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Effect of phosphogypsum and turkey litter on the erodibility of agrochernozems of the southern *Cis*-Ural (Russia) under artificial heavy rainfall

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Abstract

In the present study, we evaluated the effects of surface application and plowing of phosphogypsum and turkey litter to a depth of 20 cm on the erodibility of clay-illuvial agrochernozem (Luvic Chernozems (Aric, Pachic)) in the Southern Cis-Urals (Republic of Bashkortostan, Russia). Under laboratory conditions, 1°, 3°, and 7° slopes were modeled. Soil loss, runoff onset time, and turbidity were measured with a rainfall simulator. Particle size distribution and total organic carbon were measured. Under simulated heavy rainfall (360–420 mm h^{-1}) for 30 min, the untreated control had the highest soil loss (28.9 t ha^{-1}). Separate and combined introductions of phosphogypsum and turkey litter significantly increased soil resistance to water erosion. Co-introduction of the amendments strengthened this effect especially when the phosphogypsum to turkey litter ratio increased from 1:10 to 1:2 at the higher dose (60 t ha^{-1}). The turbidity of the runoff from a 1° slope reached a small peak within the first 3 min then gradually decreased thereafter. At 3°, the turbidity remained nearly constant over time and was uniformly distributed. At 7°, the turbidity sharply increased then gradually decreased and its distribution was a deformed bell. Washed-out (trapped) sediments from all treatments and slopes had relatively more very fine sand, silt, and clay and a slightly higher total organic carbon content than the original soil. Phosphogypsum and turkey litter wastes may be effective anti-erosion amendments and potential fertilizers because they increase flocculation, improve the structure, and enrich the organic matter and nutrient content of the soil.

Keywords: Sprinkling, modeling, turkey litter, phosphogypsum, erosion

Introduction

Erosion is a major type of soil degradation which occurs worldwide (Ali *et al.*, 2006; Khan *et al.*, 2013; Addis and Klik, 2015; Golmohammadi *et al.*, 2017). In Russia, erosion is also common (Golosov *et al.*, 2011; Krasilnikov *et al.*, 2013; Litvin *et al.*, 2017; Golosov *et al.*, 2018; Gusarov *et al.*, 2018) especially in the central regions such as the Republic of Bashkortostan (RB) (Sobol *et al.*, 2015). The RB is located between the Volga River and the Ural Mountains and active soil water erosion occurs there. About 64% of the agricultural land in the RB is already eroded. The high organizational, economic, agrotechnical, forestry, and hydrotechnical costs of reclamation in this region are incentives to seek alternative erosion remediation methods.

Pork manure (Barbosa *et al.*, 2015), sheep manure (Gholami *et al.*, 2016), and turkey litter (TL) (Costa *et al.*, 2008) have been used to reduce top soil erosion and increase crop yield (Adeli *et al.*, 2017). Certain polymers and structure-building amendments such as polyacrylamide (PAM) (Tang *et al.*, 2006; Abu-Hamdeh *et al.*, 2018) and gypsum or phosphogypsum (PG) (Cochrane *et al.*, 2005; Mamedov *et al.*, 2010) also increase soil resistance to erosion. PG is calcium sulfate hydrate, a by-product of fertilizer production from phosphate rock. It consists mainly of gypsum ($CaSO_4 \cdot 2H_2O$). In central Russia (Saratov Oblast; near RB), PG is used to reduce deflation and water erosion (Belobrov *et al.*, 2018). In Brazil, the introduction of TL (1,200–4,800 kg ha^{-1}) into red ferralitic soil (Dystrophic Red Latosols (Oxisols)) improved aggregation and increased aggregate water resistance especially in the 0–20 cm layer (Costa *et al.*, 2008).

The use of PAM during irrigation improves aggregate water resistance and soil infiltration capacity (Sepaskhah and Shahabizad, 2010). When PAM was added to irrigation water at the rate of 1 kg 100 m^{-3} ha^{-1}, runoff and soil loss decreased by 70-75% compared with the control (Aase *et al.*, 1998). When PAM was added to furrows, the surface runoff decreased by 94% relative to the untreated one (Sojka *et al.*, 1998).

Gypsum and PG amendments reduce surface runoff because they flocculate soil particles during rainfall or irrigation. The anti-erosion effect of gypsum is related to its

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ability to flocculate dispersed soil colloids, and it is stronger in PG than gypsum. The former dissolves faster and produces higher calcium concentrations in the soil solution than the latter during rainfall or irrigation (Keren and Shainberg, 1981). In the southern steppe of the Ukraine, the introduction of PG into dark chestnut soil (Haplic Kastanozems) reduced its density, lowered its silt content, promoted aggregation, and increased its humic content (Martynenko, 2014).

Recently, the practice of applying fertilizers consisting of agroindustrial and woodworking waste (Gabbasova *et al.*, 2007; Amin, 2018) and PG has become widespread (Hentati *et al.*, 2015; Kammoun *et al.*, 2017; Rakhimova *et al.*, 2017). The use of PG alone or in combination with organic additives improves the physical and hydrological properties of the soil, delays runoff generation, and reduces the severity of water erosion.

To the best of our knowledge, this study is the first to test the efficacy of the PG-organic waste combination on water erosion mitigation in the RB. There are several reasons why this region is suitable for this particular research: 1) The RB region is characterized by a highly heterogeneous topography. Most of its agricultural land is situated on slopes of varying steepness (Gabbasova *et al.*, 2016) and the soil can be easily washed out during water erosion, 2) The climate of the region is continental with severe, snowy winters, deep soil freezing, and frequent onset of soil erosion during spring thaw (Komissarov and Gabbasova, 2014), 3) Up to 37.3% of the annual precipitation in the southern Urals contributes to soil erosion (Sobol *et al.*, 2015), 4) Slopes irrigated by sprinkler in this region are susceptible to erosion. Sprinkling is the most common type of irrigation in the RB (Komissarov and Gabbasova, 2017), 5) In Russia and the RB, poultry farming is intensifying and generating thousands of tons of underutilized litter every year (Rusakova and Eskov, 2015), 6) In Russia and the RB, mineral fertilizer factories producing various chemicals based on apatite and sulfur pyrite generate ~500,000 tons of PG annually. Currently, > 10,000,000 tons of PG have been dumped in the RB. PG was traditionally used in the region to reclaim saline soils, solonets, and technogenic saline lands (Gabbasova and Suleimanov, 2007; Gabbasova *et al.*, 2013), 7) There are large, readily accessible turkey farms and PG dumps in the Meleuz district of RB.

Whereas field research is usually long-term, simulations may accelerate data acquisition. For example, rainfall simulators have already proven to be effective in soil erosion studies (Aziz and Liatim, 2018; Polykov *et al.*, 2018; Mhaske *et al.*, 2019). The purposes of this study were to evaluate the resistance of agrochernozems to water erosion and determine the stabilization efficacy of PG and TL and their combination on model slopes of varying steepness using a small laboratory-scale rainfall simulator.

In view of climate change and increasing erosion in the RB (Sobol *et al.*, 2015), our approach may establish the feasibility of using the abundant, cheap, underutilized local farm and mining wastes as soil anti-erosion amendments there. This practice has multiple benefits: it can (a) reduce the amount of industrial waste from factories; (b) help decrease soil erosion; (c) improve soil fertility and crop productivity; (d) prolong the useful life and improve the quality of existing arable land; and (e) help ensure and maintain food security.

Materials and Methods

The field study was conducted in the Ufimsky district of the RB (54° 50′ 23″ N, 55° 44′ 55″ E; 170 m a.s.l.). The arable horizon (0–20 cm) of a clay-illuvial, medium-eroded agrochernozem (Luvic Chernozems (Aric, Pachic)) formed on alluvial-diluvial carbonate parent material was studied. This soil type is the most common in the Southern *Cis*-Ural region and > 70% of it lies on slopes of 1–7° (Gabbasova *et al.*, 2016).

The PG and TL were brought to the study area from the factories of the Meleuz district of the RB. According to laboratory analyses, PG contained ~87% gypsum. TL was disinfected with "PX-Ornikill" (Killgerm Chemicals Ltd., Ossett, UK), and PG and TL were mixed in a tank. Then these ameliorants were added to surface of the soil on a gently inclined (3–5°) slope with a northern exposure according to the following scheme:

1. Control (no PG or TL (C);
2. PG, 5 t ha^{-1} (PG-5);
3. PG, 10 t ha^{-1} (PG-10);
4. PG, 20 t ha^{-1} (PG-20);
5. PG+TL, 1:10, 40 t ha^{-1} (PG+TL-40 (1:10));
6. PG+TL, 1:10, 60 t ha^{-1} (PG+TL-60 (1:10));
7. PG+TL, 1:5, 40 t ha^{-1} (PG+TL-40 (1:5));
8. PG+TL, 1:5, 60 t ha^{-1} (PG+TL-60 (1:5));
9. PG+TL, 1:2, 40 t ha^{-1} (PG+TL-40 (1:2));
10. PG+TL, 1:2, 60 t ha^{-1} (PG+TL-60 (1:2));
11. TL, 40 t ha^{-1} (TL-40);
12. TL, 60 t ha^{-1} (TL-60).

To ensure uniform mixing of PG and TL, the soil was plowed to a depth of 20 cm with a two-wheel tractor. One year after moldboard-plowing and PG and TL supplementation, the undisturbed soil monoliths were accurately excavated, and placed in polypropylene trays (L = 1.0 m, W = 0.2 m, H = 0.15 m) for the subsequent laboratory experiments. The soil in the trays was air-dried (to hygroscopic water at 10% moisture by weight) and used to assess the effects of artificial sprinkling on the induction of water erosion using a rainfall simulator (Figure 1). Technical details of the simulator and procedure are described in Sobol *et al.* (2017). Irrigation was performed at a rain intensity of 360–420 mm h^{-1} which is considered heavy (> 2.0 mm min^{-1}) according to Kiryushin (1996). The total irrigation time was 33–45 min depending on the onset of runoff. The intensity and duration of sprinkling used in this study enabled monitoring of the dynamics of erosion development over time (Znamenskaya *et al.*, 2018). Soil trays were irrigated on slopes of 1°, 3°, and 7° because these are the most common inclinations in the region (gentle, declivous, and aslant-steep, respectively).

The time of appearance of surface runoff after the start of irrigation was evaluated in this experiment. Fluid samples were taken at 0, 3, 5, 8, 15, and 30 min after the onset of runoff to measure the amount of suspended sediment in the flow (turbidity). The runoff samples (trapped sediments) during irrigation were transported to a special reservoir fitted with absorbent paper. The sediments on the filters were air-dried to constant mass and weighed, and total soil losses were calculated (Surmach, 1976). Particle size distributions in the original soil and sediment samples were measured by gravitational sedimentation (pipette method). Total organic carbon (TOC) was determined by thermochemical oxidation with $K_2Cr_2O_7$.

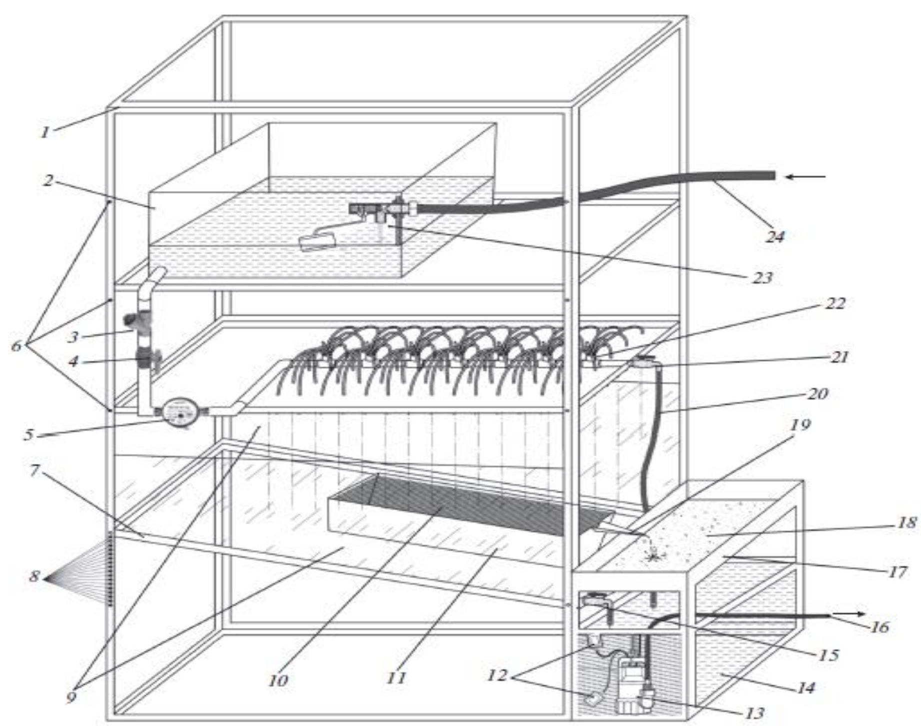

Figure 1: Sprinkler installation diagram

(*1*) frame; (*2*) reservoir; (*3*) filter; (*4*) water supply and valve; (*5*) flow meter; (*6*) height adjustment holes (0.5, 1.0, and 1.5 m); (*7*) base for flume with soil; (*8*) slope adjustment holes (0–15°); (*9*) anti-splash screen; (*10*) irrigated soil; (*11*) plastic flume (length 100 cm, width 20 cm, height 12 cm); (*12*) switch with float sensor; (*13*) submersible pump; (*14*) runoff reservoir; (*15*) water discharge hole; (*16*) drainage hose; (*17*) collection tray with filter; (*18*) filter; (*19*) discharge trough; (*20*) water discharge hose; (*21*) drain valve; (*22*) sprinkler frame; (*23*) float valve; (*24*) water supply intake hose (Sobol *et al.*, 2017)

Field soil sampling, rainfall experiments, and laboratory analyses were conducted in triplicate. The data were averaged and reported in tables and graphs. All data were processed in MS Excel 2007 (v. 12.0) (Microsoft Corp., Redmond, WA, USA). Significance of the differences between means was estimated by a *t*-test.

Table 1. TOC and particle size distribution of original soil (0–20 cm depth) and sediment (depending on the tray tilt angle)

Variant	TOC %	Fraction size (mm) and name					
		1–0.25 (coarse sand)	0.25–0.05 (fine sand)	0.05–0.01 (very fine sand)	0.01–0.005 (medium silt)	0.005–0.001 (very fine silt)	< 0.001 (clay)
				Content%			
Original slope soil	3.6 ± 0.1	7.5 ± 0.4	12.8 ± 0.8	16.9 ± 0.7	9.9 ± 0.6	23.8 ± 1.4	29.1 ± 1.8
			Inclination 1°				
1. C	4.0 ± 0.2	0.4 ± 0.1	3.1 ± 0.2	24.6 ± 1.0	7.0 ± 0.6	18.0 ± 1.2	46.9 ± 2.5
2. PG-5	4.1 ± 0.2	1.9 ± 0.1	10.0 ± 0.6	20.1 ± 0.7	7.6 ± 0.5	12.4 ± 0.6	48.1 ± 2.4
3. PG-10	4.0 ± 0.1	0.7 ± 0.2	9.6 ± 0.4	18.7 ± 0.8	9.1 ± 0.7	13.9 ± 0.9	47.9 ± 2.4
4. PG-20	4.1 ± 0.1	1.1 ± 0.1	7.5 ± 0.5	20.1 ± 1.1	10.4 ± 0.9	12.2 ± 0.8	48.8 ± 3.1
5. PG+TL-40 (1:10)	4.3 ± 0.3	0.5 ± 0.1	7.8 ± 0.3	22.3 ± 0.6	10.8 ± 1.0	13.3 ± 0.8	45.2 ± 2.7
6. PG+TL-60 (1:10)	4.4 ± 0.2	0.7 ± 0.1	7.8 ± 0.3	18.7 ± 0.5	10.5 ± 0.8	13.5 ± 0.9	48.9 ± 2.6
7. PG+TL-40 (1:5)	4.2 ± 0.2	0.3 ± 0.1	7.3 ± 0.3	20.2 ± 0.9	10.4 ± 0.9	13.7 ± 1.1	48.0 ± 2.9
8. PG+TL-60 (1:5)	4.2 ± 0.3	0.5 ± 0.1	8.7 ± 0.4	21.5 ± 0.9	8.7 ± 0.8	15.1 ± 1.1	45.6 ± 3.0
9. PG+TL-40 (1:2)	4.3 ± 0.1	1.1 ± 0.1	6.6 ± 0.4	20.6 ± 0.9	9.5 ± 0.7	12.8 ± 1.0	49.5 ± 3.2
10. PG+TL-60 (1:2)	4.4 ± 0.2	1.5 ± 0.2	7.6 ± 0.2	20.3 ± 0.7	9.7 ± 0.8	14.5 ± 1.2	46.4 ± 2.8
11. TL-40	4.4 ± 0.3	1.2 ± 0.1	6.6 ± 0.3	18.3 ± 0.7	10.7 ± 0.8	14.3 ± 0.9	48.8 ± 2.3
12. TL-60	4.2 ± 0.1	1.3 ± 0.1	5.3 ± 0.3	18.9 ± 0.5	11.3 ± 10.6	13.6 ± 1.0	49.6 ± 2.6
			Inclination 3°				
1. C	4.0 ± 0.2	0.6 ± 0.2	4.8 ± 0.4	22.5 ± 0.8	7.8 ± 0.4	18.5 ± 1.2	46.2 ± 1.9
2. PG-5	3.9 ± 0.2	1.4 ± 0.2	9.4 ± 0.3	19.1 ± 0.8	9.2 ± 0.5	13.3 ± 1.1	47.7 ± 2.7
3. PG-10	4.0 ± 0.1	0.7 ± 0.2	7.0 ± 0.1	21.3 ± 0.9	11.6 ± 0.8	11.1 ± 0.8	48.3 ± 2.9
4. PG-20	4.0 ± 0.1	0.4 ± 0.1	7.1 ± 0.2	20.8 ± 0.8	9.3 ± 0.8	11.5 ± 1.2	47.9 ± 3.0
5. PG+TL-40 (1:10)	4.2 ± 0.1	0.5 ± 0.1	9.3 ± 0.2	20.0 ± 0.6	8.7 ± 0.5	13.6 ± 1.0	47.9 ± 2.9
6. PG+TL-60 (1:10)	4.1 ± 0.2	0.9 ± 0.1	7.9 ± 0.5	20.1 ± 0.7	9.9 ± 0.5	14.3 ± 0.8	47.0 ± 2.6
7. PG+TL-40 (1:5)	4.2 ± 0.1	0.4 ± 0.1	9.3 ± 0.6	20.4 ± 0.5	8.2 ± 0.6	15.7 ± 0.9	46.0 ± 2.5
8. PG+TL-60 (1:5)	4.2 ± 0.2	0.3 ± 0.1	10.1 ± 0.8	19.5 ± 0.6	8.4 ± 0.7	15.4 ± 1.3	46.3 ± 2.8
9. PG+TL-40 (1:2)	4.2 ± 0.2	0.4 ± 0.1	9.1 ± 0.5	20.3 ± 0.9	8.9 ± 0.6	15.4 ± 1.1	46.0 ± 2.7
10. PG+TL-60 (1:2)	4.1 ± 0.3	1.0 ± 0.1	9.0 ± 1.0	19.0 ± 0.7	10.4 ± 0.7	15.3 ± 1.0	45.3 ± 3.0
11. TL-40	4.0 ± 0.3	0.8 ± 0.2	7.0 ± 0.6	19.8 ± 0.9	11.4 ± 0.7	13.6 ± 0.8	47.5 ± 2.7
12. TL-60	4.2 ± 0.2	0.9 ± 0.1	4.5 ± 0.5	18.5 ± 0.7	11.8 ± 1.0	14.9 ± 1.0	48.4 ± 2.5
			Inclination 7°				
1. C	3.9 ± 0.3	0.4 ± 0.1	3.6 ± 0.3	20.7 ± 0.7	10.2 ± 0.6	17.8 ± 1.2	47.3 ± 2.9
2. PG-5	3.9 ± 0.2	1.1 ± 0.3	7.3 ± 0.3	20.6 ± 1.2	10.8 ± 0.6	15.2 ± 1.2	45.1 ± 3.1
3. PG-10	4.0 ± 0.2	0.4 ± 0.1	8.5 ± 0.3	17.9 ± 0.8	12.7 ± 0.8	16.0 ± 1.2	44.8 ± 3.1
4. PG-20	4.0 ± 0.2	0.3 ± 0.1	6.0 ± 0.2	18.4 ± 0.7	11.8 ± 0.8	12.8 ± 0.9	46.8 ± 3.0
5. PG+TL-40 (1:10)	4.2 ± 0.1	0.2 ± 0.1	4.3 ± 0.2	20.9 ± 0.8	11.5 ± 0.7	15.6 ± 1.0	47.4 ± 2.7
6. PG+TL-60 (1:10)	4.2 ± 0.3	0.2 ± 0.1	5.1 ± 0.3	20.8 ± 0.8	10.6 ± 0.4	16.7 ± 1.0	46.7 ± 2.8
7. PG+TL-40 (1:5)	4.0 ± 0.2	0.4 ± 0.2	7.1 ± 0.5	20.2 ± 0.8	11.1 ± 0.5	16.5 ± 0.8	46.7 ± 3.0
8. PG+TL-60 (1:5)	4.0 ± 0.1	0.3 ± 0.1	4.8 ± 0.4	20.4 ± 0.8	10.0 ± 0.5	17.6 ± 0.8	46.9 ± 3.3
9. PG+TL-40 (1:2)	4.1 ± 0.2	0.8 ± 0.1	7.9 ± 0.5	19.0 ± 0.7	13.5 ± 0.9	14.7 ± 0.8	44.2 ± 2.9
10. PG+TL-60 (1:2)	4.1 ± 0.4	0.7 ± 0.1	7.9 ± 0.7	20.7 ± 0.7	9.8 ± 0.8	17.9 ± 0.9	44.2 ± 3.1
11. TL-40	4.1 ± 0.2	0.2 ± 0.1	7.3 ± 0.5	19.9 ± 0.6	10.5 ± 0.7	16.5 ± 0.8	45.7 ± 3.1
12. TL-60	4.1 ± 0.3	0.9 ± 0.1	5.2 ± 0.5	20.3 ± 0.7	11.3 ± 0.6	17.1 ± 0.8	47.1 ± 3.2

Results and Discussion

Arable agrochernozems have an average TOC content of ~3.6%, weak-acid pH, and 50–60 cmol (eq) kg^{-1} absorbed bases of which calcium predominates. Nutrient availability is generally high. These soils have an optimal density range of 1.1–1.2 kg m^{-3} and a silty-clay-loam texture (Komissarov and Gabbasova, 2017) (Table 1).

The most important indicators of the resistance of soils to water erosion are the onset time of runoff and total soil loss. Figure 2 shows that surface runoff first occurred in the control at all slopes. At 3° and 7°, runoff started ~1 min and ~2 min earlier than it did at 1°. The introduction of ameliorants delayed the onset of runoff by 65–186% at 1°, 33–98% at 3°, and 5–67% at 7°. Therefore, the onset time of runoff decreased with increasing slope. Higher anti-erosion resistance at all slopes was determined for the variants PG+TL-40 (1:2) and (1:5), and PG+TL-60 (1:5) and (1:10).

Turbidity depends on the number of suspended particles in the soil and can be used to elucidate the dynamics of rainfall erosion. Maximum stream turbidity was observed from the onset of runoff for 3 min on all 1° slope variants. When the runoff started, the finest and loosest soil particles were detached and washed out first. Other researchers reported similar results for tray-based soil erosion experiments in which the first wave of the runoff was the most turbid (Grigor'ev *et al.*, 2008; Larionov *et al.*, 2016). Runoff turbidity then gradually decreased over the next 5–30 min (Table 2). For the 3° and 7° slope variants, the maximum water flow turbidity was measured at 3–5 min after the onset of runoff. At that time, the effect of the arrival of slope runoff is observed and it gradually decreases thereafter.

The turbidity of the runoff was 2–4.5× greater at a 3° slope than it was at 1° and the values remained nearly constant throughout the irrigation period. The turbidity dynamics gradually assumed a deformed bell distribution with increasing steepness up to 7°. The average turbidity during irrigation on all variants at 7° slope was 9× and ~2× greater than it was at 1° and 3°, respectively. The introduction of PG and TL into the soil at 3° and 7° slope decreased the level of stream turbidity, but it was nearly identical to that of the control. Thus, these amendments had only weak influences on the turbidity. In summary, the turbidity of the runoff from agrochernozem subjected to simulated heavy rain tended to increase with slope.

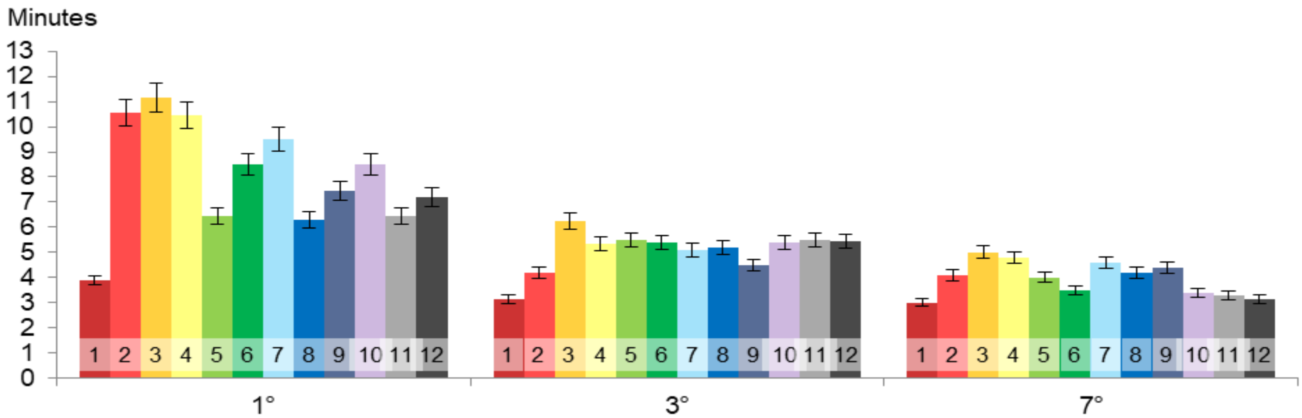

Figure 2: Time of appearance of surface runoff depending on angle of inclination and doses of FG and TL
Note: 1. C; 2. PG-5; 3. PG-10; 4. PG-20; 5. PG+TL-40 (1:10); 6. PG+TL-60 (1:10); 7. PG+TL-40 (1:5); 8. PG+TL-60 (1:5); 9. PG+TL-40 (1:2); 10. PG+TL-60 (1:2); 11. TL-40; 12. TL-60

The soil loss was 2.3 t ha^{-1} for the control at a slope of 1° (Figure 3). When the slope was increased to 3°, the soil loss increased by 4× and at 7° it had increased by 10×. The introduction of ameliorants reduced the sediment mass by 5–25% for all slopes. The lowest sediment mass during irrigation at 1° slope was measured for PG+TL-60 (1:5) and PG+TL-40 (1:2). However, the value for the latter variant was only slightly higher than that of the former. Very fine and medium silt particles (0.005–0.001 mm and 0.05–0.01 mm, respectively) were washed out in these variants and the TOC in their sediments was ~10% higher than that which was washed out of the control. The lowest soil losses at 3° and 7° slope were measured for PG+TL-60 (1:2) and PG+TL-40 (1:2). The mud fraction comprised the smallest proportion of the sediments in these variants.

At 3° and 7°, most of the particles washed out containing of very fine sand fractions. The TOC in the sediments washed out at 3° was lower than that in the sediments washed out at 1° because the flow rate and the movement of the humus- and nutrient-poor sand fraction increased with slope. Therefore, the lowest TOC was observed in sediments from the 7° slope variants.

Relative to the control, in the sediments from all PG variants, the proportions of very fine silt and very fine sand decreased and increased, respectively, because of flocculation induced by PG. Compared with the control, the sand, silt, and clay content did not significantly change in the washed-out material fertilized with TL. Even in sediments, however, a slight increase in clay content is

Table 2. Changes in turbidity (g L^{-1}) of runoff during heavy rains at different slopes

Variant	Slope, °	Turbidity of runoff						
		Runoff start	3 min from runoff onset	5 min	8 min	15 min	30 min	Average
1. C	1	3.8 ± 0.5	2.7 ± 0.4	2.7 ± 0.3	1.3 ± 0.1	1.6 ± 0.2	1.1 ± 0.1	2.2
	3	4.8 ± 0.4	11.7 ± 0.5	7.8 ± 0.6	7.0 ± 0.4	11.2 ± 0.8	10.5 ± 1.2	8.8
	7	3.8 ± 0.2	30.8 ± 0.8	23.0 ± 1.3	21.1 ± 1.4	11.6 ± 0.7	8.8 ± 0.7	16.5
2. PG-5	1	2.1 ± 0.2	1.3 ± 0.1	1.0 ± 0.1	0.9 ± 0.2	0.8 ± 0.2	0.7 ± 0.2	1.1
	3	4.4 ± 0.3	9.1 ± 0.6	8.5 ± 0.4	8.3 ± 0.4	9.0 ± 0.5	7.7 ± 0.9	7.9
	7	1.5 ± 0.1	26.4 ± 1.0	21.9 ± 1.4	14.2 ± 1.0	7.6 ± 0.6	9.2 ± 1.0	13.5
3. PG-10	1	1.5 ± 0.1	1.4 ± 0.2	1.2 ± 0.1	1.1 ± 0.2	1.0 ± 0.2	1.1 ± 0.3	1.2
	3	3.5 ± 0.2	6.9 ± 0.5	8.2 ± 0.3	7.9 ± 0.5	6.9 ± 0.3	6.9 ± 0.8	6.7
	7	1.7 ± 0.2	17.8 ± 0.7	18.5 ± 1.0	13.8 ± 0.7	7.0 ± 0.6	5.5 ± 0.7	10.7
4. PG-20	1	1.4 ± 0.1	1.5 ± 0.3	1.2 ± 0.2	1.0 ± 0.1	0.8 ± 0.1	0.8 ± 0.2	1.1
	3	2.8 ± 0.2	4.6 ± 0.5	6.5 ± 0.5	6.8 ± 0.4	5.1 ± 0.4	6.4 ± 0.6	5.4
	7	1.9 ± 0.2	12.4 ± 0.8	19.5 ± 0.8	11.9 ± 0.8	6.7 ± 0.7	6.5 ± 0.8	9.8
5. PG+TL-40 (1:10)	1	1.5 ± 0.1	1.4 ± 0.2	1.2 ± 0.2	1.0 ± 0.2	0.9 ± 0.2	0.9 ± 0.2	1.2
	3	2.8 ± 0.3	7.4 ± 0.6	7.7 ± 0.6	8.4 ± 0.5	8.6 ± 0.5	7.2 ± 1.0	7.0
	7	3.0 ± 0.4	14.0 ± 0.8	14.1 ± 0.9	10.4 ± 0.6	18.4 ± 1.1	5.6 ± 0.8	10.9
6. PG+TL-60 (1:10)	1	1.5 ± 0.2	1.1 ± 0.2	0.6 ± 0.1	0.7 ± 0.1	1.0 ± 0.1	1.7 ± 0.3	1.1
	3	2.6 ± 0.1	7.7 ± 0.6	8.1 ± 0.5	7.9 ± 0.9	7.5 ± 0.5	7.0 ± 0.5	6.8
	7	1.4 ± 0.1	15.9 ± 0.6	15.3 ± 1.0	8.5 ± 0.9	13.2 ± 0.9	8.6 ± 0.8	10.5
7. PG+TL-40 (1:5)	1	1.7 ± 0.2	1.4 ± 0.2	1.3 ± 0.3	1.0 ± 0.2	0.9 ± 0.1	0.7 ± 0.2	1.2
	3	2.7 ± 0.2	7.8 ± 0.8	8.2 ± 0.4	8.0 ± 0.5	7.9 ± 0.9	9.8 ± 0.7	7.4
	7	1.6 ± 0.1	13.5 ± 0.9	16.4 ± 0.9	9.5 ± 0.8	9.3 ± 1.0	11.4 ± 1.3	10.3
8. PG+TL-60 (1:5)	1	2.0 ± 0.1	1.0 ± 0.1	0.9 ± 0.1	1.7 ± 0.1	1.4 ± 0.2	1.2 ± 0.2	1.4
	3	5.4 ± 0.3	10.9 ± 0.3	8.8 ± 0.5	6.1 ± 0.8	11.2 ± 0.5	7.9 ± 0.6	8.4
	7	1.3 ± 0.1	12.7 ± 0.7	18.6 ± 0.9	13.5 ± 1.0	4.7 ± 0.6	4.8 ± 0.5	9.3
9. PG+TL-40 (1:2)	1	1.2 ± 0.2	0.9 ± 0.2	0.9 ± 0.2	1.0 ± 0.3	0.8 ± 0.2	0.8 ± 0.2	0.9
	3	3.5 ± 0.2	4.6 ± 0.3	7.5 ± 0.7	5.9 ± 0.8	6.2 ± 0.5	5.3 ± 0.3	5.5
	7	1.3 ± 0.1	11.6 ± 0.6	13.0 ± 0.8	8.5 ± 1.0	7.2 ± 0.7	6.2 ± 0.7	8.0
10. PG+TL-60 (1:2)	1	2.0 ± 0.1	1.6 ± 0.1	1.4 ± 0.1	1.0 ± 0.1	1.2 ± 0.2	1.0 ± 0.1	1.4
	3	1.7 ± 0.1	7.1 ± 0.5	8.1 ± 0.5	9.8 ± 0.6	7.1 ± 0.7	10.0 ± 0.7	7.3
	7	1.6 ± 0.1	11.8 ± 1.0	12.9 ± 0.8	8.3 ± 0.6	8.4 ± 0.9	5.6 ± 0.7	8.1
11. TL-40	1	1.6 ± 0.1	0.6 ± 0.1	0.9 ± 0.1	1.0 ± 0.2	1.0 ± 0.1	0.7 ± 0.2	1.0
	3	3.0 ± 0.3	7.2 ± 0.4	7.8 ± 0.9	9.2 ± 0.8	8.1 ± 0.6	8.1 ± 0.9	7.2
	7	3.6 ± 0.2	10.3 ± 0.6	20.0 ± 1.3	13.9 ± 1.1	9.8 ± 1.0	4.6 ± 0.6	10.4
12. TL-60	1	1.5 ± 0.1	1.5 ± 0.1	0.9 ± 0.2	0.8 ± 0.1	0.9 ± 0.2	0.8 ± 0.2	1.1
	3	2.0 ± 0.2	7.2 ± 0.5	8.1 ± 0.9	9.8 ± 0.7	7.9 ± 0.7	7.6 ± 0.6	7.1
	7	1.6 ± 0.1	21.6 ± 1.2	22.1 ± 1.4	21.6 ± 1.2	8.9 ± 0.9	8.0 ± 0.5	14.0

Note: for all variants, the differences between treatments and slopes in terms of turbidity at the beginning of runoff were insignificant. Three- to five minutes after the onset of runoff, the turbidity increased depending on the degree of the slope. It was significantly higher ($p< 0.01$) on 7° ($p< 0.01$) than on 3° and significantly higher on 3° ($p< 0.01$) than on 1°. From 8 min onward, the relative differences in turbidity between the 3° and 7° slopes smoothed out and remained significantly higher than that for the 1° slope.

accompanied by a slight increase in organic matter. Erosion usually washes out the humus-rich silt and clay fractions (Sato and Kuwano, 2018; Nyawade *et al.*, 2018).

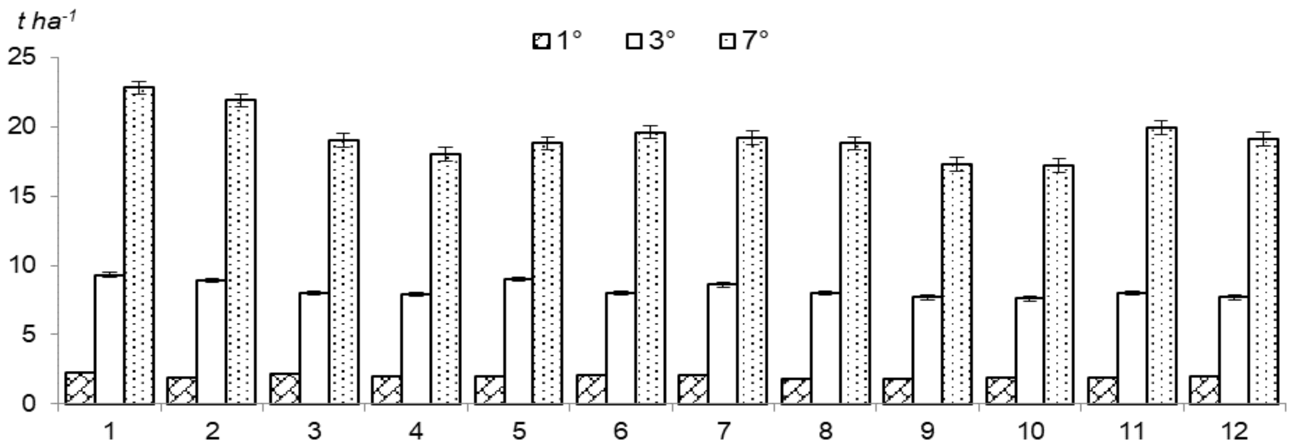

Figure 3: Soil losses on different slopes after artificial rainfall
Note: 1. C; 2. PG-5; 3. PG-10; 4. PG-20; 5. PG+TL-40 (1:10); 6. PG+TL-60 (1:10); 7. PG+TL-40 (1:5); 8. PG+TL-60 (1:5); 9. PG+TL-40 (1:2); 10. PG+TL-60 (1:2); 11. TL-40; 12. TL-60

As stated in the Materials and Methods, we performed a three-year field study on the impact of PG and TL on agrochernozem properties and crop yields. This trial was conducted on the same slope as that where the monoliths were taken and used the same amendment variants as before. Previously, potatoes had been grown on the experimental plots. The addition of PG and TL increased yield by 14–120%. The highest gains were determined for the TL variants at 40 and 60 t ha^{-1}. The amendments also affected the hydrological and agrochemical properties of the soil in the arable (0–20 cm) layer. Relative to the control, the structure of the amended soil improved. The number of agronomically valuable and water-resistant aggregates increased. Bulk density decreased while air porosity and soil moisture content increased. The water level rose from 150 mm to 170 mm. The TOC content increased from 3.6% to 4.2%, and the nitrogen, phosphorus, and potassium levels also increased. The pH rose from weakly acidic to neutral. Therefore, the introduction of PG and TL into moderately eroded agrochernozem in the Southern *Cis*-Ural increased crop yield, improved soil properties, and reduced water erosion.

Conclusion

When an untreated agrochernozem was subjected to a simulated rain intensity of 360–420 mm h^{-1} (heavy rain), maximum soil loss was observed at the 7° slope. It was 10× and 2.5× higher than those at 1° and 3°, respectively. Introduction of PG and TL separately or in combination significantly increased soil resistance to water erosion. All amendments reduced soil loss, but the lowest sediment weights were determined for the PG:TL variants. This effect increased with ratio (1:10, 1:5, 1:2) when a higher ameliorant dose (60 t ha^{-1}) was used. Regardless of steepness, the silt and clay fractions predominated in the sediment and their TOC content was somewhat higher than that of the soil before irrigation. Increasing the doses of PG at 1° slope did not significantly affect runoff intensity. Increasing the steepness to 3° incrementally raised erosion resistance. At 7°, however, runoff resistance decreased with PG dose. PG and TL could be effective agricultural soil amendments which could reduce the risk of water erosion and increase crop productivity.

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