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Evaluation of Soil Manipulation to Prepare Engineered Earthen Waste Covers for Revegetation

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Abstract

Seven ripping treatments designed to improve soil physical conditions for revegetation were compared on a test pad simulating an earthen cover for a waste disposal cell. The field test was part of study of methods to convert compacted-soil waste covers into evapotranspiration covers. The test pad consisted of a compacted layer of fine-textured soil simulating a barrier protection layer overlain by a gravelly sand bedding layer and a cobble armor layer. Treatments included combinations of soil-ripping implements (conventional shank [CS], wing-tipped shank [WTS], and parabolic oscillating shank with wings [POS]), ripping depths, and number of passes. Dimensions, dry density, moisture content, and particle size distribution of disturbance zones were determined in two trenches excavated across rip rows. The goal was to create a root-zone dry density between 1.2 and 1.6 Mg m^{-3} and a seedbed soil texture ranging from clay loam to sandy loam with low rock content. All treatments created V-shaped disturbance zones as measured on trench faces. Disturbance zone size was most influenced by ripping depth. Winged implements created larger disturbance zones. All treatments lifted fines into the bedding layer, moved gravel and cobble down into the fine-textured protection layer, and thereby disrupted the capillary barrier at the interface. Changes in dry density within disturbance zones were comparable for the CS and WTS treatments but were highly variable among POS treatments. Water content increased in the bedding layer and decreased in the protection layer after ripping. The POS at 1.2-m depth and two passes created the largest zone with a low dry density (1.24 Mg m^{-3}) and the most favorable seedbed soil texture (gravely silt loam). However, ripping also created large soil aggregates and voids in the protection layer that may produce preferential flow paths and reduce water storage capacity.

Core Ideas

- Soil-forming and ecological processes are changing engineering properties of earthen covers.
- These changes may transform compacted soil designs into evapotranspiration covers.
- Ripping implements were tested as a way to enhance transformation of layered rock/soil covers.
- Disturbed soil volume, cover layer mixing, and change in dry density were greater for winged rippers.
- Ripping also created large soil aggregates and voids in compacted soil layers.

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Natural soil-forming and ecological processes can change the engineering properties of earthen covers for waste containment (NRC, 2011). The US Department of Energy (USDOE) is evaluating the effects of these changes on cover performance and options for long-term stewardship of waste disposal cells (USDOE, 2013, 2014). Many engineered covers include an earthen barrier layer composed of compacted fine-textured soil designed to control percolation of meteoric water and migration of gases out of the waste (USDOE, 1989). Earthen barrier layers are often overlain by a compacted protection layer intended to prevent damage from freeze–thaw and wet–dry cycles. Some covers are armored at the surface with a durable cobble layer designed to withstand water and wind erosion (NRC, 2002).

The as-built engineering properties of earthen covers are subject to change by natural ecological and soil-forming processes over relatively short time periods regardless of climate or the type of cover design (Benson et al., 2007, 2008; Waugh et al., 1999, 2007; NRC, 2011). A rock-armored surface can create favorable habitat for deep-rooted plants in all climates by reducing soil evaporation, increasing soil water storage, and trapping windblown dust, thereby providing water and nutrients for plant germination and establishment (Groenevelt et al., 1989; Waugh et al., 1994; Kemper et al., 1994; Sackschewsky et al., 1995). Tap roots often extend vertically through armor and bedding layers and then branch and spread laterally at the interface with an underlying protection layer. Secondary and tertiary roots often extend vertically into and through protection and barrier layers where they become fibrous root mats following soil structural planes (Albright et al., 2006b; Benson et al., 2008; Waugh et al., 1999, 2007; USDOE, 1990, 1992).

Within 5 to 10 yr, natural soil-forming processes create structure with larger pores in compacted fine-textured soil layers, increasing porosity and saturated hydraulic conductivity and reducing the air entry pressure, sometimes by several orders of magnitude (Benson et al., 2007; Waugh et al., 1999, 2007; Albright et al., 2006a,b; NRC, 2011). Percolation rates and gas

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Abbreviations: CS, conventional shank; POS, parabolic oscillating shank with wings; USDOE, US Department of Energy; WTS, wing-tipped shank.

fluxes may increase as a result of these changes (NRC, 1989; Lewis and MacDonell, 1990; Morris and Fraley, 1989; Albright et al., 2006a,b, 2010). Processes that initiate these changes include freeze–thaw and desiccation cracking (Kim and Daniel, 1992; Benson and Othman, 1993; Albrecht and Benson, 2001), retention of borrow soil structure during construction (NRC, 2011; Albright et al., 2006), and biointrusion (Hakonson, 1986; Suter et al., 1993; Bowerman and Redente, 1998; NRC, 2011). Changes in hydraulic properties after construction are generally greater in less permeable, highly compacted clayey soil layers than in more permeable, less compacted, less clayey soils (Benson et al., 2007; NRC, 2011). Over time, the hydraulic properties of cover soils become similar to the original undisturbed borrow soil properties regardless of the as-built condition (NRC, 2011).

These natural changes in engineered soil properties may also introduce an alternative means for controlling percolation in the long term. In arid and semiarid ecosystems, relatively low precipitation, high potential evapotranspiration, and thick unsaturated soils often limit percolation and recharge (Gee and Tyler, 1994; Scanlon et al., 2005). Disposal cell covers designed to mimic this natural soil water balance, often referred to as water balance covers or evapotranspiration covers (Albright et al., 2010), can provide hydraulic isolation in semiarid and arid regions (Albright et al., 2004; Anderson et al., 1993; Ward and Gee, 1997; Waugh et al., 2009; Benson and Bareither, 2012; Apiwantragoon et al., 2015). Therefore, natural soil-forming and ecological processes that slowly transform engineered earthen covers with compacted fine-textured layers into vegetated soil profiles resembling water balance covers may provide long-term advantages compared with the original compacted soil designs (USDOE, 2013, 2014).

Reclamation of drastically disturbed land (e.g., mine land reclamation) often involves soil manipulation and revegetation practices that accelerate these natural processes (Munshower, 1993; Barnhisel et al., 2000; Glenn et al., 2001; Sinnett et al., 2006; Albright et al., 2010). Similar methods might be used to accelerate and enhance transformation of engineered earthen covers with compacted fine-textured soil layers. Common soil manipulation methods include the use of plows, chisels, disks, and harrows to loosen compacted soils, kill shallow-rooted weeds, break up large clods, and incorporate amendments and fertilizers. Less common methods include ripping, gouging, and dozer basins for deeper loosening and mixing of soil layers, trapping water in depressions, and disrupting slippage planes on slopes (Dollhopf et al., 1977; Munshower, 1993; Montalvo et al., 2002). At arid and semiarid sites, loosening the soil and roughening the soil surface can create micro-environments for plant germination and establishment (Munshower, 1993). Ripping a highly compacted soil layer so that the soil bulk density (or dry density) is more optimal (1.2–1.6 Mg m^{-3}) (Sheley et al., 2008) allows roots to more easily exploit the water and nutrients in that layer (Andrus and Froehlich, 1983; Sinnett et al., 2006), enhancing revegetation success (Montalvo et al., 2002). Ripping or furrowing on the contour also creates depressions or "microcatchments" that store runoff water, a form of water harvesting (Fidelibus and Bainbridge, 2006), and reduce erosion (Dollhopf et al., 1977; Dollhopf, 1985). Blending the protection and armor layers, thereby creating a clay loam to sandy loam soil with low rock content near the surface, may increase water and nutrient retention, creating a more favorable seedbed for native plants (Bradshaw and Chadwick, 1980; McLendon and Redente, 1997; Colorado Natural Areas Program, 1998; Sheley et al., 2008).

This paper describes the first phase of a study conducted for USDOE to evaluate the effectiveness of physical soil manipulation methods to accelerate transformation of engineered earthen covers that rely on compacted fine-textured soil layers armored with rock, with the goal of enhancing soil conditions for water storage, vegetation establishment, and evapotranspiration. Results of a field experiment are reported where the compacted fine-textured protection layer, coarse-grained bedding layer, and cobble armor were manipulated in a test pad constructed at a waste disposal site near Grand Junction, Colorado. Three soil-ripping implements were tested to evaluate their ability to loosen the protection layer (reduce dry density) and bring fine-textured soil up into the bedding and armor layers, creating a more favorable soil texture for revegetation. This paper focuses on the extent of soil loosening and vertical mixing of cover layers using heavy equipment implements designed for soil ripping. A complementary study evaluating the effects of soil physical manipulation on soil hydraulic properties and revegetation success is ongoing.

Materials and Methods

Construction of the test pad used the same materials, design, construction specifications, and placement methods used for the upper three layers of the full-scale cover at the USDOE Grand Junction disposal site (Fig. 1; from top to bottom: an armor layer, a bedding layer, and a protection layer). The compacted barrier layer in the full-scale cover was not included in the test pad because the intention was to manipulate layers above the barrier layer.

The test pad is 23 m wide by 45 m long, with the longitudinal dimension oriented along the contour, and graded to maintain a 2% slope (Fig. 2). The test pad is divided into three areas (Fig. 2): two larger areas for the revegetation study and a smaller, central area for the soil manipulation study. Soil manipulation treatments ranged from shallow ripping into the surface of the

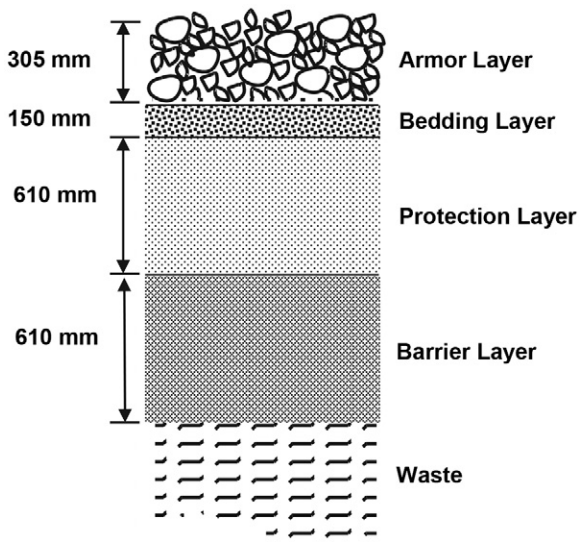

Fig. 1. Profile of earthen cover over waste.

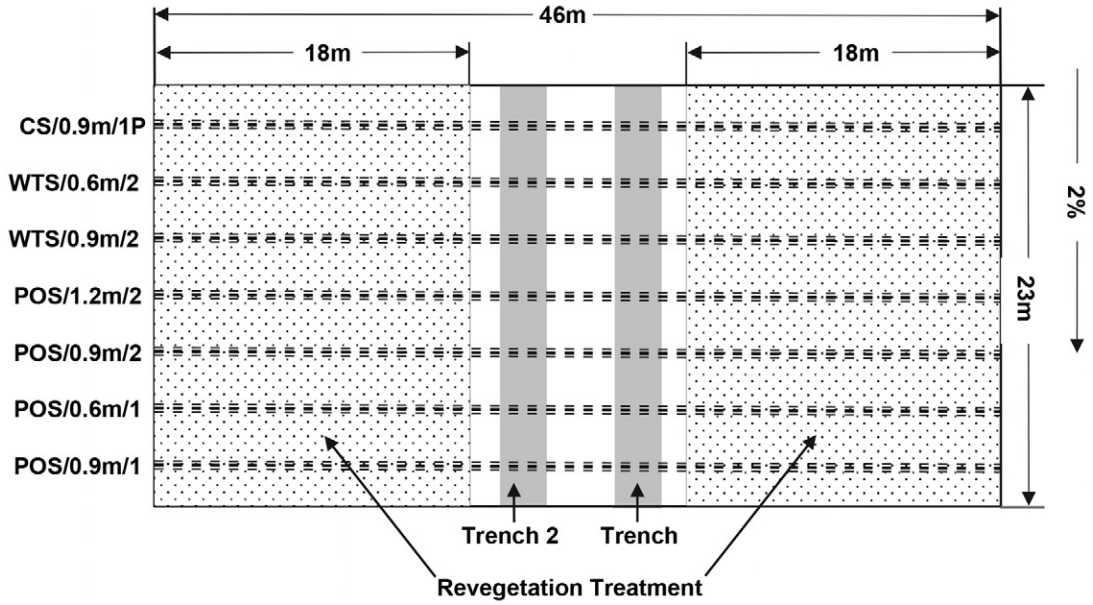

Fig. 2. Plan view schematic of test pad showing revegetation treatment areas, central area for destructive sampling with locations of exhumation trenches, and contours used for soil manipulation treatments. See Table 2 for treatment descriptions.

protection layer to deep ripping and blending of the armor, bedding, and protection layers. The test pad was constructed in June 2010, ripped in August 2011, and sampled in May 2012. The periods between construction, ripping, and sampling exposed the cover profile to internal settlement and compression as well as seasonal wet–dry and freeze–thaw cycles, both before and after ripping.

Soils and Placement Conditions

Geotechnical index properties of the cover soils, as defined by American Society for Testing and Materials classification ASTM D2487, are summarized in Table 1. The protection layer is fine-textured moderately plastic clay, the bedding layer is well-graded coarse sand, and the armor layer is cobble and gravel with 90% of the particle sizes between 47 and 108 mm.

Soil for the protection layer was moisture conditioned to a target gravimetric water content of 14.5%, placed in three 200-mm lifts, and compacted with three passes of a Case 1150G dozer. The protection layer is not a barrier for liquids and gases, and therefore a minimum dry density was not specified for this layer. However, dry density and water content of each lift of the protection layer were measured during construction at three randomly selected locations using a nuclear density gauge in accordance with ASTM D6938. Dry density ranged between 1.67 and 1.80 Mg m^{-3} (93–101% compaction), and gravimetric water content ranged between 12.3 and 17.0%. The bedding and armor layers were spread with the Case 1150G dozer without compaction control, as was done on the full-scale cover, and grade control for each layer was maintained with a laser level.

Soil Manipulation Treatments

Seven soil manipulation treatments were applied using three different implements: (i) a conventional ripping shank with a wingless tine (CS), (ii) a conventional ripping shank with a winged tine (WTS), and (iii) a parabolic oscillating shank with adjustable wings (POS) (Table 2; Fig. 3, 4). Ripping involved pulling a shank through the soil to break up or "shatter" compacted soil (Steinfeld et al., 2007).

The CS treatment used a "variable giant ripper" (Fig. 3a). The WTS treatment consisted of the same conventional shank pulled by a Komatsu 155AX dozer but tipped with a winged tine (Fig. 3b). The winged tine, based loosely on designs by Andrus and Froehlich (1983) and Cass et al. (2003), was fabricated by welding a 12-mm-thick triangular steel plate to the shoe of a conventional tine. The 550-mm-wide wing (Fig. 3b) was positioned to create a 20° rake angle as recommended by Cass et al. (2003). The POS treatment used a "vibrosoiler" developed by California Agricultural SoilWorks LLC to prepare soils for planting vineyards. This patented implement has a parabolic shank with adjustable wings that hydraulically move up and down as the shank is pulled through the soil (Fig. 3c). A Caterpillar Challenger with rubber tracks and low ground pressure pulled the POS.

Conventional shanks generally create a relatively narrow band of soil disturbance with limited mixing (Andrus and Froehlich,

Table 1. Geotechnical index properties of soils used for test pad.†

Layer	% Fines	% Sand	% Gravel	% Cobbles	Liquid limit	Plasticity index	USCS‡ designation
Armor	0	0	31	69	–§	–	none
Bedding	7	35	50	0	–	–	SW
Protection	94	6	0	0	43	27	CL-CH

† Fines < 0.074 mm, 0.074 < sand < 4.8 mm, 4.8 < gravel < 75 mm, 75 < cobble < 305 mm.

‡ Unified Soil Classification System.

§ Dash indicates no test was conducted.

Table 2. Treatment details for the rip test pad.

Ripping implement	Ripping depth† and number of passes	Equipment
Conventional shank (CS)	0.9 m, one pass (CS/0.9m/1P)	Komatsu 155AX dozer
Wing-tipped shank (WTS)	0.6 m, two passes (WTS/0.6m/2P) 0.9 m, two passes (WTS/0.9m/2P)	Komatsu 155AX dozer
Parabolic oscillating shank (POS)	0.6 m, one pass (POS/0.6m/1P) 0.9 m, one pass (POS/0.9m/1P) 0.9 m, two passes (POS/0.9m/2P) 1.2 m, two passes (POS/1.2m/2P)	Caterpillar Challenger

† Ripping depth is measured from the surface of the cobble armor layer.

1983; Cass et al., 2003). The WTS and POS treatments were evaluated as a means to laterally loosen a larger volume of soil and to achieve greater mixing compared with that obtained with the CS treatment. Winged tines can also break up deeper compacted soil and mix soil more thoroughly than wingless tines (Spoor and Godwin, 1978; Croton and Ainsworth, 2007). The winged POS reportedly loosens and mixes an even broader and deeper zone, achieves greater uniformity of soil loosening, and, due to the oscillating action, requires less draft energy compared with a stationary shank to break up and mix a given volume of compacted soil (Alfred P. Cass, personal communication, 2010).

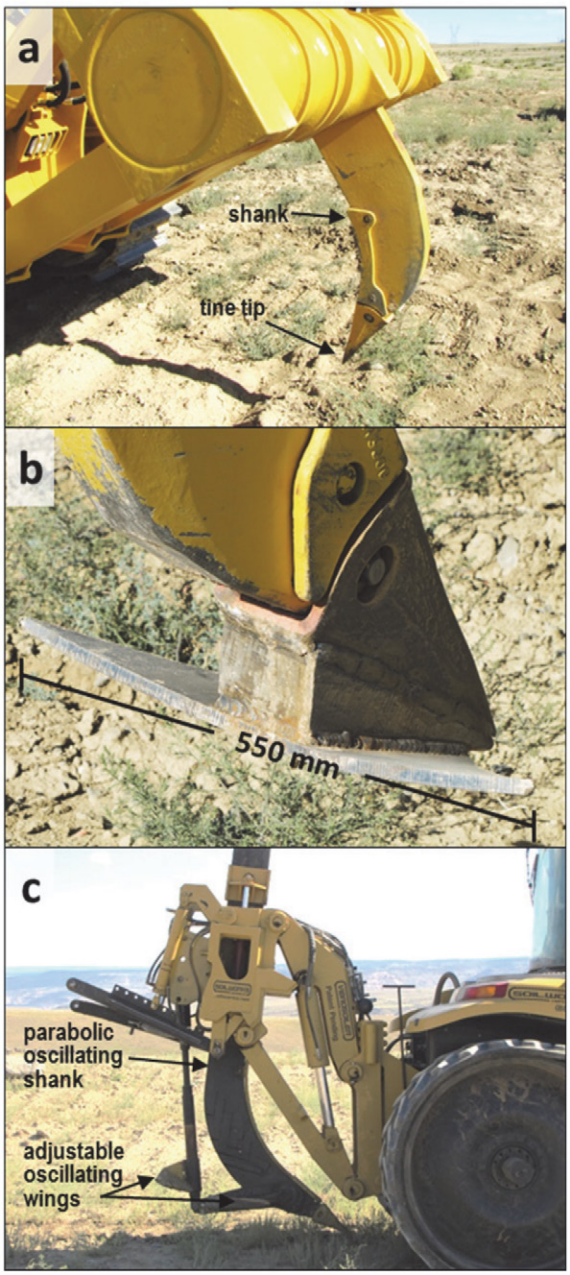

Fig. 3. Photos of the conventional shank with a wingless tine (CS) (a), conventional shank with a wing-tipped tine (WTS) (b), and the parabolic oscillating shank with adjustable wings (POS) (c).

Exhumation, Sampling, and Analysis

Two 1.5-m-wide trenches were excavated to the subgrade and across the width of the test pad with a trackhoe in May 2012 (Fig. 2) to observe the soil structure, measure soil properties in situ, and collect samples for analysis. For each ripping treatment, the depth and width of soil disturbance was measured, photographed, and marked with pin flags on trench faces (Fig. 4). Depths were measured from the interface of the bedding and protection layers to the lowest observed point of disturbance, widths were measured at the interface, and the area of disturbance as observed on a trench face was calculated.

Particle size distributions of samples collected from above and below the original interface between the bedding and protection layer were determined using a combination of ASTM D5519 and ASTM D422. The bulk samples were thoroughly blended before testing to eliminate segregation that may have occurred during transportation to the laboratory. Each sample was hand washed over a US No. 200 sieve to separate the fine and coarse fractions. The coarse fraction was mechanically sieved following the method in ASTM D422 using a standard sieve set with a 25-mm sieve at the upper end. The portion retained on the 25-mm sieve was analyzed using Method A of ASTM D5519, with the size and weight of each particle measured by hand. The fines fraction was analyzed by sedimentation using a hydrometer (ASTM D 422).

Dry density and water content were measured at the original interface of the bedding and protection layers using a nuclear density gauge. Bulk samples were also collected above and below the original interface in 20-L buckets for laboratory analysis of gravimetric water content according to ASTM D 2216 and particle size analysis. Cobble remaining on the surface was not removed before sampling.

Results and Discussion

Zone of Disturbance

Cross-sectional dimensions of the zone of disturbance for each treatment, measured on faces of trenches excavated in the central region of the test pad, are summarized in Table 3. The zone of disturbance for all treatments generally was V-shaped (i.e., wider near the surface and narrower at the bottom) (Fig. 4). The depths, widths, and cross-sectional areas of disturbance

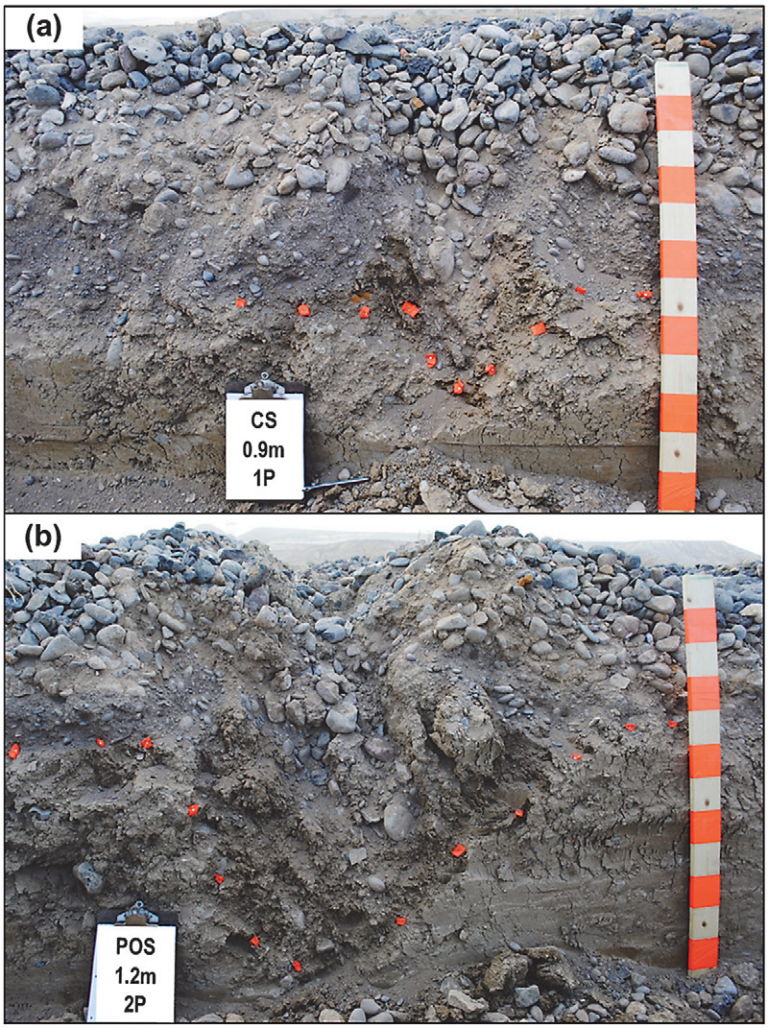

Fig. 4. Example photos of the cross-sectional disturbance zones for soil manipulation treatments (a) CS/0.9m/1P (conventional shank with a wingless tine, 0.9 m depth, one pass) and (b) POS/1.2m/2P (parabolic oscillating shank with adjustable wings, 1.2 m depth, two passes). Scale is in increments of 0.1 m. The orange-flagged pins mark the original interface between the bedding and protection layers and the area of disturbance.

observed on trench faces varied greatly among ripping treatments and between the two trench faces for a given treatment (Table 3; Fig. 5, 6). The disturbed zones generally were larger in Trench 2 than in Trench 1 (depths 0.9–1.5 times greater, widths 0.9–10.9 times greater, cross-sectional area 0.7 and 7.0 times greater). The two WTS treatments were most variable in the width of disturbance; the POS treatment at 1.2 m depth was most variable in depth of disturbance (Fig. 6).

Although variability was high, several treatment differences were evident. In a comparison of treatments with the same depth of ripping and number of passes, measurements suggest that the winged implements disturbed a greater cross-sectional area than the conventional shank and that the disturbed areas of soil for the two winged implements were similar. The cross-sectional area of disturbance for the POS treatment was more than twice that for the CS treatment at 0.9 m depth/one pass (0.9m/1P), and the depth of disturbance for the POS was nearly twice that

Table 3. Dimensions of the zones of disturbance.

Treatment†	Trench 1				Trench 2			
	Cross-sectional area	Width‡	Depth§	W/D	Cross-sectional area	Width	Depth	W/D
	m^2	——— m ———			m^2	——— m ———		
CS/0.9m/1P	0.02	0.18	0.23	0.8	0.08	0.46	0.34	1.4
WTS/0.6m/2P	0.02	0.10	0.29	0.4	0.21	1.16	0.37	3.2
WTS/0.9m/2P	0.14	0.64	0.45	1.4	0.32	1.14	0.56	2.0
POS/0.6m/1P	0.05	0.40	0.23	1.7	0.10	0.55	0.36	1.5
POS/0.9m/1P	0.14	0.66	0.43	1.5	0.26	0.98	0.53	1.8
POS/0.9m/2P	0.25	0.83	0.60	1.4	0.20	0.72	0.55	1.3
POS/1.2m/2P	0.38	1.10	0.70	1.6	0.85	1.23	1.37	0.9

† Treatments are defined in Table 2.

‡ Width of disturbance measured at original interface between the bedding and protection layers.

§ Depth measured from the original interface between the bedding and protection layers to the lowest point of disturbance. This differs from the "ripping depth" shown in Table 2.

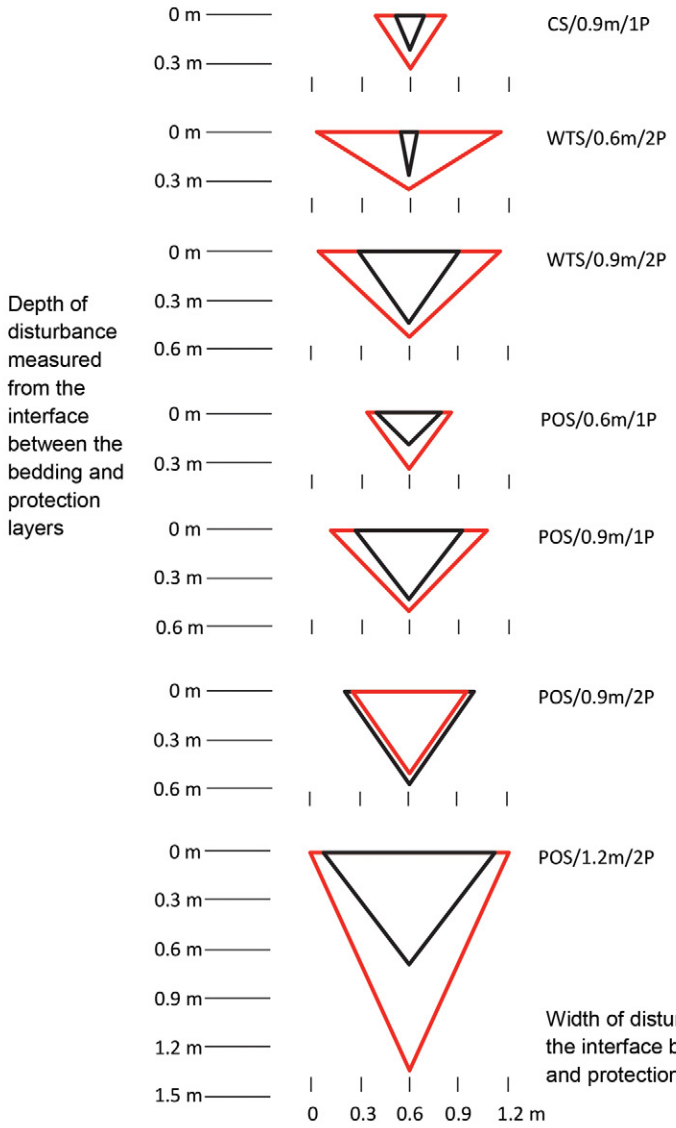

Fig. 5. Vertical and horizontal dimensions of disturbance from treatments. Black triangles are for Trench 1; red triangles are for Trench 2. See Table 2 for treatment descriptions.

of the CS. In contrast, at 0.9m/2P, the widths, depths, and cross-sectional areas of disturbance were similar for the POS and WTS treatments (Table 3; Fig. 5, 6). Additional passes did not necessarily increase measures of soil disturbance. Widths, depths, and cross-sectional areas of disturbance for one versus two passes of the POS at the 0.9-m depth were similar.

Type of implement and depth of ripping had little effect on the width-to-depth ratio (Fig. 6c). However, the cross-sectional area of disturbance was influenced more by the depth than by the width of disturbance (Fig. 7). The POS treatment at 1.2 m depth with two passes (POS/1.2m/2P), the deepest treatment, had the greatest width, depth, and area of disturbance of all treatments in both trenches (Table 3; Fig. 5, 6).

Soil Mixing

Particle size distributions and soil textural classes above and below the original interface between the bedding and protection layers are summarized in Table 4 for each treatment. The four primary particle size classes (fines, sand, gravel, and cobbles as defined in ASTM D 422) are also shown graphically in Fig. 8 for conditions above and below the original interface of the bedding and protection layers. The shape of each diamond in Fig. 8 depicts the relative quantities of cobbles, gravel, sand, and fines (see Table 4 footnote for definitions); a vertically and horizontally symmetric diamond would have equal amounts of the four particle size fractions.

Before treatment, the bedding layer above the interface was composed primarily of sand and gravel (tall and slender red diamonds in Fig. 8). The preripping size fractions of the protection layer (93% fines and 7% sand; silty clay loam) would appear as a horizontal line on the fines axis in Fig. 8 and are not shown. The black diamonds (above the interface in the bedding layer) and green diamonds (below the interface in the protection layer) depict size fractions after ripping.

Moving fine-textured soil into the bedding and rock layers may improve conditions for successful revegetation. Loam soil texture is considered ideal (Sheley et al., 2008); however, many species are adapted to soils higher in sand or clay. Mixing of fines from the protection layer into the bedding layer varied considerably among treatments, as evinced by comparisons of the red and black diamonds in Fig. 8. Preripping fractions in the bedding layer were 7% fines, 35% sand, 50% gravel, and 8% cobble (very gravely loamy sand). After ripping, the fines fractions ranged from 9 to 50%, the sand fractions ranged from 14 to 36%, the

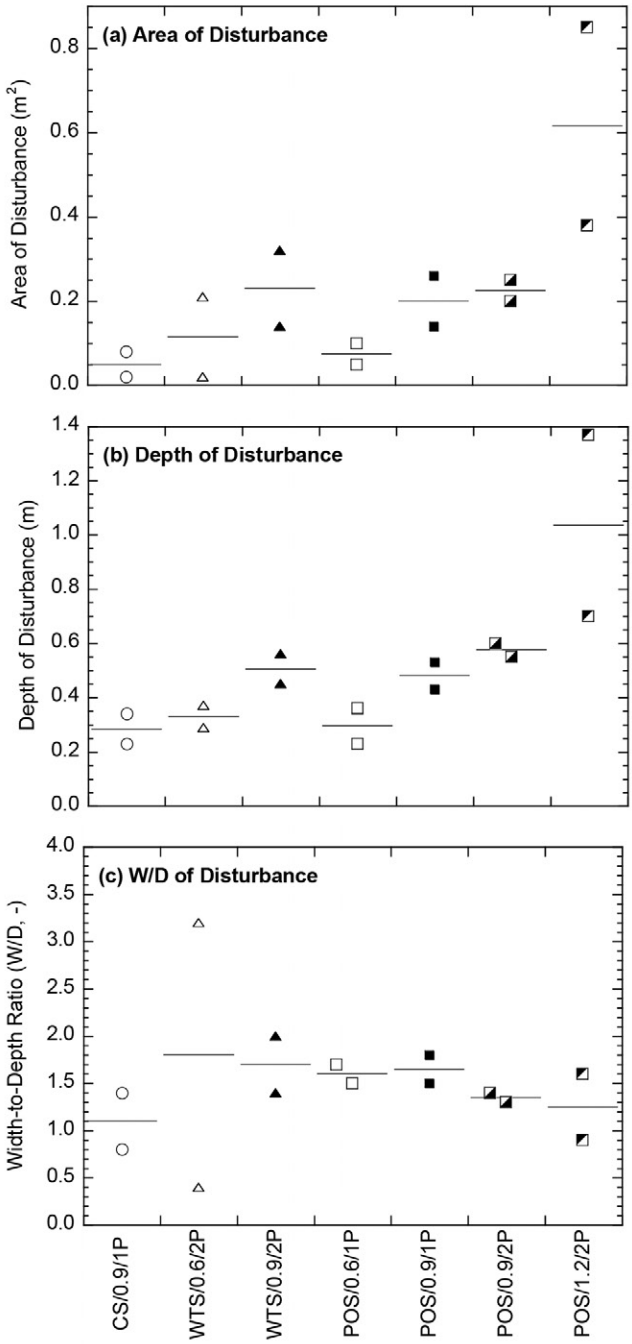

Fig. 6. Dimensions of zone of soil disturbance for each treatment: area (a), depth (b), and width-to-depth ratio (c). See Table 2 for treatment descriptions.

gravel fractions ranged from 13 to 45%, and the cobble fractions ranged from 5 to 44%. The postripping fractions of fines in the bedding layer exceeded 40% for two treatments (WTS/0.9m/2P, POS/1.2m/2P) and exceeded 30% for two additional treatments (CS/0.9m/1P, POS/0.6m/1P). The POS/1.2m/2P treatment drew the highest percentage of fines (49%) up into the bedding layer, changing the top layer to a gravely silt loam. The CS implement with one pass (CS/0.9m/1P) evenly blended materials both above and below the interface as well as or better than the winged WTS and POS implements with two passes. The CS ripping brought fines up into the bedding layer and blended sand, gravel, and cobbles down into the protection layer, creating

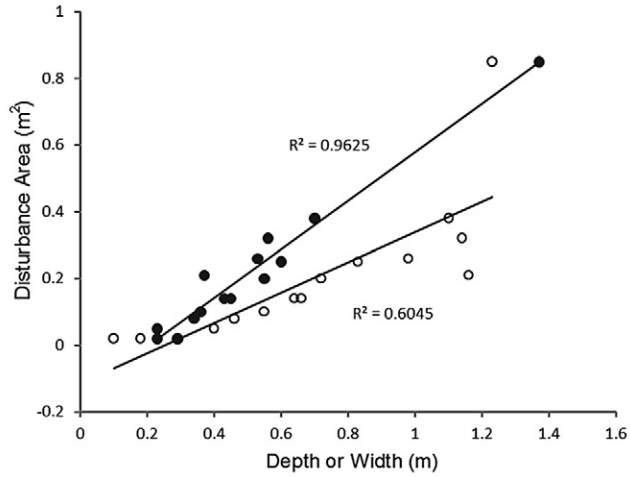

Fig. 7. Comparison of simple linear correlations of disturbance area with disturbance depth (closed circles) and disturbance width (open circles).

similar postripping particle size fractions in the two layers (Fig. 8a).

At the 0.6-m depth, the WTS (WTS/0.6m/2P) extended about 0.15 m into the top of the protection layer but drew few fines up into the bedding layer (Fig. 8b). However, the WTS/0.6m/2P treatment effectively blended cobbles, gravel, and sand from the armor and bedding layers into the protection layer, creating nearly equal particle size fractions (Fig. 8b). With the shank extended about 0.45 m into the protection layer, the WTS/0.9m/2P effectively blended cobbles, gravel, and sand into the protection layer and drew up more fines into the bedding layer but blended down fewer cobbles and gravels into the bedding layer (Fig. 8c).

The POS/0.6m/1P treatment was as effective as the CS/0.6/1P treatment in bringing fine soil up into the bedding layer but brought fewer cobbles down into the bedding layer than the CS or WTS treatments (Fig. 8d). The POS/0.6m/1P treatment also moved less cobble, gravel, and sand into the protection layer (20% or less for each fraction) than the CS or WTS treatments. Increasing the depth of the POS to 0.9 m (POS/0.9m/1P) produced similar results (Fig. 8e), but using two passes at the 0.9-m depth (POS/0.9m/2P) effectively blended both the bedding and protection layers (Fig. 8f), creating fairly even particle size fractions in both layers, similar to the CS treatment. Increasing the depth of the POS to 1.2 m and using two passes (POS/1.2m/2P) moved the greatest fractions of fine soil up into the bedding layer and cobbles down into the protection layer (Fig. 8g).

Soil Density and Water Content

Reducing soil compaction may also enhance conditions for successful revegetation. Dry density and gravimetric water content, sampled after ripping both above and below the original interface of bedding and protection layers, are summarized in Table 5 and shown by treatment in Fig. 9 and 10. Most ripping treatments reduced the dry density of bedding and protection layers when compared with controls (Fig. 9) and with dry densities at the time of construction (see Soils and Placement Conditions). Exceptions included (i) the bedding layer after

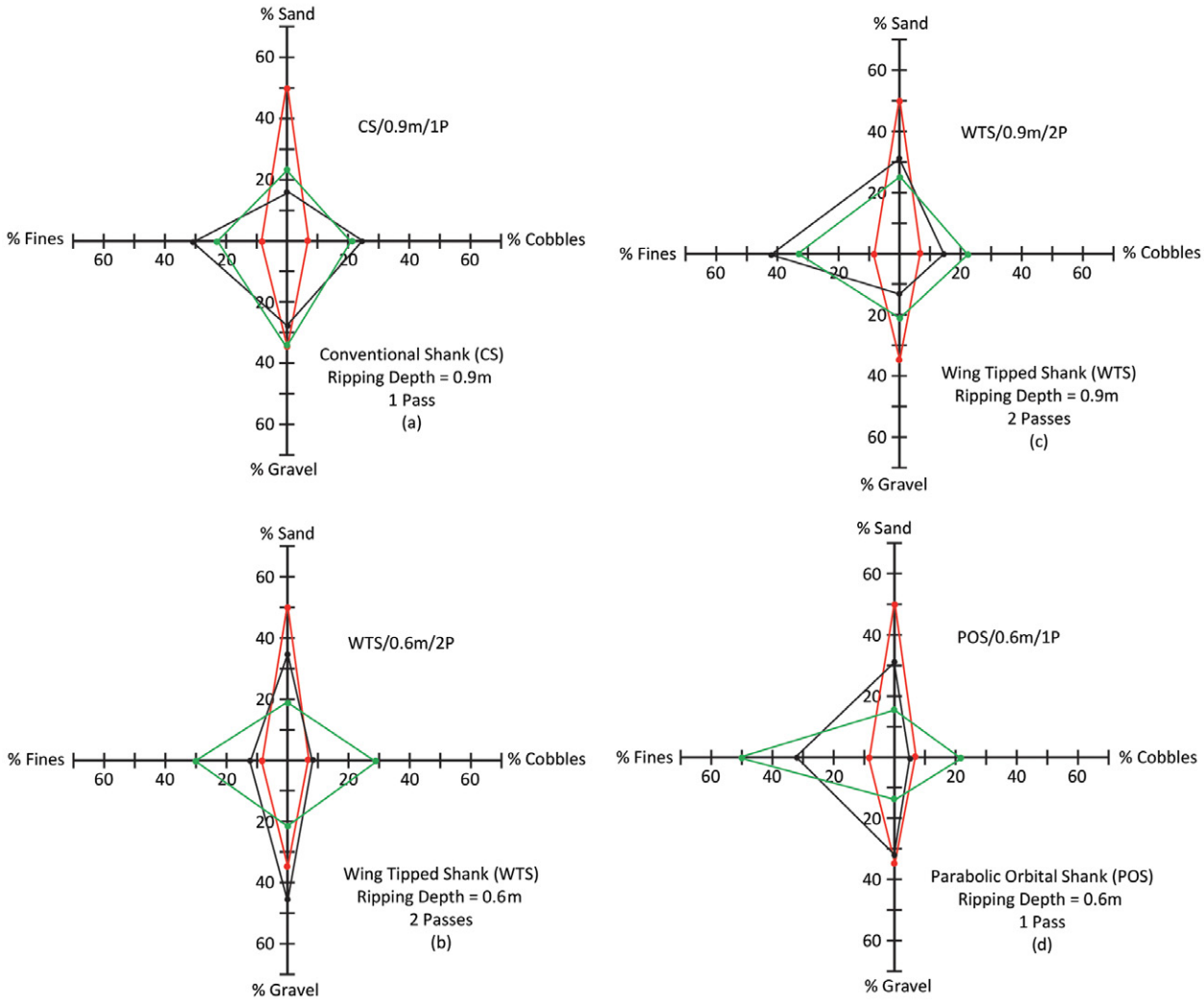

Fig. 8. Percentages cobbles, gravel, sand, and fines immediately above the original interface between the compacted fine-textured protection layer and the coarse-textured bedding layer. Red lines show the particle size distribution before disturbance; black lines show the particle size distribution after disturbance. Green lines show the zone associated with the protection layer after disturbance. See Table 2 for treatment descriptions.

Table 4. Summary of particle size fractions for samples collected at exhumation.

Treatment†	Sampling location	Particle size‡					
		Cobbles or larger	Gravel	Sand	Fines§	Silt	Clay
		%					
CS/0.9m/1P	above	24	28	17	31	18	13
CS/0.9m/1P	below	21	33	23	23	13	10
WTS/0.6m/2P	above	9	45	34	12	–¶	–
WTS/0.6m/2P	below	29	22	19	30	17	13
WTS/0.9m/2P	above	14	13	31	42	20	22
WTS/0.9m/2P	below	22	21	24	33	18	15
POS/0.6m/1P	above	5	32	31	32	18	14
POS/0.6m/1P	below	21	14	15	50	24	26
POS/0.9m/1P	above	14	41	36	9	–	–
POS/0.9m/1P	below	9	15	25	51	32	19
POS/0.9m/2P	above	27	31	20	22	12	10
POS/0.9m/2P#	below	44	11	14	31	19	12
POS/0.9m/2P	below	20	18	30	32	19	13
POS/1.2m/2P	above	7	18	26	49	44	5
POS/1.2m/2P	below	42	12	16	30	16	14

† Treatments are defined in Table 2.

‡ Particle sizes per USCS classification as defined in ASTM D2487 (cobbles > 75 mm, 75 mm > gravel > 4.75 mm, 4.75 mm > sand > 0.075 mm, fines < 0.075 mm, 0.002 mm > silt < 0.075 mm).

§ Fines = silt + clay.

¶ Dash indicates sedimentation analysis not performed for these samples. "Above" sampling location is above the original interface between the bedding and protection layers after removal of the armor layer. "Below" sampling location is at a depth of 0.3 m below the original interface between the bedding and protection layers after removal of the armor layer.

POS/0.9m/2P Below had duplicate samples.

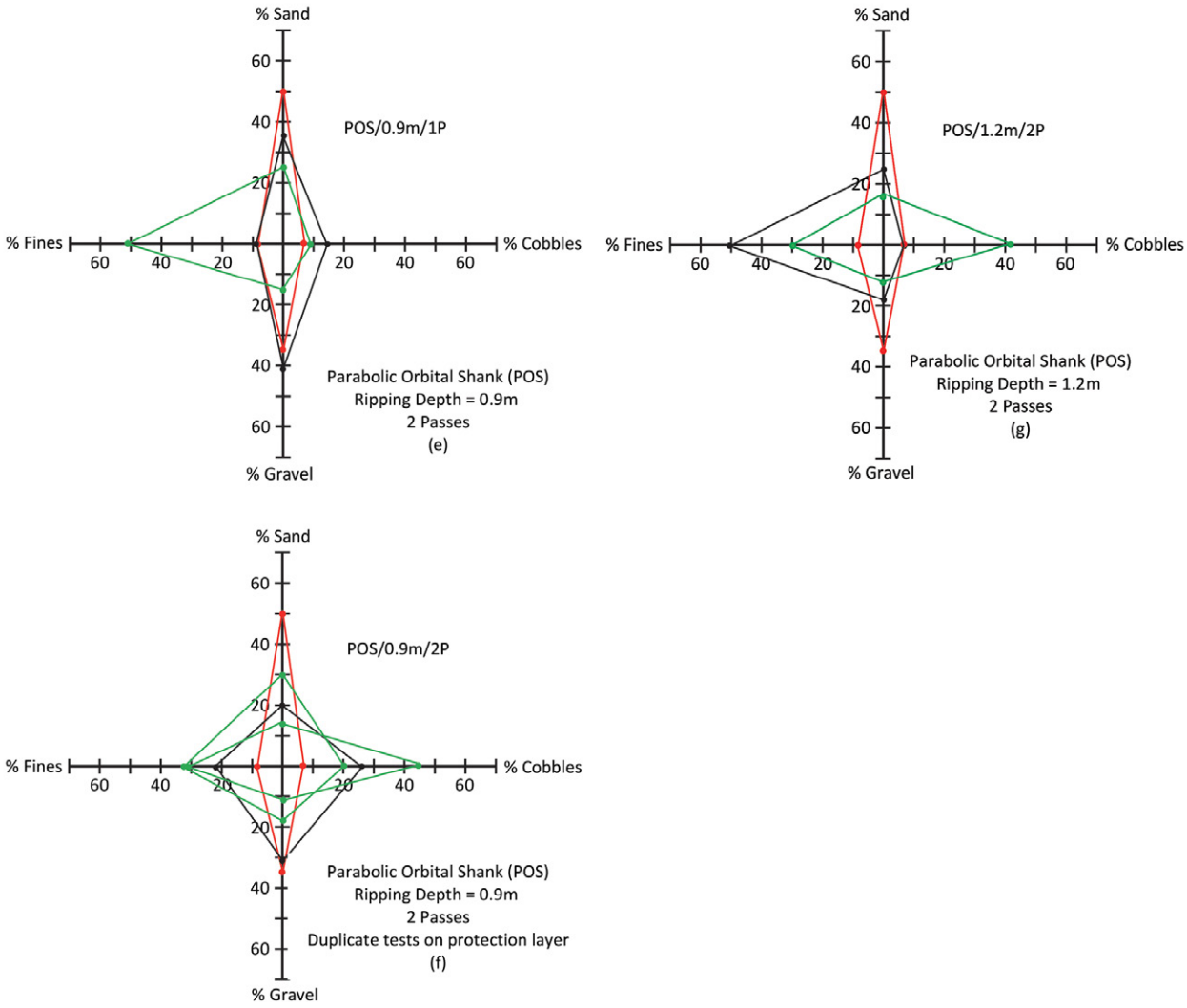

Fig. 8. Continued.

Table 5. Dry density and gravimetric water content at exhumation above and below the original interface between the bedding and protection layers.†

Treatment	Above bedding/protection interface			Below bedding/protection interface		
	Field dry density	Gravimetric water content		Field dry density	Gravimetric water content	
		Field	Lab		Field	Lab
	Mg m^{-3}	%		Mg m^{-3}	%	
CS/0.9m/1P	1.48	5.1	8.0	1.53	5.1	13.6
	1.47	5.3	–‡	1.47	10.0	14.0
WTS/0.6m/2P	1.74	4.7	10.3	1.51§	11.4§	7.8
	1.68	4.9	–	1.37§	13.1§	15.9
WTS/0.9m/2P	1.37	7.3	9.8	1.37	15.7	5.7
	1.39	7.1	–	1.46	14.2	13.3
POS/0.6m/1P	1.53	7.5	8.3	1.62	11.3	18.6
	1.37	3.3	–	1.63	11.6	14.0
POS/0.9m/1P	1.54	7.6	11.6	1.28	12.2	15.6
	1.49	7.4	–	1.22	12.3	15.3
POS/0.9m/2P	–	–	15.8	1.83	12.3	16.2
	–	–	–	1.65	4.7	14.5
POS/1.2m/2P	–	–	5.3	1.22	12.7	13.6
	–	–	–	1.26	13.0	13.3
Control	1.48	3.9	2.5	1.67	15.2	17.3
	1.78	3.3		1.68	15.9	14.9
	1.92	2.4	2.2	1.72	17.8	14.1
	1.89	2.5		1.73	17.2	16.3
	1.76	4.1	1.6	1.72	13.8	17.8
	1.79	4.1		1.80	14.6	16.7

† "Below" tests at depth of 0.3 m below original interface between bedding and protection layers after removal of the armor layer.
‡ Dash indicates no test was conducted.
§ Test conducted at 0.2-m depth due to large rocks and voids.

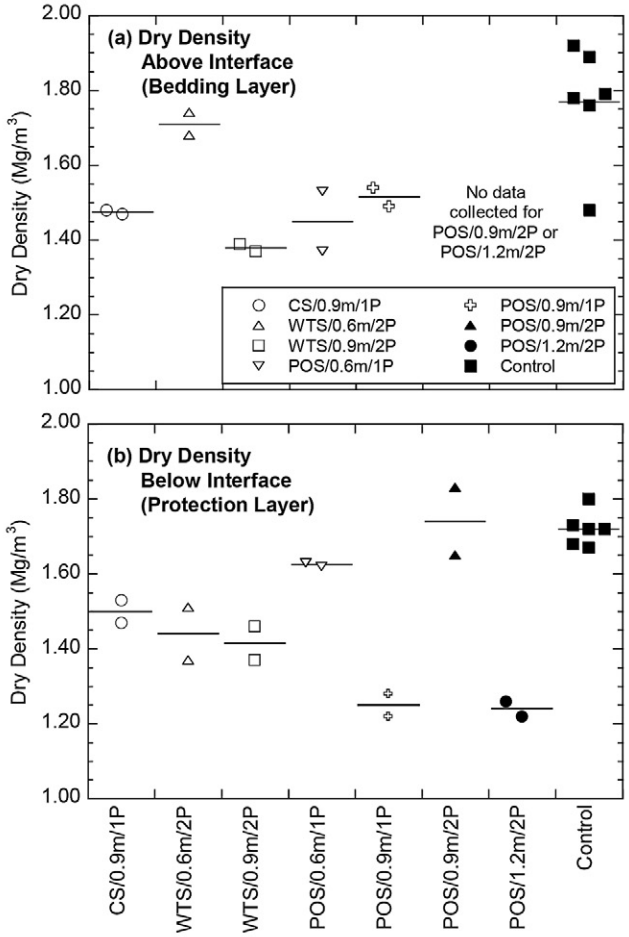

Fig. 9. Dry density above (a) and below (b) the original interface between the bedding and protection layers before (control) and after treatments. Solid horizontal lines are means. See Table 2 for treatment descriptions.

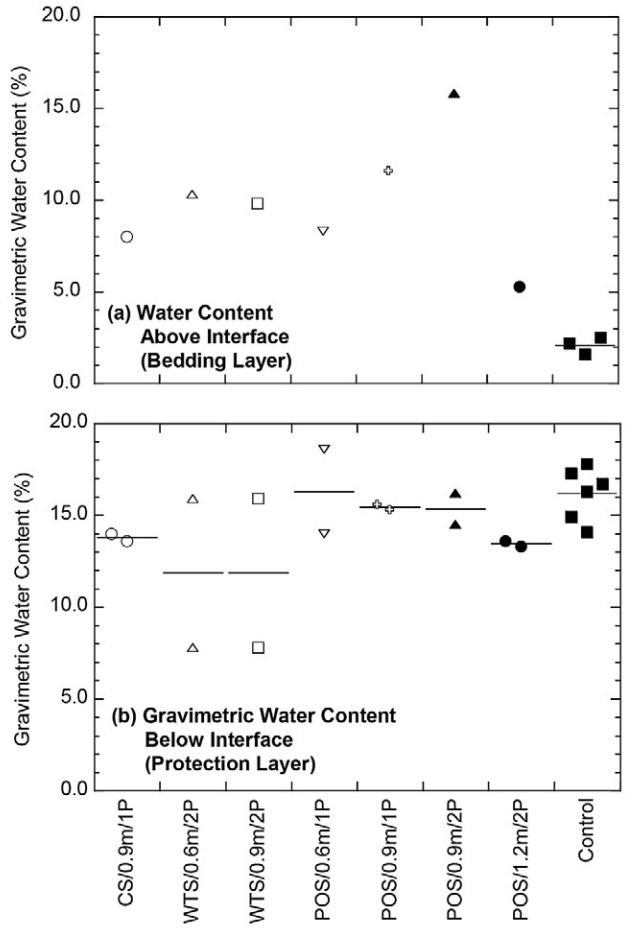

Fig. 10. Gravimetric water content above (a) and below (b) the original interface between the bedding and protection layers before (control) and after treatments. Solid horizontal lines are means. See Table 2 for treatment descriptions.

shallow (0.6 m) ripping with the WTS, (ii) the protection layer after shallow (0.6 m) ripping with the POS (slight reduction in dry density), and (iii) the protection layer after 0.9-m-deep ripping in two passes with the POS (no measurable change in dry density). Gravimetric water content of the bedding layer increased from 3 to 14% (Fig. 10), possibly due to fines brought up into the bedding layer (Fig. 8). In contrast, except for the WTS rows, gravimetric water content of the protection layer decreased only slightly, if at all. Decreases may have been due to mixing with sand and gravel brought down from the bedding layer (Fig. 8, 10). Water content values for the WTS treatment were more variable.

For the bedding layer, most treatments (all except for the WTS at 0.6 m) resulted in essentially the same dry density (~1.4–1.5 Mg m^{-3}), approximately 18% lower than the dry density before ripping (1.77 Mg m^{-3}) (Fig. 9a). Changes in dry density were more variable among treatments for the protection layer than for the bedding layer (Fig. 9b). More active ripping implements (POS > WTS > CS), greater ripping depths, and more passes did not necessarily result in lower dry density. For example, the change in dry density was greater for CS/0.9m/1P and POS/0.9/1P than for POS/0.9m/2P. However, the POS treatment with the deepest ripping and two passes (POS/1.2m/2P) resulted in the lowest dry density and the greatest reduction in dry density (27%) (Fig. 9b).

The unsystematic variability in dry density of the protection layer for several of the treatments may have been due in part to poor soil blending. Ripping often created large, unbroken soil aggregates and large voids in the disturbed zone (Fig. 11) and probably did not uniformly change the cover profile in zones of disturbance. Furthermore, the large voids induced by ripping may have increased the propensity for preferential transmission of water during infiltration events.

Conclusions

Achieving a root-zone dry density between 1.2 to 1.6 Mg m^{-3} and a seedbed soil texture ranging from a clay loam to sandy loam with low rock content would enhance revegetation success and the conversion of hazardous waste covers that rely on a rock-armored, compacted soil layer to limit percolation into covers that rely on soil water storage and evapotranspiration.

All ripping treatments reduced dry density and mixed fine and coarse cover layers in V-shaped zones of disturbance as observed on trench faces. Ripping depth most influenced the size of the disturbed zone, followed by type of implement. The CS created the smallest disturbance zone and the POS the largest. Size of the disturbance zones varied between the two trench faces, with greater variation for the winged implements (WTS

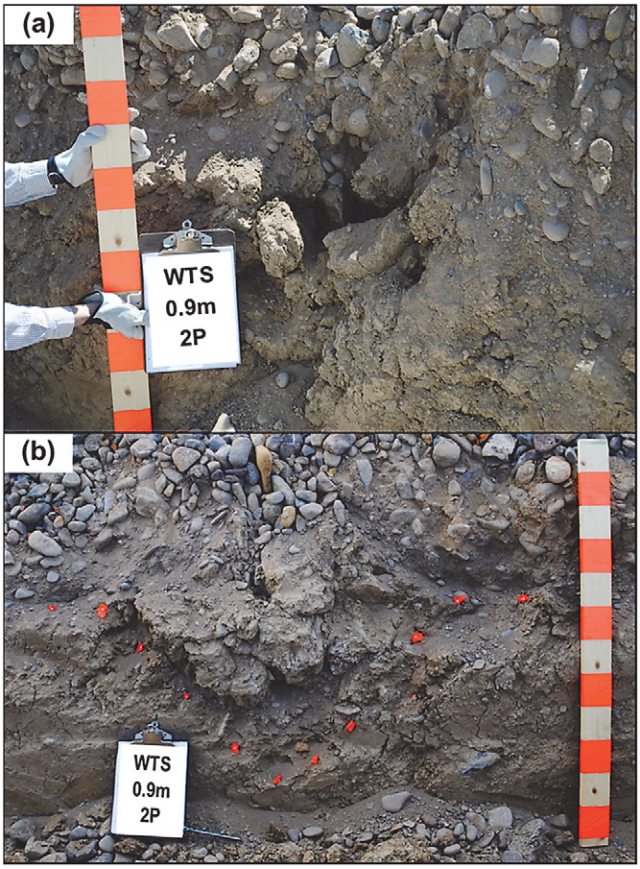

Fig. 11. Example photographs of large voids (a) and large soil aggregates (b) in the disturbed zone of the protection layer for the WTS/0.9m/2P (wing-tipped shank, 0.9 m depth, two passes_ treatment on the two trench faces.

and POS). All three implements mixed the bedding and protection layers. Changes in particle size distributions for the CS were comparable to those for the winged implements (WTS and POS). The POS at 1.2 m depth and two passes was most effective at bringing fine-textured soil from the protection layer up into the bedding layer, thereby changing the textural class from very gravely loamy sand to gravely silt loam. Mixing also disrupted the capillary break at the interface of the bedding and protection layers, possibly allowing water to be more readily removed by evapotranspiration. Changes in dry density within disturbance zones were comparable for the CS and WTS treatments but were highly variable among POS treatments. However, the POS at 1.2 m depth with two passes resulted in the greatest reduction in dry density (27%), changing the protection layer from about 1.77 to 1.24 Mg m^{-3}. Mixing the layers also increased soil water content in the original bedding layer as moist, fine-textured soil moved up from the underlying protection layer and decreased soil water content of the protection layer as dry, coarse gravel and cobbles moved down from the bedding layer.

Overall, of the seven soil ripping treatments, one proved most effective in loosening compacted soil in the root zone and moving fine-textured soil into the seedbed. The POS drawn at the 1.2-m depth with two passes created the largest zone with the lowest dry density and moved more fine-textured soil up into the bedding and armor layers. High variability in dry density and other measures of disturbance may be attributable in part to the locations of test trenches relative to the oscillation cycles of the POS. Finally, most treatments created large aggregates and voids in the protection layer that may function as preferential flow paths and cause a reduction in soil water storage capacity. An ongoing study will evaluate effects of ripping treatments on soil hydraulic properties and revegetation success.

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