Dry Ravel Laboratory Experiment

Pete Wohlgemuth
USDA Forest Service
Pacific Southwest Research Station
Riverside, CA

Introduction

Dry ravel--the gravity-induced downslope surface movement of soil grains, aggregates, and rock material--is a common form of hillslope erosion after wildfires. However, the topographic and soil characteristics that govern dry ravel are poorly understood. Knowledge of these controlling factors is necessary for modeling this hillslope erosion process. To help fill this knowledge gap, an initial laboratory study was conducted to assess the effects of soil texture, slope angle, vegetation density, and disturbance on dry ravel occurrence and magnitude.

Tilting Table

The laboratory study was performed on a tilting table. The table consisted of a 1 meter by 1 meter soil tray set into a frame that pivoted on upright posts. The posts were welded to a base that was set on swivel plate casters. The table was tilted by a cable and pulley system connected to a split drum worm gear winch. The table could be tilted to over 50 degrees, and the angle was measured with a magnetic protractor attached to the tilting frame. The soil tray was 5 cm deep and constructed with an expanded metal base covered with siltcloth material. The siltcloth was fastened to the uphill side of the soil tray to prevent slippage across the metal base. Transverse wooden or metal ribs, 2-3 cm high, were attached to the bottom of the tray to prevent the soil from sliding downhill as a mass failure at high angles. A gutter was fastened to the downhill end of the frame to catch the soil material as it rolled off the tray.

Soils

Five different soil materials were used in this study. All of the soils came from the surface layer of burn sites in the southern California area. Two of the soils (SDEF and Bridge) came from the San Gabriel Mountains and were developed on metamorphic rocks under brush vegetation. Three of the soils (Pine, Mixing Coarse, and Mixing Fine) came from the San Jacinto Mountains and were developed on granitic rocks under mixed forest and brush vegetation. These upland soils are coarse-textured, all falling within the range of loamy sands, but the San Gabriel soils are considerably rockier. The average of five sand:silt:clay and rock:sand:fines ratios for the various soils are listed below.

Soil ID	Sand:Silt:Clay	Rock:Sand:Fines
SDEF	89:7:4	35:58:7
Bridge	81:15:4	37:51:12
Mixing Coarse	82:15:3	18:67:15
Mixing Fine	74:22:4	11:66:23
Pine	79:17:4	9:72:19

Soil Tray Preparation

After trying different protocols, the soil trays were prepared for the tilting table in the following manner. Five 120 cubic centimeter soil tins were placed on the bottom of the tray to determine soil bulk density. The tray was then filled with soil by shaking shovels full of material evenly across the tray. Excess soil was scraped off the top of the tray with a wooden screed, and the leveled surface was tapped repeatedly with a soft bristle brush to remove the tool marks. After each trial run, the surface was raked and refinished. Upon completion of a series of runs, the soil tins were excavated, excess soil was scraped away, and the material was weighed to calculate bulk density.

Soil Bulk Densities

The bulk density of a soil is an indicator of the degree of packing of the soil grains. As mentioned above, bulk densities were measured for each soil type after each set of trial runs. The following table shows the average soil bulk density of five replicates for each trial run by soil type.

Average Bulk Density (g/cm^3) (n=5)

Soil ID	First Trials	Second Trials	Third Trials	Fourth Trials	Fifth Trials
SDEF	1.34	1.39	1.41	1.36	1.39
Bridge	1.23	1.32	1.28	1.33	1.33
Mix. Coarse	1.19	1.23	1.31	1.34	1.32
Mix. Fine	1.12	1.21	1.16	1.20	1.24
Pine	1.14	1.19	1.18	1.22	1.23

The table indicates that the rockiest soils (SDEF and Bridge) have the greatest bulk densities, while the finest-textured soils (Mixing Fine and Pine) have the least. More importantly, the table shows that there is a general progressive increase in bulk density over the course of the study. The explanation for this trend may lie in the fact that the same soil material was being used over and over again. Any residual soil structure would be destroyed as the material was progressively reworked. A consequence of this reworking may be the increase in bulk density.

Threshold Angle

The threshold angle is the degree of table inclination where the soil just starts to ravel. In practice, the determination of the threshold angle is somewhat subjective. As the table angle gets steeper, individual soil particles may move slightly or may even roll several centimeters. However, for the purposes of this experiment, the threshold angle was not reached until soil grains from the upper half of the table rolled all the way down to the gutter. The following table shows the average threshold angle of six replicates for each trial run by soil type.

Average Threshold Angle in Degrees (n=6)

Soil ID	First Trials	Second Trials	Third Trials	Fourth Trials	Fifth Trials
SDEF	32.5	30.8	31.1	31.3	32.1
Bridge	29.7	30.7	30.7	31.8	31.8
Mix. Coarse	30.5	31.2	30.3	31.5	32.3
Mix. Fine	31.5	29.5	31.8	31.7	32.5
Pine	29.8	30.2	30.3	32.0	32.2

The table indicates that there is a very narrow range (3 degrees) of threshold angles for these upland soils. There appears to be no relationship between threshold angle and soil texture. Generally, the threshold angle for each soil type increased slightly over the course of the study, perhaps as the soil material became progressively reworked. This may also explain the reduced variation in threshold angle between soil types with successive trials.

Slope Angle

Once the threshold angle for an individual trial was determined, the table was slowly tilted to four progressively steeper angles, up to a maximum slope of 45 degrees. Depending on the initial threshold angle, these slope angle classes ranged in size from 3 to 4 degrees. After each angle was reached, the gutter was cleaned of soil and the material was weighed. The following table shows the average soil catch of six replicates for each angle class by soil type.

Average Sediment Catch in Grams (n =6)

Soil ID	Threshold Angle (°)	First Angle Class	Second Angle Class	Third Angle Class	Fourth Angle Class
SDEF	32.5	2	16	339	827
Bridge	29.7	5	348	837	607
Mix. Coarse	30.5	4	18	322	246
Mix. Fine	31.5	1	3	10	38
Pine	29.8	2	59	454	245

The table indicates that there is a general progressive increase in ravel with slope angle. In several soils, the catch of the third angle class exceeds that of the fourth angle class. In these cases, it was observed that the supply of loose surface material had been considerably diminished prior to 45 degrees, and that the more compact and less erodible soil mass produced less sediment. The table also indicates that the rockiest soils (SDEF and Bridge) generated the most sediment, while the finest-textured soil (Mixing Fine) produced the least.

Vegetation Density

Even after a fire, the burnt plant stems form barriers to dry ravel, and may help stabilize the surrounding soil material. For this study, pieces of wooden molding 1.5 cm wide were used as surrogate plant stems. The sticks were placed into the soil mass in a regular diagonal grid for each soil type at three different densities: 14 sticks/m^2; 27 sticks/m ; and 55 sticks/m^2. According to the protocols explained above, the table was first tilted to the threshold angle then to four progressively steeper angles (reaching a maximum at 45 degrees), with the gutter cleaned out after every angle. The following table shows the average soil catch of six replicates for each angle class by soil type and stick density.

Average Sediment Catch in Grams (n = 6)

Soil ID	Stick Density	Threshold Angle °	First Angle Class	Second Angle Class	Third Angle Class	Fourth Angle Class	Total
SDEF	14	32.5	10	399	894	250	1553
SDEF	27	32.2	15	537	966	280	1798
SDEF	55	31.7	17	802	847	397	2063
Bridge	14	31.8	24	556	594	366	1540
Bridge	27	31.8	29	431	687	327	1474
Bridge	55	31.8	16	420	629	437	1502
Mixing Coarse	14	32.5	12	358	306	211	977
Mixing Coarse	27	32.0	19	354	473	190	1036
Mixing Coarse	55	32.5	13	438	405	178	1034
Mixing Fine	14	32.8	2	15	53	170	240
Mixing Fine	27	32.0	4	11	101	184	300
Mixing Fine	55	32.7	3	18	142	159	322
Pine	14	32.0	5	349	484	180	1018
Pine	27	32.2	9	504	446	135	1094
Pine	55	32.3	12	516	391	190	1109

The table indicates that there is again a general increase in ravel with slope angle, but that the third angle class usually exceeds the fourth angle class for the reasons given above. Again, the rockiest soils generate the most sediment, while the finest produces the least. There appears to be no pattern (or a counterintuitive positive relationship) between stick density and sediment for most of the angle classes and the totals. The differences in the sediment catch for the trials with the sticks compared to the trials with no sticks (previous section) can be explained (I believe) by the soil material getting progressively reworked over the course of the experiment.

Disturbances

Dry ravel usually requires a disturbance event to trigger the downhill flow of material. Soil particles at the threshold angle should ravel if enough energy is applied. Moreover, the amount of ravel should be proportional to the applied forces. Furthermore, soils below threshold angle may also ravel in response to a trigger. Three common triggers are examined here: vibration, direct contact, and drop impact.

Vibration

The best example of natural vibrations is earthquakes. For this study, vibrations were produced by swinging a weighted pendulum against a table upright post. Although it is unclear how this energy is distributed through the soil tray, at least the methods were consistent for the variety of soil materials. The pendulum consisted of a 1.575 kilogram trailer hitch tied to a fixed fulcrum. The length of the pendulum was 1 meter. By hand, the pendulum was pulled back and released, swinging freely under the force of gravity to strike the table post. The pendulum was swung at three different arcs, producing three different energy levels, as seen in the following table.

Energy Produced by a 1 meter long 1.575 kg Pendulum

Arc Swing (degrees)	Elevation Drop (meters) {y}	Impact Velocity (m/s) $\{v = (2gy)^{0.5}\}$	Kinetic Energy (kgm^2/s^2) $\{E = (mv^2)/2\}$
8	0.0098	0.438	0.151
22	0.0750	1.212	1.157
45	0.2958	2.408	4.556

The soil trays were initially tilted to the threshold angle. The trial run consisted of successive pendulum impacts of low, medium, and high energy. The soil was not resurfaced between these three impacts, and it is assumed that sediment catch was cumulative. After six replicate runs at the threshold angle, the table was tilted to threshold then backed down 3 degrees to a lower angle. After six replicate runs at this lower angle class, the table was tilted to threshold then backed down 6 degrees. Replicate runs at this next lower angle class ranged from 1 to 6. The following table shows the average soil catch of six replicates for each angle class by soil type and pendulum energy.

Average Soil Catch in Grams (n=6)

Soil ID	Pendulum Energy	Threshold Angle	First Angle Class	Second Angle Class*
SDEF	Low	0.5	0	0
SDEF	Med.	1.6	0.3	0
SDEF	High	3.4	0.9	0.1
Bridge	Low	0.2	0	0
Bridge	Med.	0.7	0.1	0
Bridge	High	1.7	0.2	0
Mix. Coarse	Low	0.1	0.1	0
Mix. Coarse	Med.	0.2	0.1	0
Mix. Coarse	High	0.5	0.2	0.1
Mix. Fine	Low	0.3	0.1	0.1
Mix. Fine	Med.	0.6	0.2	0.1
Mix. Fine	High	1.1	0.5	0.3
Pine	Low	0.2	0.1	0
Pine	Med.	0.9	0.1	0
Pine	High	2.2	0.3	0.1

*sample size ranges from 1 to 6

The table indicates that, as expected, more ravel is generated with the higher pendulum energies. Moreover, as slope angle class decreases, sediment catch becomes negligible. There appears to be no relationship between sediment catch and soil texture for vibration disturbance.

Direct Contact

In the field, direct contact could be objects rolling or creatures walking across the soil surface. For this study, direct contact was produced by dragging three different sized spheres transversely across the soil tray. The objects (a tennis ball, a golf ball, and a marble) were suspended from a cord attached to a roller that set in a track above the table. The spheres rested slightly on the soil surface, rather than being perfectly tangent. This yielded continuous and uniform contact of the objects across the soil tray. The suspended contact mass of the spheres was measured on an inclined surface. Characteristics of the objects are presented in the following table.

Characteristics of the Direct Contact Objects

Object	Mass (g)	Diameter (cm)	Contact Mass (g)
Tennis Ball	57.6	6.3	14.2
Golf Ball	48.5	4.1	6.5
Marble	17.5	2.1	3.8

The soil trays were initially tilted to the threshold angle. The trial run consisted of successive contact tracks of the small, medium, and large objects. Each object was dragged across the soil tray ten times. The soil was not resurfaced between these three contacts. After six replicate runs at the threshold angle, the table was tilted to threshold then backed down 3 degrees to a lower angle. After three replicate runs at this lower angle class, the table was tilted to threshold then backed down 6 degrees. A single run was made at this next lower angle class. The following table shows the average soil catch for each angle class by soil type and object size.

Average Soil Catch in Grams (n=6)

Soil ID	Object Size	Threshold Angle	First Angle Class*	Second Angle Class**
SDEF	Small	0.6	0	0
SDEF.	Med	0.1	0.1	0
SDEF	Large	0.1	0.4	0
Bridge	Small	0.6	0	0
Bridge.	Med	0.2	0	0
Bridge	Large	0.2	0	0
Mix. Coarse	Small	0.3	0.1	0
Mix. Coarse.	Med	0.1	0	0
Mix. Coarse	Large	0.4	0	0
Mix. Fine	Small	0.2	0.1	0
Mix. Fine.	Med	0.1	0	0
Mix. Fine	Large	0.1	0	0
Pine	Small	0.3	0	0
Pine.	Med	0.1	0	0
Pine	Large	0.3	0	0

*sample size = 3

** sample size= 1

The table indicates that very little soil material is produced by the direct contact of these objects. Virtually nothing is generated at the lower angle classes. There appears to be no relationship between sediment catch and soil texture for direct contact disturbance. Curiously, the smaller object produced more ravel for several of the soil types, while the medium-sized object generated the least. This may reflect the surface material of the various spheres: the marble is hard and smooth, the golf ball is hard and dimpled, and the tennis ball is soft and fuzzy. Future work should use objects of similar surface texture.

Drop Impact

Objects falling from trees or bushes are examples of natural drop impacts. For this study, drop impacts were produced by allowing different sized hexagonal machine nuts to strike the soil tray after falling controlled distances. The nuts were tied to a thin cord that ran through a plastic pipe section fitted with a stop plate. An adjustable slide stop on the cord restricted the nuts from bouncing or rolling down the soil surface after the initial impact. Characteristics of the nuts are presented in the following table.

Nut Size	Mass (g)	Diameter (cm)	Thickness (cm)
Small	7.7	1.4	0.8
Medium	16.8	1.9	1.1
Large	56.7	2.8	1.6

The three different nuts were dropped at three different heights to produce the following energy levels.

Energy Produced by Drop Impacts

Mass (grams)	Elevation Drop (meters) {y}	Impact Velocity (m/s) $\{v = (2gy)^{0.5}\}$	Kinetic Energy (gm^2/s^2) $\{E=(mv^2)/2\}$
7.7	0.25	2.21	18.80
7.7	1.0	4.43	75.56
7.7	2.0	6.26	150.87
16.8	0.25	2.21	41.03
16.8	1.0	4.43	164.85
16.8	2.0	6.26	329.18
56.7	0.25	2.21	138.46
56.7	1.0	4.43	556.37
56.7	2.0	6.26	1110.97

The soil trays were initially tilted to the threshold angle. The trial run consisted of successive drop impacts of the small, medium, and large nuts at each of the three heights.

Each nut was dropped five times from each height. The soil was not resurfaced between these impacts. After six replicate runs at the threshold angle, the table was tilted to threshold then backed down 3 degrees to a lower angle. After two replicate runs at this lower angle class, the table was tilted to threshold then backed down 6 degrees. A single run was made at this next lower angle class. The following table shows the average soil catch for each angle class by soil type, drop distance, and nut size.

Average Soil Catch in Grams (n=6)

Soil ID	Nut Size	Drop Distance (m)	Threshold Angle	First Angle Class*	Second Angle Class**
SDEF	Small	0.25	0.1	0	0
SDEF	Small	1.0	0.8	0	0
SDEF	Small	2.0	0.4	0	0
SDEF	Med.	0.25	0.4	0	0
SDEF	Med.	1.0	0.6	0	0
SDEF	Med.	2.0	0.5	1.2	0
SDEF	Large	0.25	0.5	0	0

SDEF	Large	1.0	1.2	0.1	0.1
SDEF	Large	2.0	2.9	0.9	1.1
Bridge	Small	0.25	0.2	0	0
Bridge	Small	1.0	0.1	0.2	0
Bridge	Small	2.0	0.3	0.1	0
Bridge	Med.	0.25	0.1	0	0
Bridge	Med.	1.0	0.2	0	0
Bridge	Med.	2.0	0.5	0.4	0
Bridge	Large	0.25	0.3	0	0
Bridge	Large	1.0	1.2	0.1	0.1
Bridge	Large	2.0	2.0	0.5	0.1
Mix. Coarse	Small	0.25	0.1	0	0
Mix. Coarse	Small	1.0	0.1	0.1	0
Mix. Coarse	Small	2.0	0.6	0	0
Mix. Coarse	Med.	0.25	0.1	0	0
Mix. Coarse	Med.	1.0	0.2	0.1	0
Mix. Coarse	Med.	2.0	0.2	0	0
Mix. Coarse	Large	0.25	0.1	0	0
Mix. Coarse	Large	1.0	1.1	0.2	0.1
Mix. Coarse	Large	2.0	1.3	0.3	0.1
Mix. Fine	Small	0.25	0.1	0	0
Mix. Fine	Small	1.0	0.2	0	0
Mix. Fine	Small	2.0	0.1	0	0
Mix. Fine	Med.	0.25	0.1	0	0
Mix. Fine	Med.	1.0	0.1	0.1	0
Mix. Fine	Med.	2.0	0.3	0	0
Mix. Fine	Large	0.25	0.1	0.1	0
Mix. Fine	Large	1.0	1.0	0.2	0
Mix. Fine	Large	2.0	1.2	0.5	0
Pine	Small	0.25	0	0	0
Pine	Small	1.0	0.1	0	0
Pine	Small	2.0	0.2	0	0
Pine	Med.	0.25	0.1	0.1	0
Pine	Med.	1.0	0.1	0	0
Pine	Med.	2.0	0.1	0	0
Pine	Large	0.25	0.1	0	0
Pine	Large	1.0	0.4	0.1	0
Pine	Large	2.0	0.7	0.1	0

*sample size = 2

**sample size = 1

The table indicates that, as expected, the higher energy drop impacts produce more ravel. The large nut overwhelmingly generated more sediment than did the others for all soil types. The small and medium nuts produced comparable sediment amounts. However, there is no clear relationship between drop energy and the amount of ravel. Most of the sediment came from the threshold angle class, with catch rapidly attenuating at the lower angle classes. The rockier soils produced the most sediment for all angle classes.

Summary

The methods and protocols for the dry ravel laboratory experiment have been described. Soil materials were characterized and the effects of soil texture, slope angle, vegetation density, and three types of disturbance have been analyzed. Coarser soils produce more sediment at higher slope angles and when subjected to drop impacts, but not to vibration or direct contact. There is a general progressive increase in ravel with slope angle. Stick density (a surrogate for vegetation) had no impact on ravel production. More ravel is generated with higher levels of disturbance for vibration and drop impact, but not for direct contact. Ravel quickly attenuates with decreasing angle class for all disturbance types.