmland wheat, and scrub grassland, silt showed a
negative correlation with root parameters. The changes in the correlation among the soil properties (SOM, STP, BD, RB, and related soil properties) indicated that soil factors have a significant effect on soil hydraulic properties.

5 | CONCLUSION

Usually, vegetation restoration is a promising approach to control soil losses, especially in areas such as the Chinese Loess Plateau. The observation of this study showed that plant roots of different communities could be effective factors in improving soil hydraulic properties and controlling soil losses. The dense root growth system is highly effective for favorable soil infiltration rates and many other related soil properties (such as SOM, root biomass, soil moisture content, and flow of water). The positive effect of different plant communities on surface and subsurface soil layers were observed in natural grassland, abandoned apple orchard, and scrub grassland compared with farmland wheat and maize. The considerably improved soil infiltration was mainly attributed to the perfection of soil particle distributions, soil porosity, and root mass density.

Root image analysis shows that the root system (root biomass, root length density, root surface area, and average root diameter) of natural grassland, abandoned apple orchard, and farmland wheat occupied more space than apple orchard and farmland maize. In conclusion, this study suggests that the transformation of different land uses is important for improving soil hydraulic conductivity and mitigating soil and water losses in the Chinese Loess Plateau, particularly for cultivated cropland.

ACKNOWLEDGMENTS

The authors wish to thank the National Natural Science Foundation of China for financial support to this study under the project (41471439 and 41701025). We also thank to Changwu State Key Laboratory of China (NSFC) for financial support to this study under the project (41471439 and 41701025). We also thank to Changwu State Key Laboratory of China (NSFC) for financial support to this study under the project (41471439 and 41701025). We also thank to Changwu State Key Laboratory of China (NSFC) for financial support to this study under the project (41471439 and 41701025). We also thank to Changwu State Key Laboratory of China (NSFC) for financial support to this study under the project (41471439 and 41701025). We also thank to Changwu State Key Laboratory of China (NSFC) for financial support to this study under the project (41471439 and 41701025). We also thank to Changwu State Key Laboratory of China (NSFC) for financial support to this study under the project (41471439 and 41701025). We also thank to Changwu State Key Laboratory of China (NSFC) for financial support to this study under the project (41471439 and 41701025). We also thank to Changwu State Key Laboratory of China (NSFC) for financial support to this study under the project (41471439 and 41701025).

CONFLICT OF INTEREST

All authors have declared that no competing of interest exists.

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