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Evaluation of ultrasonic aggregate stability and rainfall erosion resistance of disturbed and amended soils in the Lake Tahoe Basin, USA

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ABSTRACT

Application of organic soil amendments to disturbed soil has been shown to improve aggregate stability and reduce soil susceptibility to erosion. Employing ultrasonic aggregate stability assessment techniques described earlier [Fristensky, A. and Grismer, M.E., 2008. A simultaneous model for ultrasonic aggregate stability assessment. Catena, 74: 153–164.], we assess the effect of two experimental organic soil amendments – a compost and a woodchip mulch incorporated at a rate of 2000–6000 kg ha^{-1} N-equivalence – on soil aggregation and aggregate stability at four drastically disturbed sites within the Lake Tahoe Basin, USA. Experimental plots were established 1–3 years prior to testing. The soils were of granitic or volcanic origin, and disturbed by either ski run or road development. Soil treatments were observed to significantly ($p<0.05$) increase both aggregation (300% average increase) and ultrasonic aggregate stability (600% average increase) relative to the untreated soil. However, at the two sites disturbed by ski run development, the control treatment (tilling and surface application of pine–needle mulch) performed comparably to the two incorporated compost treatments, suggesting that the effects of the experimental amendments on aggregation were negligible at these sites, or their effective duration was shorter than the evaluation period.

Rainfall simulations (72–120 mm h^{-1}) were performed on the treatment plots, and results were compared with the ultrasonic aggregate stability indices. Significant ($p<0.05$) positive correlations were obtained between the measurements of aggregate instability and indices of soil susceptibility to runoff, including steady-state infiltration rate (measured values between 1 and 120 mm h^{-1}), and the level of kinetic energy of applied rainfall at which runoff commences (*EBR*, measured values between 12 and 224 J m^{-2}). However, no correlation was found between the ultrasonic aggregate stability indices and observed soil erosion variables. Interestingly, positive relationships ($p<0.05$) were observed between both infiltration rate and *EBR* and the proportion of 2–20 µm and <2 µm particles liberated from the largest aggregates detected in each soil. Our results suggest that ultrasonic aggregate stability indices may be useful indicators of soil susceptibility to runoff and erosion under rainfall.

1. Introduction

Among the many factors affecting soil susceptibility to erosion and runoff, soil structure and the stability of aggregates are of principal importance. Disruption and detachment of aggregated particles by raindrop impact and the reorganization, coalescing, and compaction of particles in the soil surface may lead to formation of a structural crust and sealing (Moss, 1991; Le Bissonnais, 1996; Green and Hairsine, 2004). Concomitant reductions in hydraulic conductivity promote surface ponding and earlier commencement of overland flow (Le Bissonnais and Singer, 1993). Furthermore, the capacity of overland flow to detach and transport sediment is bolstered by greater total flow volume, as well as the increase in the amount of fine particles with low settling rates obtained from fragmented aggregates (Owoputi and Stolte, 1995a). The stability of soil aggregates therefore directly influences both the occurrence of runoff and total sediment discharge.

For disturbed, structurally degraded soils, remedial application of organic soil amendments has been observed to improve structure and stability (Sun et al., 1995; Amezketa, 1999; Albiach et al., 2001; Cox et al., 2001), albeit not invariably (e.g. de Leon-Gonzalez et al., 2000). Many studies involving natural or simulated rainfall have also observed applied organics to increase infiltration, encourage plant growth, and reduce runoff and sediment yield (Cox et al., 2001; Persyn et al., 2004; Grismer and Hogan, 2005b; Singer et al., 2006). However, the amplitude and duration of organic amendment effects on soil structure and aggregate stability may vary depending on the type (e.g. animal manure, etc.), texture, predominant components, nutrient composition, level of microbial activation, and rate of decomposition

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of applied amendments (Tisdall et al., 1978; Diaz et al., 1994; Hadas et al., 1994; Sun et al., 1995; Amezketa, 1999; Tejada and Gonzalez, 2007).

The principal aim of this study is to evaluate and compare the effects of two incorporated organic soil amendments on the aggregate stability of drastically disturbed soils throughout the Lake Tahoe Basin. Soil erosion and enhanced surface flow and erosion from developed areas within the Lake Tahoe Basin, USA, are important factors contributing to the decline of Lake clarity (Hatch et al., 2001). Areas of concern include ski runs and drastically disturbed soils of highway cut and fill slopes (Grismer and Hogan, 2005a). Soil susceptibility to erosion is increased in these areas due to the removal of vegetation, loss of topsoil, and exposure of compacted subsoils or parent material. Moreover, associated losses in nutrient levels (particularly nitrogen) and organic matter in the soil on these slopes may limit plant growth for years or decades following the disturbance (Claassen and Hogan, 2002). As a consequence, these exposed and erodible areas are potentially long-term sources of water quality impairment to the Lake and its tributaries.

Two experimental amendment types – plant and animal manure compost, and woodchip mulch – are currently under long-term evaluation at various disturbed areas throughout the Lake Tahoe Basin, providing an opportunity to evaluate amendment effects on different soil types subject to different forms of disturbance. The results of this investigation are intended to aid evaluation of the selected soil treatments as possible management practices for reducing soil erosion potential in disturbed areas in the Tahoe region.

Ultrasonic processing was selected as the method of aggregate stability assessment (North, 1976; Imeson and Vis, 1984; Fuller and Goh, 1992; Levy et al., 1993; Raine and So, 1993; Tippkotter, 1994; Field and Minasny, 1999; Field et al., 2006) according to the technique described previously (Fristensky and Grismer, 2008); together with a fast- and slow-wetting treatment to test soil susceptibility to slaking. Ultrasonic methods offer an advantage over conventional aggregate stability methods (e.g. wet-sieving) in that they allow for precise quantification of the mechanical energy applied to a soil–water suspension (attempts have also been made to quantify the energy transferred to the soil throughout aggregate fragmentation (North, 1976; Raine and So, 1993)); moreover, ultrasonic methods afford considerable control and flexibility in both the power and duration of applied treatments. This approach enables controlled, repeatable experiments; measurement of aggregate stability following the rate of aggregate breakdown under prescribed mechanical stresses; and comparisons along continuous stability indices that can be precisely estimated.

However, while many studies have performed statistical correlation of conventional aggregate stability measurements with indices of soil susceptibility to crusting and erosion under simulated or natural rainfall (e.g., Bajracharya et al., 1992; Amezketa et al., 1996; Barthes et al., 2000; Barthes and Roose, 2002; Levy and Mamedov, 2002; Legout et al., 2005; Le Bissonnais et al., 2007), to our knowledge there have been no such studies involving ultrasonic aggregate stability indices (although there have been correlations between results of ultrasonic and water-drop impact tests (Imeson and Vis, 1984), and qualitative comparisons ultrasonic stability indices and rainfall simulation variables (Levy et al., 1993; Cerda et al., 1995)). Therefore, a second objective of this study is to correlate selected ultrasonic stability indices with infiltration and erosion variables of in situ rainfall simulation tests of the disturbed/amended soils.

2. Materials and methods

2.1. Sites

All field sites were located within the Lake Tahoe Basin, California, U.S.A. Four sites were investigated, including two highway banks (Highway 187 near Brockway Summit ("Road-Loam"), and Highway 50 near Meyers ("Road-Sand")) and two ski runs (Northstar-at-Tahoe Ski Resort ("Ski-Loam") and Heavenly Ski Resort (Ski-Sand")). Experimental soil treatment plots at each of the four sites were constructed and monitored by Integrated Environmental Restoration Services (IERS, Tahoe City, CA) between 2003 and 2005. Amended soil plots were constructed in triplicate, randomly located within the study area. Studied organic soil amendments included: incorporated compost (Full Circle brand, Integrated Tahoe Blend ("FC"); incorporated composted woodchips ("WC"); and tilling without incorporation of organics ("CT" was present only at the ski run sites). At each site, a reference soil was obtained from within the disturbed area directly upslope of the treated plots ("DU"). Also, for the sites located on ski runs, soil samples were obtained from nearby, relatively undisturbed forested areas ("N"). Table 1 summarizes site information and native soil classification for each site; and Table 2 summarizes characteristics of the experimental plots and applied treatments for each site.

2.2. Rainfall simulation

Simulated rainfall experiments were performed on each of the experimental treatment plots according to the methodology and simulator design described in detail in Battany and Grismer (2000) and Grismer and Hogan (2004). The portable simulator was modified from that used by Grismer and Hogan (2004): the paired acrylic plastic needle tanks were substituted with polycarbonate tanks of identical dimensions (to increase durability); and the height of the simulator tower was reduced to a minimum of 1 m above the plot surface (to increase portability). The kinetic energy of the applied raindrops (average diameter approximately 2.1 mm) at 1 m fall distance is approximately 33% of that of natural rainfall with an equivalent drop size distribution. Raindrop velocity was estimated according to Laws (1941), and kinetic energy of applied rainfall was estimated assuming a uniform drop size (Battany and Grismer, 2000). The results of rainfall simulation experiments were used to calculate the following variables for comparison with the aggregate stability indices:

(1) *EBR*, the cumulative kinetic energy (J) of the applied rainfall needed to initiate runoff (J m^{-2});
(2) *INF*, steady-state infiltration rate (mm h^{-1});
(3) *ROF*, the ratio of steady-state runoff to rainfall rate (mm h^{-1} mm^{-1} h);
(4) *SY*, sediment yield (g m^{-2} mm^{-1}), calculated as the slope of the linear regression of cumulative sediment discharge vs. cumulative runoff depth (Grismer and Hogan, 2004);
(5) *ERO*, soil erodibility (kg h m^{-2} mm^{-2}), calculated as *SY* divided by the applied rainfall rate (mm h^{-1}).

2.3. Soil sample analysis

All soil samples were obtained between July and August, 2006. Samples of approximately 500 g were obtained from each experimental plot (3 plots per treatment) to a depth of 10 cm (excluding litter layer, where present). In addition, 3 samples were obtained from untreated soil within the disturbed area, directly upslope of the treated plots. At the ski run sites only, 3 samples were obtained from nearby forested areas. Samples were allowed to air-dry, and sieved to 2 mm. Subsamples of approximately 100 g were obtained from each sample for chemical analyses. Samples of the same treatment at a particular site were homogenized, sealed, and stored at room temperature until the time of analysis.

In the laboratory, total soil organic matter (*OM*) was determined gravimetrically using the ignition method (24 h at 430 °C (Davies, 1974)). Oven-dry (24 h at 105 °C) weight of the samples was