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Evaluating aggregate stability of soils under different plant species in Ziwuling Mountain area using three renowned methods

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A R T I C L E I N F O

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A B S T R A C T

Soil stability is a characteristic property and is frequently used as an indicator of soil quality. Considering the large variation among stability tests, existing studies usually employ more than one stability test in order to better understand soil behavior against various disruptive forces. The main purposes of this study were to evaluate the impact of aggregate disruptive mechanisms (slaking, clay swelling, mechanical breakdown, and cavitation) on soils developed under different plant species. We aimed as well to compare the results of three renowned soil stability methods: modified Yoder (Yod), Le Bissonnais (LB) and Ultrasonic agitation (UA) on surface (0–20 cm) and subsurface (20–40 cm) soils. Overall, soils of three plant communities developed under eight plant species were investigated. These include forestland (*Quercus wutaishansea, Pinus tubulaeformis, Platycladus orientalis*, and *Robinia pseudoacacia*), shrubland (*Sophora viccifolia*, *Hippophae rhamnoides*, and *Rosa xanthina*) and grassland (*Stipa bungeana*). The mean weight diameter (MWD) was used as a stability parameter for modified Yoder's and Le Bissonnais' methods. In contrast, specific dispersion energies (SE) at the initial (10%, w/w), middle (50%, w/w) and final (90%, w/w) stages of aggregate disruption were used as stability parameters by the UA method. The results of MWD (Yod) indicated that surface and subsurface soils were in the range of 1.23–2.86 mm, which accounted for medium (0.8–1.3 mm) to very stable (>2 mm) soils. Among the three LB tests (fast wetting (FW), slow wetting (SW), and wet stirring (WS)), the order of aggregate disruption was FW > WS > SW, suggesting that FW was the most destructive among the three tests with the lowest MWD value (0.45 mm, unstable soil). SW showed the highest MWD values (0.82–2.82 mm), and most of the soils were ranked in the stable (1.3–2 mm) to very stable (>2 mm) range. The MWD trend of WS was similar to FW test. Although the range of SE at three levels was different: SE_{10} (8.1–29.4 J g^{-1}), SE_{50} (53.0–193.4 J g^{-1}), and SE_{90} (176–642 J g^{-1}), they all showed a similar association with soil characteristics and stability parameters of other tests. The strong positive correlation of soil organic carbon (SOC), total nitrogen (TN), fine root biomass (FRB), and clay contents, and the negative correlation of soil water content (SWC) with the five tests, indicated that these five factors were the major characteristics responsible for the resistance of the studied soils against different destructive mechanisms ($p < 0.05$–0.01). Overall, the results of all five tests indicated that soil under *Quercus wutaishansea* (QW) was the most stable, while that under *Robinia pseudoacacia* (RP) was the most unstable. Although all methods were based on different breakdown mechanisms, initial and final soil fractions and parameters, they were strongly positively correlated with each other. This indicated that all these tests were equally good at stability assessment, with some distinctions and limitations.

1. Introduction

Soil stability is a vital structural characteristic that directly and indirectly affects many other soil quality parameters (Karami et al., 2012). The fact that soil stability is interlinked with many other soil characteristics makes it a unique and complex marker in predicting the qualitative value of soils. Plant communities influence soil stability directly through litter decomposition, binding materials, nutrient contents, and microbial interactions, as well as indirectly by controlling other properties, such as porosity, soil water content, soil temperature, and bulk density (Zhang et al., 2017). SOC is firmly believed to have a positive association with the aggregate stability of soils, especially

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macro-stability (Xiao et al., 2020).

Owing to the complexity of evaluating the stability of soils, many researchers have introduced various indices, tests and methods (Amézketa, 1999). Meanwhile, many studies have emphasized using more than one test for better soil stability assessment, especially when there are soils with distinct soil characteristics and stability status. The modified Yoder is the most classical soil stability method based on the comparative quantity of aggregates > 250 mm in size (macro-aggregates). Therefore, this method addresses the quantitative stability of soil (Kemper and Rosenau, 1986). Another ISO (International Organization for Standardization) certified method, Le Bissonnais (commonly known as the LB method) was selected because of its significance as a precise stability method. The LB method is equipped with three subtests (fast wetting, FW; slow wetting, SW; wet stirring, WS), which are based on the condition of soils subjected to various rainfall intensity levels (Le Bissonnais, 2016). The Loess Plateau region of China (LPC) is known to cause severe soil erosion. Several aggregate stability assessment studies have been conducted so far, and most of them used the modified Yoder method (Liu et al., 2014; Kalhoro et al., 2017). Few of them had adopted Le Bissonnais' method and found it quite useful, especially for erosion-based studies (Liu et al., 2013; Wang et al., 2014; Xiao et al., 2018; Zeng et al., 2018). Similarly, two studies used the ultrasonic agitation method to estimate the ultrasonic soil aggregate stability (USAS) index (An et al., 2009, 2010). None of the existing studies have estimated the true dispersion energy required to disrupt aggregates. Ultrasonic agitation has been used for decades since it has been proven that soil stability can be assessed by a soil and water mixture (North, 1976; Raine and So, 1993; Field and Minasny, 1999). The characteristics that make this method unique among the other stability methods are that post-sonification material (soil–water suspension) could be used for other physicochemical analyses, as no chemical agent is required to perform sonification (Ashman et al., 2009; Schomakers et al., 2011). Furthermore, it accounts for the dispersion energy used for aggregate disruption (Raine and So, 1993; Almajmaie et al., 2017). The dispersion energy is related to the relative strength of soils; therefore, it compares soils based on the energy used for soil disruption (Kaiser et al., 2012; Gyawali and Stewart, 2019). To compare the soil stability based on dispersion energy, Field et al. (2006) outlined the critical energy (E_{crit}) required to initiate the dispersion of liberated aggregates for evaluating the aggregate hierarchy. Some studies also used the specific dispersion energy (SE) as a stability parameter at a specific predefined percentage level of aggregate disruption, that is, $SE_{50,}$ the dispersion energy point where 50% (w/w) of soil aggregates were dispersed. These few studies used SE values ranging from SE_{10} to SE_{98} (North, 1976; Fuller and Goh, 1992; Raine and So, 1993; Fristensky and Grismer, 2008; Zhu et al., 2009b). All these studies calculated the SE based on various aggregate fraction classes, but none used MWD. In this study, we calculated SE at three key stages of aggregate disruption: initial 10% (w/w), middle 50% (w/w), and final 90% (w/w, after which there was no more or minute dispersion) stage of dispersion. Many researchers have compared various soil stability methods, such as the modified Yoder with Le Bissonnais (Zeng et al., 2018; Duan et al., 2021) and ultrasonic agitation with a modified Yoder (Zhu et al., 2017; Abbas et al., 2021). However, none have been published that compare these three stability methods (Yod, LB, and UA) in tandem. This may be due to their major methodological differences. Therefore, we selected these three methods and five tests to investigate their relative impact on the stability of eight soils and to study their interaction with each other, despite the fact that all methods were based on different stability parameters and different initial and final fraction classes. The specific objectives of the study were i) to investigate the influential role of soil characteristics on soil stability and their interaction with breakdown mechanisms, ii) to evaluate the effect of soils with different plant covers (species) and depths (0–20 and 20–40 cm) on soil stability, and iii) to compare the aggregate stability results obtained by different stability methods and tests.

2. Materials and methods

2.1. Study area

This study was conducted on the Ziwuling Mountains, Fuxian County, Shaanxi Province, China (33°50–36°50 N, 107°30–109°40 E) (Fig. 1). Ziwuling is considered one of the most forest-populated areas of the Loess Plateau of China (LPC) region, which covers an area of 23,000 km^2 (Yuan and Yue, 2012). The region is also known for severe and frequent thunderstorms, which can cause soil degradation. Conserving the soils of this area could eventually lead to the conservation of the LPC region (Kang et al., 2014). Most soils in this region are categorized as Calcic Chernozems (FAO taxonomy).

2.2. Soil sampling

To compare the various aggregate stability tests and evaluate the effect of different soil characteristics (i.e., organic carbon, total nitrogen, fine root biomass, and soil texture) on aggregate breakdown mechanisms, we selected soils with three dominant vegetation types under eight different plant species in the Ziwuling Mountain area. Basic information is presented in Table 1, including the topographical features of the sampling sites. The experimental design included four forest soils (i.e., *Quercus wutaishansea* (QW), *Pinus tabuliformis* (PT), *Platycladus orientalis* (PO), and *Robinia pseudoacacia* (RP)), three shrub soils (i.e., *Sophora viccifolia* (SV), *Rosa xanthine* (RX), and *Hippophae rhamnoides* (HR), and one grass soil (i.e., *Stipa Bungeana* (SB)). For the collection of soils, fine roots, bulk density, and other basic topographical information, 12 plots (i.e., four plant species and three field replicates) with a size of 20 m × 20 m for forest soil, nine plots (5 m × 5 m) for shrub soils, and three plots (1 m × 1 m) for grass soils were selected. In August 2019, we collected soil samples at the surface (0–20 cm) and subsurface (20–40 cm) layers using aluminum boxes with dimensions of 19 × 11 × 4.5 cm. For the calculation of bulk density (BD), the ring-cutting method was used, as outlined by Wang et al. (2016). Fine roots with a diameter < 2 mm were collected by screening them through a tray filled with water (Deng et al., 2014).

2.3. Analysis of the soil physical and chemical characteristics

Initially, the collected fresh soil samples were air-dried at room temperature for 48 h, and then passed through a 10 mm sieve to separate litter and root debris. Soil pH was determined using a mixture of soil and water with 0.01 M $CaCl_2$. SOC was measured using the $K_2Cr_2O_7$ wet oxidation method (Nelson et al., 1979). Total nitrogen (TN) was analyzed using element equipment, while total phosphorus (TP) of the soil was determined calorimetrically using a spectrophotometer (UV 2800) following a wet digestion procedure (Nelson et al., 1979). Soil water content (SWC) was calculated using the oven-drying method (Dou et al., 2020). Soil particle size distribution was measured using a laser diffraction instrument (Mastersizer 2000, Malvern Instruments, Malvern, England), and soil textural classes were determined based on the comparative percentages of clay, silt, and sand (USDA taxonomy), as reported by Zeng et al. (2018).

2.4. Soil aggregate stability assessed by modified Yoder method

The macro- and microaggregates of the soils were segregated by the modified Yoder's method with a set of five sieves <0.25, 0.25–0.5, 0.5–1, 1–2, 2–5, and >5 mm, respectively (An et al., 2013). Following dry sieving, a 50 g soil sample was taken on a percentage basis for wet sieving. Later, the water level of the sieving-column containing bucket was adjusted so that the top sieve was fully submerged in the water. Prior to the oscillation process, the soil samples were placed over the top sieve and submerged in deionized water for 5 min. Afterward, the staking sieve column was vibrated at a speed of 30 cycles/min for 1 min.

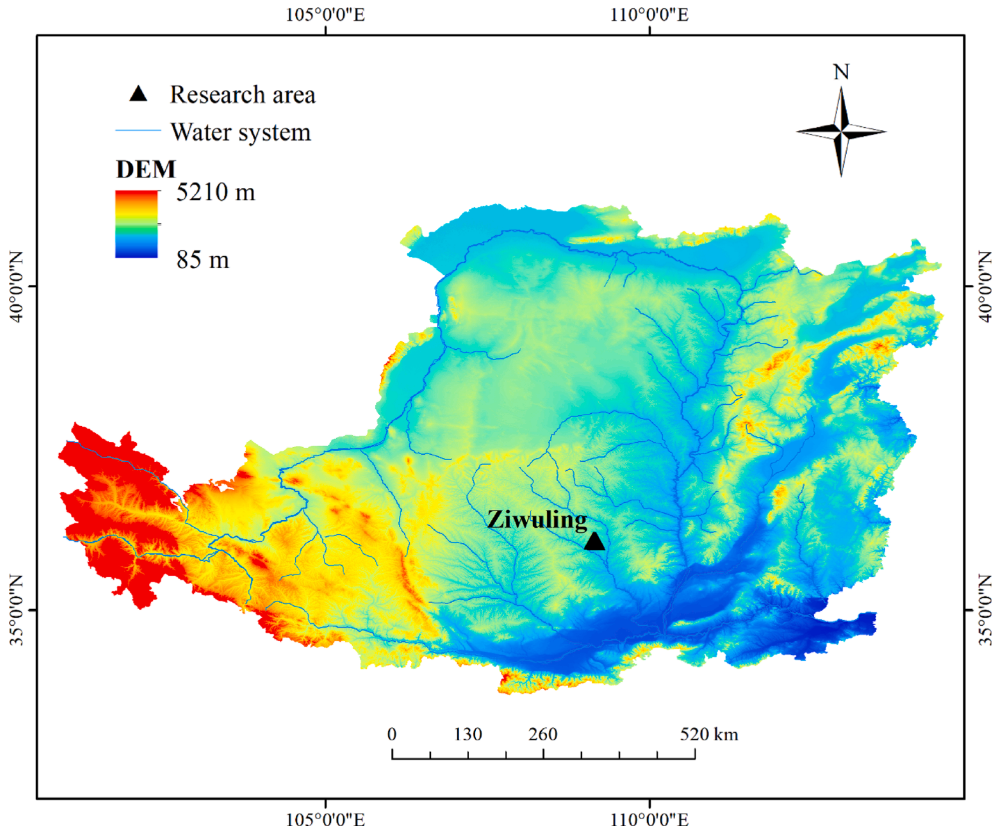

Fig. 1. Location of the sampling site.

Table 1
Basic information of sample site in the Ziwuling Mountains.

Vegetation types	Plant species	Abbr.	Plot No.	Longitude	Latitude	Altitude (m)	Slope (%)	MPH (m)	P.DBH (cm)
Forest land	*Quercus wutaishansea*	QW	1	109° 8′ 24″	36° 4′ 48″	1269	14	8.74	60.4
			2	109° 9′ 0″	36° 5′ 24″	1240	12	8.33	55.4
			3	109° 8′ 24″	36° 4′ 48″	1272	21	10.71	63.4
	Platycladus orientalis	PO	1	109° 8′ 24″	36° 3′ 36″	1298	25	9.69	24.6
			2	109° 8′ 24″	36° 3′ 36″	1298	25	8.67	37.4
			3	109° 8′ 24″	36° 3′ 36″	1298	25	6.63	38.2
	Pinus tabuliformis	PT	1	109° 10′ 12″	36° 4′ 1″	1170	17	7.59	57
			2	109° 11′ 24″	36° 2′ 60″	1180	25	9.70	52.2
			3	109° 10′ 48″	36° 2′ 60″	1175	20	10.20	51.8
	Robinia pseudoacacia	RP	1	109° 8′ 24″	36° 4′ 12″	1110	10	9.79	39.2
			2	109° 8′ 24″	36° 4′ 48″	1115	15	10.71	39
			3	109° 8′ 24″	36° 4′ 12″	1111	14	9.18	35.6
Shrub land	*Sophora viccifolia*	SV	1	109° 10′ 12″	36° 4′ 48″	1098	32	1.30	89.2
			2	109° 10′ 48″	36° 4′ 48″	1149	35	1.71	104.2
			3	109° 10′ 48″	36° 4′ 48″	1115	42	1.50	86.5
	Rosa xanthina	RX	1	109° 10′ 48″	36° 4′ 48″	1218	11	1.60	152.2
			2	109° 10′ 48″	36° 4′ 48″	1234	22	1.51	131.6
			3	109° 10′ 12″	36° 4′ 48″	1222	23	1.88	160
	Hippophae rhamnoides	HR	1	109° 9′ 0″	36° 3′ 36″	1306	10	2.10	128
			2	109° 9′ 0″	36° 3′ 36″	1288	15	2.09	145
			3	109° 9′ 0″	36° 3′ 36″	1274	12	1.81	138
Grass Land	*Stipa Bungeana*	SB	1	109° 9′ 0″	36° 3′ 36″	1294	11	–	–
			2	109° 9′ 0″	36° 3′ 36″	1310	11	–	–
			3	109° 9′ 0″	36° 3′ 36″	1306	13	–	–

MPH, stands for mean plant height; P.DBH, stands for mean plant diameter at breast height.

All fractions were dried at 70 °C for 8 h and then weighed. The mean weighted diameter (MWD) of water-stable aggregates was calculated as follows:

$$MWD = \sum_{i=1}^{n} \omega_i x_i$$

where ‘x_i’ is the mean diameter of each size fraction and ‘ω_i’ is the proportional weight of the corresponding size fraction (Kemper and Rosenau, 1986).

2.5. Soil aggregate stability estimated by Le Bissonnais' method

Le Bissonnais' method is divided into three subtests that are based on wetting duration, the medium of dispersion (distal water/ethanol), and intensity of application, which include fast wetting (FW), slow wetting (SW), and wet stirring (WS) (Le Bissonnais, 1996). Initially, 5 g soil with 3–5 mm sized aggregates was used, followed by various treatments. The dispersed soil samples were dried at 40 °C for 48 h and sieved using a column of five sieves: >2 mm, 1–2 mm, 0.5–1 mm, 0.25–0.5 mm, and <0.25 mm. Three replicates were used for each plot/soil/test. After drying, aggregates of different sizes were separated. The mean weighted diameter (MWD) was calculated using the mean weight diameter equation (Oguike and Mbagwu, 2009). Soils were evaluated based on the aggregate stability classification of Le Bissonnais (Table S1).

2.6. Soil aggregate stability evaluated by ultrasonic agitation

The ultrasonic agitation of the aggregates was analyzed according to the protocol described by Zhu et al. (2009a, 2009b) with some modifications. First, 3 g of oven-dry soil and 30 ml deionized water were placed in a 50 ml beaker (i.d. weight 34.2 g, height 6 cm). After slaking for 5 min, the suspension was exposed to ultrasonic dispersive energy using an ultrasonic instrument, UP100H (Hielscher Ultrasound Technology, Tetow, Germany). Six time steps were used: 0, 30, 60, 110, 210, and 295 s. The dispersion energy, $L_{A,}$ of soils was calculated using Eq. (1) as follows:

$$L_A = L - L_D - L_H - L_0 \quad (1)$$

where L is the total input energy of the ultrasonic system, L_D is the energy lost by the ultrasonic wave, L_H is the energy used for heating the system, and L_0 is the energy not used in heating and dispersing soils. As the load is a light load, such as soil water suspension, the lost power (energy per second) is approximately equal to the no-load lost power (Zhu et al., 2010), which can be measured by the data acquisition unit. After each ultrasonification step, the mean weight diameter was determined based on the aggregate fraction of three sieves (>0.25, 0.25–0.05, < 0.05 mm). The soil overall disruption curve (SODC) was used (Abbas et al., 2021) that was originally derived from the aggregate disruptive characteristics curve (ADCC) (Field and Minasny, 1999):

$$M = M_C + De^{-K_i E}$$

where M_c is the MWD when all the aggregates are dispersed into primary particles, and D is the change in MWD with the rate constant K_i of aggregate disruption by ultrasonic energy (J g^{-1}). As energy is a non-linear entity, we cannot take the average of energy to estimate the stability of soils; hence, we calculated the specific dispersion energy (SE) at three important stages of aggregate disruption: SE_{10} (initial point where 10% (w/w) of soil fractions were dispersed, point of most abrupt disruption), SE_{50} (middle, where 50% (w/w) of soil fractions were dispersed), and SE_{90} (final, 90% (w/w) of the soil fractions were dispersed, almost completely disrupted). We assume that the higher the SE of the soil, the more dispersion energy it requires for dispersion, and consequently, the higher the stability of the soil.

2.7. Statistical analysis

Analysis of variance (ANOVA) was performed to determine the significant differences among the aggregate stability of the eight soils, three vegetation types, and the two depths (SPSS 17.0). The correlation analysis matrix was analyzed using Origin 21, and graphical representations were made using Simplot 9.0. Variation between the treatments was determined using standard deviation and standard error values. Significance levels 0.05 and 0.01 were used to evaluate the difference and correlations.

3. Results

3.1. Basic soil properties

The pH value was varied from 8.08 to 8.27 and 8.01 to 8.28 at depths of 0–20 cm and 20–40 cm soil, respectively (Table 2). The SOC contents ranged from 8.14 to 19.47 g kg^{-1} and 6.38 to 16.58 g kg^{-1} at depths of 0–20 cm and 20–40 cm, respectively. The soil QW exhibited higher TN content than the HR soil. Among the eight plant species soils, the SWC of RX at the surface and subsurface layers was the highest (14.91% and 14.33%, respectively), while lower SWC was found with QW (10.04% and 10.27%). The FRB of forest soils was comparatively higher than that of grass and shrub soils ($p < 0.05$). Grass soil exhibited the lowest C:N ratio among all the soils. The SOC content of surface soils was higher than that of subsurface soil ($p < 0.05$). In addition, the SOC and TN contents of the QW soil were significantly higher than those of all the other soils (Table 2). The primary soil particles (clay, silt, and sand) ranged between 6.81% and 19.81%, 22.1% and 56.34%, and 31.25% and 57.52%, respectively. According to the soil textural classification system of the USDA, the forest and shrub soils were classified as loam and sandy loam soils. In contrast, the texture of the grass soil was silt loam. The QW soil contained the highest clay content of all soils ($p < 0.05$).

3.2. Soil stability by modified Yoder method

The results of the modified Yoder's mean weight diameter (MWD) demonstrated the stability of the eight soils (Fig. 2). The MWD of surface soils ranged from 1.40 (RP) to 2.86 mm (SV), and 1.23 (HR) to 2.79 (PO) for subsurface soils. The MWD of the RP surface soil was lower than that of the other soils ($p < 0.05$). Among the forest soils, the MWD of PO soil was the highest, while among the soils under shrub cover, the SV soil possessed the highest MWD value. There was no significant difference in MWD between the surface and subsurface soil layers of the PO soil ($p > 0.05$). The MWD order of the eight soils at the surface and subsurface soil layers was SV > PO > QW > RX > HR > SB > PT > RP and PO > SV > RX > QW > PT > SB > RP > HR, respectively. Overall, no significant difference was observed between the MWD values of the two soil depths ($p > 0.05$).

3.3. Soil stability under Le Bissonnais method

The results of the Le Bissonnais tests are shown in Fig. 3. For the FW test, MWD values ranged between 0.45 and 2.25 mm, with the highest and lowest values for QW and RP soils, respectively. Overall, surface soils possessed the highest MWD values compared with the subsurface soils ($p < 0.05$). According to the soil stability classification suggested by Le Bissonnais (1996) (Table S1), RP soil was the most unstable soil in both layers (0.45 and 0.67 mm). The soils QW, PO, and SV, were stable at both soil surfaces. The SB and HR surface soils were more stable than the subsurface soils ($p < 0.05$). The MWD of soils by SW test ranged from 1.31 to 2.82 mm and 0.83 to 2.63 mm at depths of 0–20 and 20–40 cm soil, respectively. All soils were in medium to the very stable range. Soils QW, PO, PT, SV, and HR were found to be stable on both surfaces. We noticed a similar trend of MWD for FW and WS, MWD (WS) ranged from 1.24 to 2.57 mm and 0.64 to 2.25 mm for surface and subsurface soils, respectively. There was a significant difference in MWD (20–40 cm) among the subsurface forest soils according to the FW, SW, and WS tests ($p < 0.05$). The MWD results of the FW and SW tests indicated that the stability of shrub soils (20–40 cm) was significantly different ($p < 0.05$). Overall, QW soil was found to be stable at both soil surfaces in all three LB tests ($p < 0.05$). RP soil was categorized as unstable to medium-stable. The FW proved to be the most destructive test, with the lowest MWD values among all three tests.

Table 2
Basic soil characteristics.

Soils	Depth(cm)	pH	SOC (g kg^{-1})	TN (g kg^{-1})	SWC (%)	Clay (%)	Silt (%)	Sand (%)	Soil texture
QW	0–20	8.11 ± 0.19AB	19.47 ± 0.56A	2.21 ± 0.35A	10.04 ± 0.88E	19.81 ± 1.77A	34.08 ± 3.19C	46.11 ± 4.05D	Loam
PO	0–20	8.08 ± 0.16B	17.27 ± 2.90B	2.13 ± 0.40A	10.90 ± 1.59DE	14.93 ± 0.65B	27.55 ± 0.97D	57.52 ± 1.61AB	Sandy Loam
PT	0–20	8.25 ± 0.13A	13.96 ± 0.26C	1.46 ± 0.20C	12.03 ± 0.88Cd	19.38 ± 0.51A	32.07 ± 0.62C	48.55 ± 1.12CD	Loam
RP	0–20	8.27 ± 0.17A	8.14 ± 0.54F	1.05 ± 0.09D	12.89 ± 1.59BC	7.28 ± 1.31D	43.47 ± 4.02B	49.27 ± 5.14CD	Loam
SV	0–20	8.27 ± 0.13A	12.26 ± 1.3DE	1.95 ± 0.36AB	11.99 ± 1.59CD	14.00 ± 0.12BC	27.85 ± 0.78D	58.16 ± 0.80A	Sandy Loam
RX	0–20	8.20 ± 0.15AB	12.67 ± 0.37CD	1.64 ± 0.48BC	14.91 ± 0.81BC	6.36 ± 0.56D	41.28 ± 0.81B	52.53 ± 1.22BC	Loam
HR	0–20	8.24 ± 0.09A	10.78 ± 1.52E	0.74 ± 0.05D	12.92 ± 0.88BC	6.61 ± 0.85D	44.18 ± 4.13B	49.21 ± 4.95CD	Loam
SB	0–20	8.25 ± 0.06A	8.68 ± 0.60F	1.91 ± 0.25AB	13.92 ± 0.88AB	12.41 ± 0.69C	56.34 ± 0.98A	31.25 ± 0.97E	Silt Loam
QW	20–40	8.16 ± 0.08abc	15.46 ± 1.76a	2.10 ± 0.18a	10.27 ± 0.88e	17.20 ± 0.01a	29.47 ± 0.01d	53.35 ± 0.02b	Sandy Loam
PO	20–40	8.19 ± 0.23ab	16.58 ± 1.76a	2.02 ± 0.25a	10.67 ± 1.59de	15.89 ± 2.32ab	33.01 ± 4.54 cd	51.18 ± 6.92bc	Loam
PT	20–40	8.25 ± 0.11a	11.28 ± 1.64b	1.14 ± 0.19bc	11.79 ± 0.88 cd	14.93 ± 1.46b	30.41 ± 0.75d	54.70 ± 0.75c	Sandy Loam
RP	20–40	8.07 ± 0.13bc	6.71 ± 0.46de	1.15 ± 0.13b	12.65 ± 1.59bc	9.96 ± 0.23 cd	22.32 ± 1.45e	67.74 ± 1.66a	Sandy Loam
SV	20–40	8.01 ± 0.07c	10.51 ± 1.92bc	0.93 ± 0.16 cd	11.76 ± 1.59 cd	15.88 ± 0.15ab	31.64 ± 3.21d	52.61 ± 3.46b	Sandy Loam
RX	20–40	8.28 ± 0.10a	8.88 ± 0.36 cd	0.98 ± 0.09bc	14.33 ± 1.09a	7.79 ± 1.21e	47.23 ± 5.45b	44.98 ± 6.64c	Loam
HR	20–40	8.19 ± 0.10ab	8.25 ± 0.73de	0.71 ± 0.09d	13.26 ± 0.61b	8.16 ± 1.84de	38.29 ± 3.82c	53.54 ± 2.04b	Sandy Loam
SB	20–40	8.19 ± 0.09ab	6.38 ± 0.17e	1.90 ± 0.40a	13.18 ± 1.22b	10.48 ± 0.40c	55.84 ± 1.80a	33.70 ± 2.18d	Silt Loam

BD means soil bulk density; pH means soil pH, SOC means soil organic carbon; TN means soil total nitrogen; SWC (Soil water content), Mean ± SD. Letters in upper case and low case represent the significant differences between soils at surface (0–20 cm) and subsurface (20–40 cm) layers respectively, at p < 0.05.

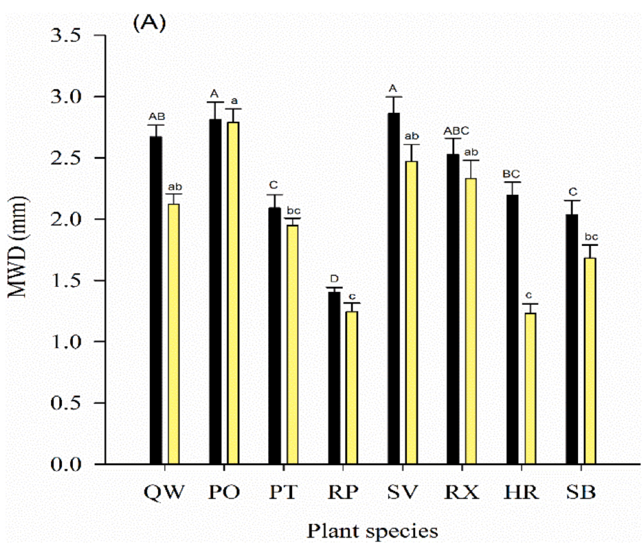

Fig. 2. The mean weight diameter (MWD) of soil water-stable aggregates under various plant species by modified Yoder's method. The black and yellow coloured columns indicated the soil at 0–20 cm and 20–40 cm depth. Error bars represent the standard errors of the mean (n = 9). Means with different uppercase letters (A-D) represented the significant difference between surface soils (0–20 cm) and lowercase letters (a-c) indicated the significant difference between subsurface soils (20–40 cm) (p < 0.05). QW, PO, PT and RP represent the forest soils under *Quercus wutaishansea, Platycladus orientalis*, *Pinus tubulaeformis and Robinia pseudo separately, SV, RX and HR stands for* shrub soils under *Sophora viccifolia*, *Rosa xanthina*, and *Hippophae rhamnoides, and SB is the* grass soil under *Stipa bungeana.* (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.4. Aggregate stability assessment by ultrasonic agitation

The results for the three specific dispersion energies (SE_{10}, SE_{50}, and SE_{90}) are listed in Table 3. The Initial SE (SE_{10}) ranged from 11.4 to 29.4 J g^{-1}, and 8.1 to 25.7 J g^{-1}, middle (SE_{50}) ranged between 74.9 and 193.4 and 53.0 to 169.3 J g^{-1}, and final (SE_{90}) varied from 248.9 to 642.3 and 176.2 to 562.4 J g^{-1} for surface (0–20 cm) and subsurface (20–40 cm) soils, respectively. Overall, the trends of SE at the three disruption stages for all soils were similar. The increasing order of SE for surface and subsurface soils was QW > SV > PT > RX > P0 > HR > RP > SB and QW > HR > PO > PT > SV > RX > SB > RP, respectively. Overall, QW soil had the highest SE values at all three disruption stages and on both surfaces than the other seven soils ($p < 0.05$). There was a significant difference between the two soils at two depths: topsoils were more stable than subsurface soils ($p < 0.05$).

3.5. Correlation analysis

To evaluate the appealing and repelling relations between various stability parameters using the five tests, a correlation analysis was performed (Fig. 4). The three tests had a significant correlation with soil characteristics; SOC (r = 0.70 for MWD (Yod), r = 0.79 for MWD (FW), r = 0.75 for MWD (SW), r = 0.76 for MWD (WS), r = 0.69 for SE_{10}, SE_{50} and SE_{90}); TN (r = 0.53 for MWD (Yod), r = 0.71 for MWD (FW), r = 0.65 for MWD (SW), r = 0.66 for MWD (WS), r = 0.52 for SE_{10}, SE_{50}, SE_{90}); FRB (r = 0.30 for MWD (Yod), r = 0.46 for MWD (FW), r = 0.48 for MWD (SW), r = 0.51 for MWD (WS), r = 0.49 for SE_{10}, SE_{50}, SE_{90}); clay (r = 0.45 for MWD (Yod), r = 0.63 for MWD (FW), r = 0.63 for MWD (SW), r = 0.57 for MWD (WS), r = 0.54 for SE_{10}, SE_{50}, SE_{90}); SWC (r = −0.54 for MWD (FW), r = −0.54 for MWD (SW), r = −0.58 for MWD (WS), r = −0.53 for SE_{10}, SE_{50}, SE_{90}) and silt contents (r = −0.35 for MWD (WS), r = −0.34 for SE_{10}, SE_{50}, SE_{90}). There were significant to highly significant positive correlations among the five tests (r = 0.55–0.93) (Fig. 5).

4. Discussion

4.1. Effect of soil characteristics on aggregate stability

The correlation results indicated that SOC content was strongly associated ($p < 0.01$) with soil stability parameters of all five tests (Fig. 4), as found in previous studies (Tisdall and Oades, 1982; Liu et al., 2014; Xiao et al., 2020) which pointed out that SOC/SOM acts as a binding agent that enhances soil stability and eventually improves soil structure. Along with SOC, total nitrogen (TN) was also strongly correlated with stability parameters ($p < 0.01$), which coincided with the existing studies that consider TN as the second most influential factor (Zhu et al., 2018; Liu et al., 2019; Sekaran et al., 2021). In the current study, FRB was strongly linked with the stability parameters of Le Bissonnais and ultrasonic agitation methods. Moreover, FRB was associated with modified Yoder's MWD, which indicated that FRB is an important factor in improving soil resistance against major breakdown mechanisms: slaking, clay swelling, immersion, mechanical breakdown, and cavitation. These results are in line with the findings of some researchers who argued that fine roots directly improved soil stability by providing a source of litter and nutrients, enriching the soil with cementing agents, and indirectly improved it through microbes and exudates (Six et al., 2004; Deng et al., 2018; Xiao et al., 2020). Soil water content could be a

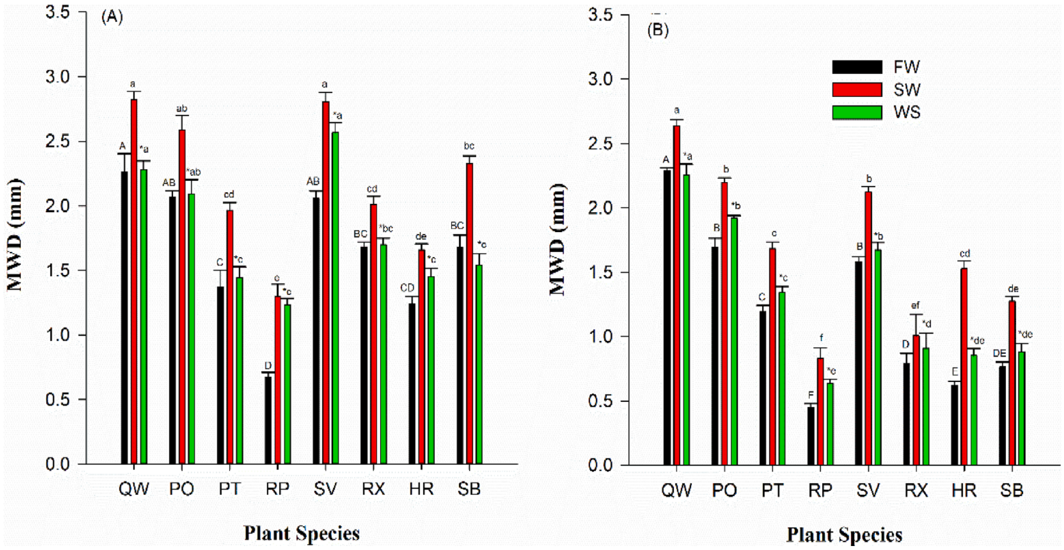

Fig. 3. The mean weight diameter (MWD) of soils under various plant species (A) at 0–20 cm and (B) 20–40 cm. Error bars represented the standard error of the means (A, B n = 9) tested by LB tests (FW, fast wetting; SW, slow wetting; WS, wet straining). Means with different uppercase letters (A-E), lowercase letters (a-f) and lowercase letters+*symbols (*a-*e) represented the significant difference among the soils by MWD of Fast wetting (FW), Slow wetting (SW) and Wet stringing (WS) ($p < 0.05$). QW, PO, PT and RP represent forest soils under *Quercus wutaishansea, Platycladus orientalis, Pinus tubulaeformis, and Robinia pseudo separately, SV, RX and HR stands for* shrub soils under *Sophora viccifolia Rosa xanthina*, and *Hippophae rhamnoides, and SB is the* grass soil under *Stipa bungeana.*

Table 3
Specific dispersion energy (SE_{10}, SE_{50}, SE_{90}) of different plant species soils at 0–20 cm and 20–40 cm depth.

Soils	Depth (cm)	SE		
		SE_{10} (J g^{-1})	SE_{50} (J g^{-1})	SE_{90} (J g^{-1})
QW	0–20	29.4 ± 3.4A	193.4 ± 22.5A	642.3 ± 74.9A
PO	0–20	16.4 ± 2.0BC	107.9 ± 13.4BC	358.5 ± 21.2BC
PT	0–20	18.4 ± 1.7B	121.2 ± 11.2B	402.8 ± 37.3B
RP	0–20	11.4 ± 1.2D	74.9 ± 7.8D	248.9 ± 25.9D
SV	0–20	26.6 ± 2.0A	174.8 ± 13.5A	580.9 ± 45.6A
RX	0–20	16.9 ± 0.4BC	111.1 ± 2.6BC	368.9 ± 8.6BC
HR	0–20	15.0 ± 0.7C	98.6 ± 1.1C	327.7 ± 3.7C
SB	0–20	11.6 ± 1.4D	76.0 ± 9.4D	252.6 ± 31.4D
QW	20–40	25.7 ± 3.7a	169.3 ± 24.5a	562.4 ± 81.3a
PO	20–40	14.6 ± 0.2b	96.1 ± 1.5b	319.4 ± 5.0b
PT	20–40	14.5 ± 1.1b	95.6 ± 7.5b	317.6 ± 24.8b
RP	20–40	8.1 ± 1.1d	53.0 ± 7.3d	176.2 ± 24.1d
SV	20–40	11.8 ± 1.2c	77.4 ± 2.9c	257.1 ± 9.8c
RX	20–40	11.3 ± 1.1c	74.2 ± 7.2c	247.9 ± 23.8c
HR	20–40	15.1 ± 0.8b	99.3 ± 5.2b	329.9 ± 17.4b
SB	20–40	10.9 ± 0.5c	72.2 ± 3.3c	239.9 ± 10.8c

SE_{10}, specific dispersion energy at 10 % (W/W).; SE_{50}, specific dispersion energy at 50 % (W/W).; $SE_{90,}$ specific dispersion energy at 90 % (W/W).. Mean ± SD. Letters in upper case (A-D) and low case (a-d) represent significant difference between soils at surface and subsurface layer, respectively at $p < 0.05$.

determinant in soil stability studies, as it strongly affects the soil's disruptive mechanisms (Algayer et al., 2014). Our results revealed that SWC was negatively correlated with all five tests. This could be because soil water ruptures the bonding of soil aggregates, weakens the cementing agents, and ultimately supports soil erosion. Many studies have indicated a negative impact of SWC on soil structure, as most soil destructive mechanisms are facilitated by soil water content (Rudolph et al., 1997; He et al., 2018; Dou et al., 2020). Many existing studies have suggested the importance of primary soil particles (clay, silt, and sand) as key factors that stabilize the soil structure (Wagner et al., 2007; Schweizer et al., 2019). In the current study, we found clay content to be the main soil particle responsible for the stability of soils. Our results indicated that clay was strongly associated ($p < 0.01$) with the stability (parameters of all three methods and five tests) of soils. These findings coincide with previous studies that concluded that finer particles affect the stability of soil either directly by improving inter-particle bonding or indirectly by enriching the soils with organic carbon and nitrogen contents, as soils with higher clay content are mostly enriched with high organic carbon and nitrogen content (Zinn et al., 2007; Erktan et al., 2016; Zeng et al., 2018). The medium-sized soil particles (silt) were found to be negatively correlated with the MWD (WS), SE_{10}, SE_{50} and SE_{90}, which revealed that soil with a high silt content was more susceptible to erosion by two breakdown mechanisms such as mechanical breakdown and cavitation. Our results also revealed that the effect of sand particles on the stability of these soils was negligible. Overall, in this study, the positive association of SOC, TN, FRB, and clay contents, and a negative relationship between SWC and stability parameters suggests that soils with high SOC, TN, FRB, clay contents, and comparatively low SWC contents are more likely to be resistant to the five disruptive mechanisms including slaking, clay swelling, immersion, mechanical breakdown, and cavitation.

4.2. Effect of plant species and soil depth on aggregate stability

The high stability of the forest soil (QW) was consistent across all five tests. This might be due to the soil characteristics, that is, high SOC (Chaplot and Cooper, 2015), TN, FRB, and clay content, and lower SWC content (Zeng et al., 2018). Previous studies revealed that soils of one particular plant community (soils developed under plant cover) are comparatively more stable than soils developed under other vegetation types/plant communities. For example, forest soils are believed to be more stable than grass soils because of their high nutrient content (Gajic et al., 2006; Zeng et al., 2018; Liu et al., 2014). However, the stability results of the QW and RP soils suggested that even the soils under the same vegetation types could be entirely different with respect to stability status, as the results of all five tests suggested that RP was the most unstable soil (except the surface soil results of modified Yoder, where it was stable when the MWD value was > 1.30 mm). The reason behind this instability (especially at the subsurface) of RP soil might be that it sucks plenty of underground water and leaves the dried subsurface soil (Liang et al., 2018). Other studies revealed that soils under RP species cause depletion of SOM/SOC at belowground levels because of their water storage mechanism which results in an unstable soil structure (Yan et al., 2017). These findings are in accordance with our results, as

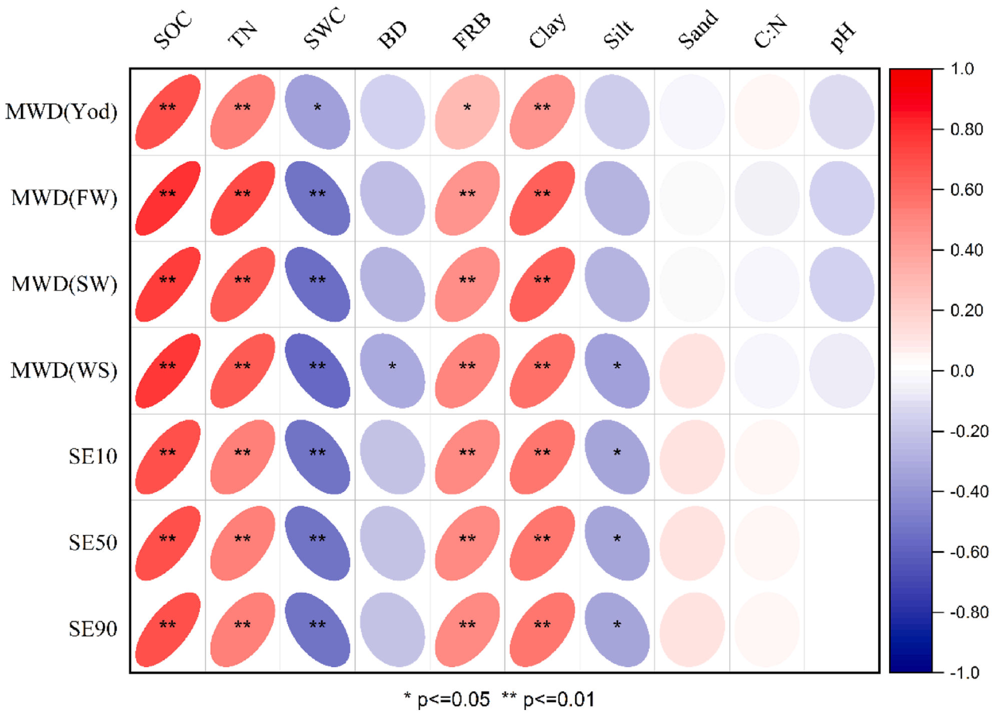

Fig. 4. Correlations between soil physicochemical properties, fine root biomass and stability parameters of the three tests. The stars indicated the significant correlation at 0.05 (*) and 0.01 (**) level of significance. The red color means positive correlation while the blue color means negative correlation; the lighter color and smaller eclipse mean the lower value of correlation coefficient and the darker color and bigger eclipse mean the higher value. MWD(Yod), MWD (FW), MWD(WS) and MWD(SW) and SE_{10}, SE_{50} and SE_{90}, the mean weight diameter of modified Yoder, Fast wetting, Slow wetting, Wet stirring and specific dispersion energy at 10, 50 and 90 % (w/w). SOC, soil organic carbon; TN, Total nitrogen; SWC, soil water content; BD, bulk density; FRB, fine root biomass; C:N, carbon to nitrogen ratio. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

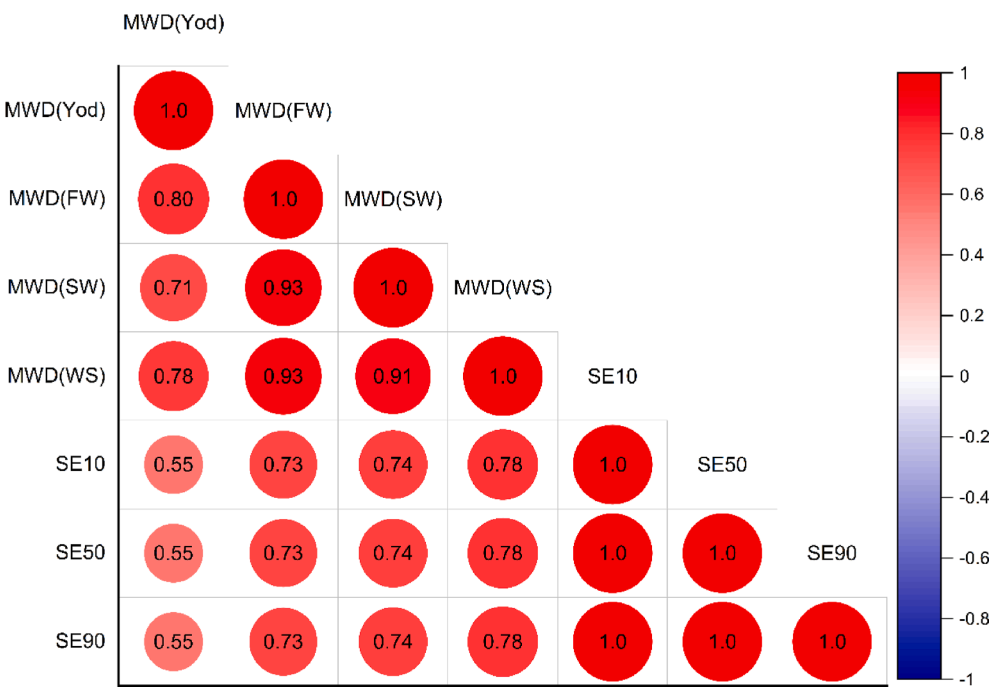

Fig. 5. Correlations between soil stability parameters of the three tests at significance levels of 0.05 and 0.01. The red color means positive correlation while the blue color means negative correlation; the lighter color and smaller circle mean the lower value of correlation coefficient and the darker color and bigger circle mean the higher value. MWD(Yod), MWD(FW), MWD(WS) and MWD(SW), SE_{10}, SE_{50} and SE_{90}, the mean weight diameter of modified Yoder, Fast wetting, Slow wetting, Wet stirring and specific dispersion energy at 10, 50 and 90 % (w/w). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

RP soil possessed the lowest SOC content among the eight soils. In a recent study in the LPC region, Wang et al. (2019) utilized soils under RP and CK (*Caragana korshinskii*) species for aggregate stability assessment of the LPC region. Wang et al. (2019) found that the average MWD of surface soil (RP) determined by the modified Yoder's method was > 1.30 mm, which is similar to the results of this study. On these bases, they recommended afforestation of the LPC region with RP species. This could be because they only studied the soils under two plant species (CK was used as a control treatment) and one stability method. In contrast, based on the findings of this study, we suggest the afforestation of the Ziwuling area with another stable forest species, that is, QW. The results indicated that there was no significant difference between the surface (0–20 cm) stability of QW (forest) and SV (shrub) soils ($p > 0.05$). The soil stability of SB soil was similar to that of the HR and RX soils. Overall, there was a significant difference in surface aggregate stability compared to the subsurface soil layer in all five tests ($p < 0.05$). This might be because surface soils contain high SOC, TN, and FRB, more litter decomposition, and lower SWC. This evidence of high surface stability was in accordance with some previous studies (An et al., 2010; LiuSui et al., 2019).

4.3. Differences and similarities of the soil stability assessment methods

As each soil stability method and index is based on specific criteria: disruptive mechanism (i.e., slaking, mechanical breakdown, clay swelling, and cavitation), initial and final soil fractions (i.e., 0.25–>5 mm, <0.25–2 mm, <2–0.05 mm), disruptive process (end-over-end shaking, rain stimulation, laser diffraction, and sonification) dispersion agents (i.e., ethanol and deionized water) (Table 4). Therefore, the comparison of various soil stability tests and indices is a complicated process. However, no single method is reliable and can be universally used for all types of soils. Therefore, the use of more than one stability test for any stability study is more productive (Almajmaie et al., 2017). Despite some serious differences (all three methods were based on different initial and final aggregate fractions and parameters), we observed a strong association among the stability tests (r = 0.54–0.93) (Fig. 5). This strong association among the methods and tests suggests that different disruptive mechanisms have a similar breakdown effect (breakdown process and erosion) for the soils of the Ziwuling area. Soil mean weight diameter (MWD) has been used as a determiner for soil stability studies because it is easy to calculate and is based on the macroaggregate percentage (Bedini et al., 2009; Lu et al., 2019). A recent study suggested that if a single method was to be solely used for soil stability assessment, then wet sieving would be the best choice (Liu et al., 2021). It is comparatively easy to handle, non-laborious, and diverse method (Pulido Moncada et al., 2015). The MWD (Yod) was positively correlated with MWD (FW, SW, and WS) ($p < 0.01$), which contradicts the findings of previous studies in this area (Guo et al., 2010; An et al., 2013), which argued that MWD (Yod) was not closely associated with MWD (FW). The MWD (Yod) also showed a positive correlation with the three parameters of the UA method ($p < 0.05$). This association of the modified Yoder's method with other methods confirms that the modified Yoder method is as efficient and authentic as the other methods. Based on Le Bissonnais's stability classification, modified Yoder's results revealed that all surface and subsurface soils (with the exception of subsurface soils under RP and HR species) were in the stable range (MWD > 1.3 mm). Similarly, the other two methods specified RP soil as the most unstable soil. This consistent stability trend of all soils could be because this method consists of two mechanisms: slaking and mechanical breakdown, making the aggregates more resistant over time against disruption and reducing soil sensitivity against disruption forces (Amézketa, 1999). There was no significant difference between the soils of the same vegetation types or between the soils of different vegetation cover types ($p > 0.05$). Compared with others, modified Yoder was found to be less discriminatory when comparing soils of various species and depths. This is in accordance with previous studies in this area (An et al., 2013; Zhu et al., 2016), which indicated that the modified Yoder is the least effective test based on its inefficiency in discriminating soils of various stability levels as well as the least destructive test. We used dry sieving followed by the modified Yoder wet sieving method for a more precise soil stability assessment. However, we observed that some soils (QW, PO, and SV) had the highest proportion of macroaggregates (>250 mm) and finally ended up (after wet sieving) with high MWD values. Based on these findings, we suggest that this method requires more precision. Similarly, the modified Yoder method only accounts for <0.25–5 mm sized aggregates; therefore, it is more or less a macro stability assessment method for soils.

The Ziwuling area, because of the frequent rains and thunderstorms throughout the year, is considered a highly eroded area (Zheng, 2006). Based on the recommendations of Le Bissonnais (1996), the FW test presented a condition of soils under intense rainfall, increased thunderstorms and high erosion rate (as in our study area, Ziwuling). SW presented a condition of soils under drizzling (soil facing light rainfall). WS can be attributed to the mechanical breakdown of soils (e.g., plowing). Our findings of LB tests indicated that FW was the most destructive (minimum MWD range, 0.67 to 2.25 mm) among the three LB tests, demonstrating the most realistic conditions (soil erodibility) of the Ziwuling area. Our findings are consistent with those of Zhu et al. (2016) and Zeng et al. (2018), who indicated FW as the most destructive and suitable test among all the LB tests for the soils of LPC. Some studies referred to SW as the least suitable test for the LPC area because of the seldom drizzling conditions (Zeng et al., 2018), and our study also found similar results, as SW showed the highest MWD values among the three LB tests and most of the soils were in the medium to stable range. The LB tests were significantly positively correlated with each other ($P < 0.01$), indicating that all three methods were equally effective and had similar stability trends with some differences. There was a significant difference between the subsurface soil of the same vegetation types in the FW and SW tests ($p < 0.05$). Topsoils were generally more stable than subsurface soils ($p < 0.05$). There are some limitations of Le Bissonnais tests as well: i) as the initial fraction class for this method is 3–5 mm, these fractions are more stable than >5 mm aggregates (as in modified Yoder); ii) after wet sieving treatment, aggregates cannot be used for further chemical and biological analyses because of the use of ethanol; and iii) soil degradation is caused by many biotic and abiotic factors. This is more specific to soil water erosion, and hence is more effective for erosion-based studies.

In the UA method, the breakdown of aggregates is a dynamic process that is subjected to applied ultrasonic energy (Schomakers et al., 2015). Cavitation is the main phenomenon involved in aggregate disruption using the UA method. This physical phenomenon initiated with bubble formation eventually resulted in aggregate disruption (Fristensky and Grismer, 2008). The specific dispersion energy (SE) is a reliable and precise way to compare the aggregate stability of soils (North, 1976; Fristensky and Grismer, 2008). Our final SE (SE_{90}) values ranged from 176 to 642 J g^{-1} in the 0–20 cm soil layer, which is consistent with Zhu et al. (2009b). Zhu et al. (2009b) used SE_{98} (98% (w/w), as the final point), and the resulting SE ranged from 100 to 600 J g^{-1} for the surface soils of New South Wales, Australia. There was a consistent stability trend of the three SE parameters for the eight studied soils, which demonstrates the authenticity of these parameters and the UA method. However, there is a lack of a soil stability classification system (i.e., Le Bissonnais) for the UA method (as in the case of the LB classification system). Although no classification system exists for the UA method, the relative SE values of soils could indicate the stability differences among the soils, with QW being the most stable soil used 2.5 and 3.5 times more dispersion energy than RP soil (least stable soil). All stability methods

Table 4
Brief Comparison of the three applied methods.

	Method	Pre-treatment fractions	Post-treatment fraction	Parameters	Mechanism	References
1	Modified Yoder	>5 mm	>5 mm, 2–5 mm, 1–2 mm, 0.5–1 mm, 0.25–0.5 mm, <0.25 mm	MWD	Slaking, mechanical dispersion	(Amézketa, 1999)
2	Le Bissonnais	3–5 mm	>2 mm, 1–2 mm, 0.5–1 mm, 0.25–0.5 mm, <0.25 mm	MWD	Slaking, immersion, Clay swelling, mechanical dispersion	(Le Bissonnais, 1996, 2016)
3	Ultrasonic agitation	<2 mm	>0.25 mm , 0.25–0.05, <0.05	SE_{10}, SE_{50}, SE_{90}	Slaking, Cavitation	(Almajmaie et al., 2017)

MWD, mean weight diameter; SE_{10}, specific dispersion energy at 10% (W/W).; SE_{50}, specific dispersion energy at 50 % (W/W).; SE_{90}, specific dispersion energy at 90 % (W/W).

have some special merits over others, but UA is unique as it uses MWD and dispersion energy for in-depth soil stability assessment. The UA method is more specific to the micro-stability of soils because it accounts for the <0.05–2 mm fraction of soils. It is also considered a laborious and complicated method compared to other methods.

In summary, each method is limited to some extent. These three methods are entirely different with regard to the initial and final fraction sizes, dispersion medium (distilled water, ethanol), breakdown mechanisms (slaking, immersion, mechanical breakdown, cavitation), and stability parameters. However, the correlation results (Fig. 5) revealed a strong association between the parameters of the three methods and the five tests. Both the LB and UA methods revealed that the stability of surface soils was higher than that of subsurface soils ($p < 0.05$).

Furthermore, although all methods were strongly correlated with each other and showed a similar stability trend of soils, the high level of stability of QW soil was consistent with all three methods. There are some general comments, however, for each method. The modified Yoder method was found to be a less discriminatory test, as it is essentially a macro-aggregate stability assessment method. The Le Bissonnais method is more suitable for erosion-based studies, as it is based on the three disruptive mechanisms that provide the ideal conditions for soil erosion. The FW tests exhibited ideal conditions of aggregate disruption for the soils of the Ziwuling area. UA using SE is an effective method because it accounts for the MWD and resulting dispersion energy used to disrupt soil aggregates. In other words, UA accessed the soil stability on a quantitative (MWD) and qualitative (dispersion energy) basis. Because of the strong association between the stability parameters of the three methods and five tests, we concluded that all stability tests were equally good at stability assessment for the soils of the Ziwuling area.

5. Conclusion

Although soils of forestland are mostly ranked as stable soils, the results of this study by all five tests revealed that the most stable soil (*Qurecus wutaishansea* (QW)) and the most unstable soil (*Robinia pseudoacacia* (RP)) were both developed under forest cover. Therefore, we concluded that soil stability was independent of vegetation type. Among the three shrub soils, subsurface soil under SV species was found to be the most stable soil, with consistent results of all the methods. The SOC, TN, FRB, and clay contents were identified as the major characteristics responsible for the stability of these soils against different destructive mechanisms ($p < 0.05, 0.01$). There were significant correlations among the five tests ($r = 0.55$–0.93); hence, all tests were found to be equally suitable for the stability assessment of the soils in the Ziwuling area. This study used stability methods with their standard protocols (based on different initial and final fraction sizes, different methodologies, and parameters) and was limited to the soils of the Ziwuling area only. Further research is required to apply these comparative methods with the same initial and final aggregate fraction classes, and to apply these methods to soils of different regions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2021.105616.

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