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The Geomorphic Effects of Gophers on Soil Characteristics and Sediment Compaction: A Case Study from Alpine Treeline, Sangre de Cristo Mountains, Colorado, USA

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Abstract: Digging by gophers disturbs near-surface soils, deposits sediment in mounds and "eskers" in non-uniform surface patterns, and affects surface penetrability of soils at alpine treeline. Soil samples were collected and soil compaction was measured at three sites in the Culebra Range of the Sangre de Cristo Mountains in southern Colorado, to determine the effects of gophers on surface compaction and soil characteristics there. At each of these three sites, soil samples were collected from two gopher mounds, two eskers, and two undisturbed sites. Penetrometer measurements were taken on thirty gopher mounds, thirty gopher "eskers" that represent redistributed soil deposited in snow tunnels during winter, and thirty adjacent surfaces not affected by gopher digging. Hydrometer analysis was employed to determine particle size distribution for the soil samples, and each soil sample was color-keyed using the Munsell soil color system. Particle sizes and colors did not substantially differ among the three soil types, or by sample site. Eskers and mounds were significantly less compacted (ANOVA) than surface samples taken from locations unaffected by gopher digging, and not significantly different from each other (eskers and mounds 1.38 and 1.43 kg cm^{-2} average compaction; unaffected soils, 2.83 kg cm^{-2} average). Excavating by gophers produces lower surface compaction at treeline that may aid tree seedling establishment.

Keywords: Sediment compaction, gopher disturbance, alpine treeline, zoogeomorphology, Rocky Mountains.

INTRODUCTION

Numerous mammals create widespread excavations at alpine treeline through the creation of a variety of burrow structures or by digging for food [1, 2]. These digging activities may have pronounced effects on nitrogen and carbon in soils there [3], but virtually no research has been done at present concerning whether or not these excavations aid or hinder tree seedling establishment and survival. Pocket gophers (Family Geomyidae) in particular have been examined for the role they play in affecting soils characteristics in alpine tundra adjacent to treeline [4-7], but no work exists on the roles of gopher digging, gopher mounds, or gopher-induced changes in soil characteristics as facilitators of tree seedling success at alpine treeline. Gopher mounds in the state of Georgia, USA. illustrated greater longevity of longleaf pine seedlings than in the surrounding matrix, although the difference was not statistically significant [8]. Mortality of seedlings tends to be very high on gopher mounds, because of exposure to herbivores and dry soil conditions [7, 8], but tree seedlings have not been specifically addressed. Individual seedlings that survive on mounds are larger and produce more seeds than similar plants embedded in the surrounding plant matrix [9]. Recently created gopher mounds in alpine tundra on Niwot Ridge, Colorado, had lower seedling emergence and survival rates than undisturbed areas in the first five years after mound creation, but the mounds had higher seedling emergence density from five years to at least 20 years after disturbance, although no tree seedlings were among those seedlings [6]. Would gopher mounds in the adjacent treeline ecotone show tree seedling emergence and survival? Given the potential significance of gopher mounds as a geomorphic facilitator or inhibiter at alpine treeline, they merit greater examination.

In addition to mounds, gophers also create tunnel-like micro-landforms referred to as gopher "tunnel fills" [10] or "eskers" (seen on a National Park Service interpretive sign on Trail Ridge Road in Rocky Mountain National Park, Colorado, in 2005; that terminology is used here). These gopher eskers are anastomosing networks of infilled tunnels, formed by the burrowing of pocket gophers aboveground in the winter snowpack, and are exposed seasonally during snowmelt. The eskers disintegrate over the several subsequent weeks following exposure; although it is possible that some may survive from one season to the next, no published data exist on gopher esker longevity. Individual gopher mounds may persist for several years, even with active slope and eolian processes washing and deflating sediment from the mounds [5]. Soil samples from gopher mounds at Niwot Ridge, Colorado, were shown to have statistically significantly lower bulk densities than adjacent undisturbed soil [5]. No prior data exists on the bulk density or compaction of gopher eskers.

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Both gopher mounds and eskers are created by the digging activities of gophers that mix soil materials and deposit them at the surface. They are comprised of a range of particle sizes, and seem upon touching to be considerably less compacted than the surrounding ground surface. Gopher mounds and eskers are visible throughout the western Cordillera, in mountain environments including Glacier National Park, Montana; Mount Rainier National Park, Washington; the Snowy Range of the Medicine Bow Mountains of southern Wyoming; and at several sites in Colorado, including Rocky Mountain National Park, Niwot Ridge, and the Culebra Range of the Sangre de Cristo Mountains. Given the nearly ubiquitous distribution of gopher mounds and eskers throughout the west, it is all the more surprising that no work has been done on the question of gopher micro-landforms as possible seedling establishment sites at alpine treeline. Gopher pedoturbation and surface micro-landform deposition might enhance the ability for tree seedlings to become established, but it is also feasible to envision how such activities could inhibit seedling establishment (Fig. **1**). Here, the questions of whether mounds and eskers have different characteristics than adjacent undisturbed soil, and whether these micro-landforms have different levels of compaction than the adjacent undisturbed soils, are examined.

Geomorphic processes may assist or hinder conifer seedling establishment above current alpine treeline in the American West. Spatial patterns of geomorphic processes and their impact upon soil in alpine tundra may determine the pattern and rate of advance by woody species into the tundra in response to climatic warming. Conversely, geomorphic processes and patterns may be operative that effectively preclude conifer invasion of tundra (see, for example, the importance of microsites for seedling facilitation or exclusion in studies in Glacier National Park, Montana) [11-15]. Several factors of soil conditions may be important for the advance of tree species into tundra. In this paper, soil characteristics from micro-landforms created by gophers are examined and compared to undisturbed soil from the surrounding alpine tundra to determine if the geomorphic effects of gopher pedoturbation can facilitate or inhibit tree seedling establishment in the treeline ecotone.

STUDY AREA

Fieldwork for this study was conducted at three sites in the Culebra Range of the Sangre de Cristo Mountains in Huerfano County, southern Colorado (Table **1**, Fig. **2**).

Table 1. Characteristics of the Study Sites

Site	Slope Angle	Slope Aspect	Elevation (m asl)	Latitude	Longitude
1	7º	310 º	3,193	37º 34’55’N	105º13’05’’W
2	5 º	265 º	3,316	37º20’10’’N	105 º08’21’’W
3	5 º	090 º	3,277	37 º20’06’’N	105 º08’36’’W

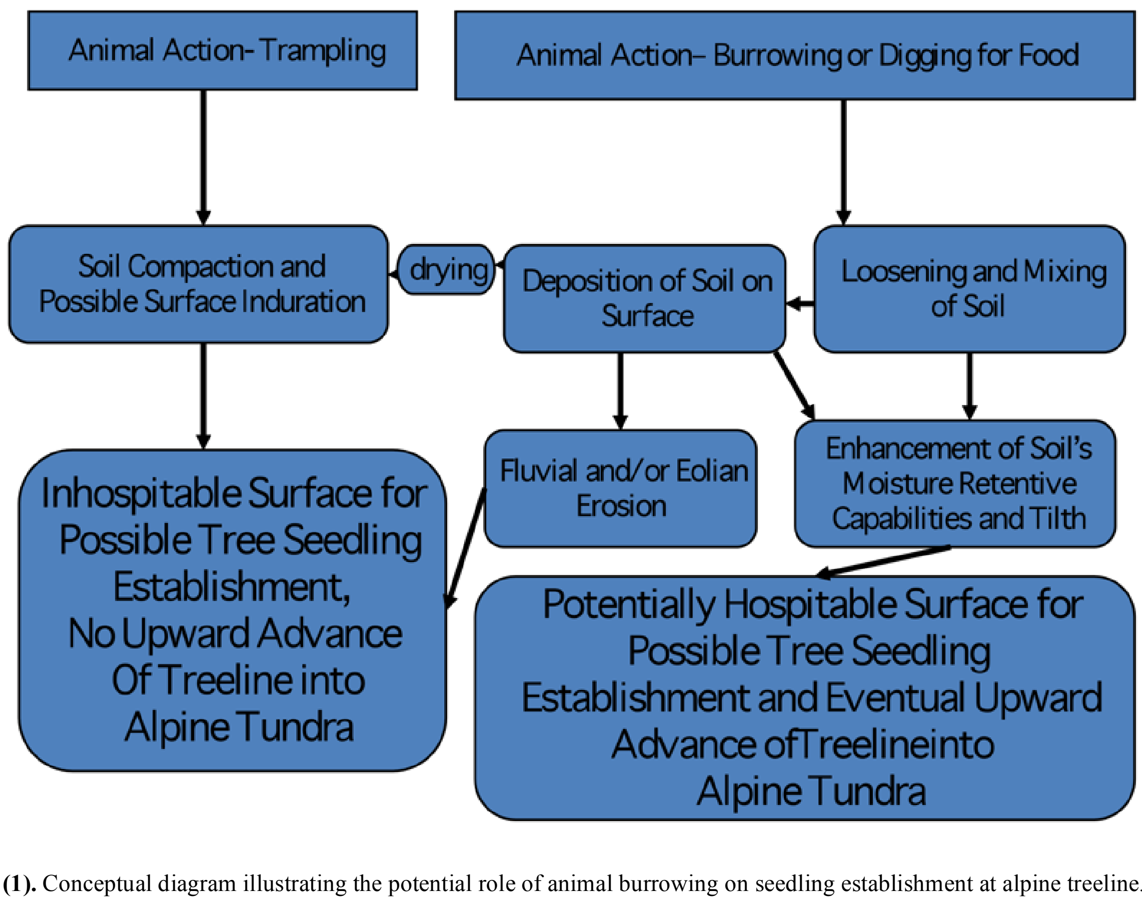

Fig. (1). Conceptual diagram illustrating the potential role of animal burrowing on seedling establishment at alpine treeline.

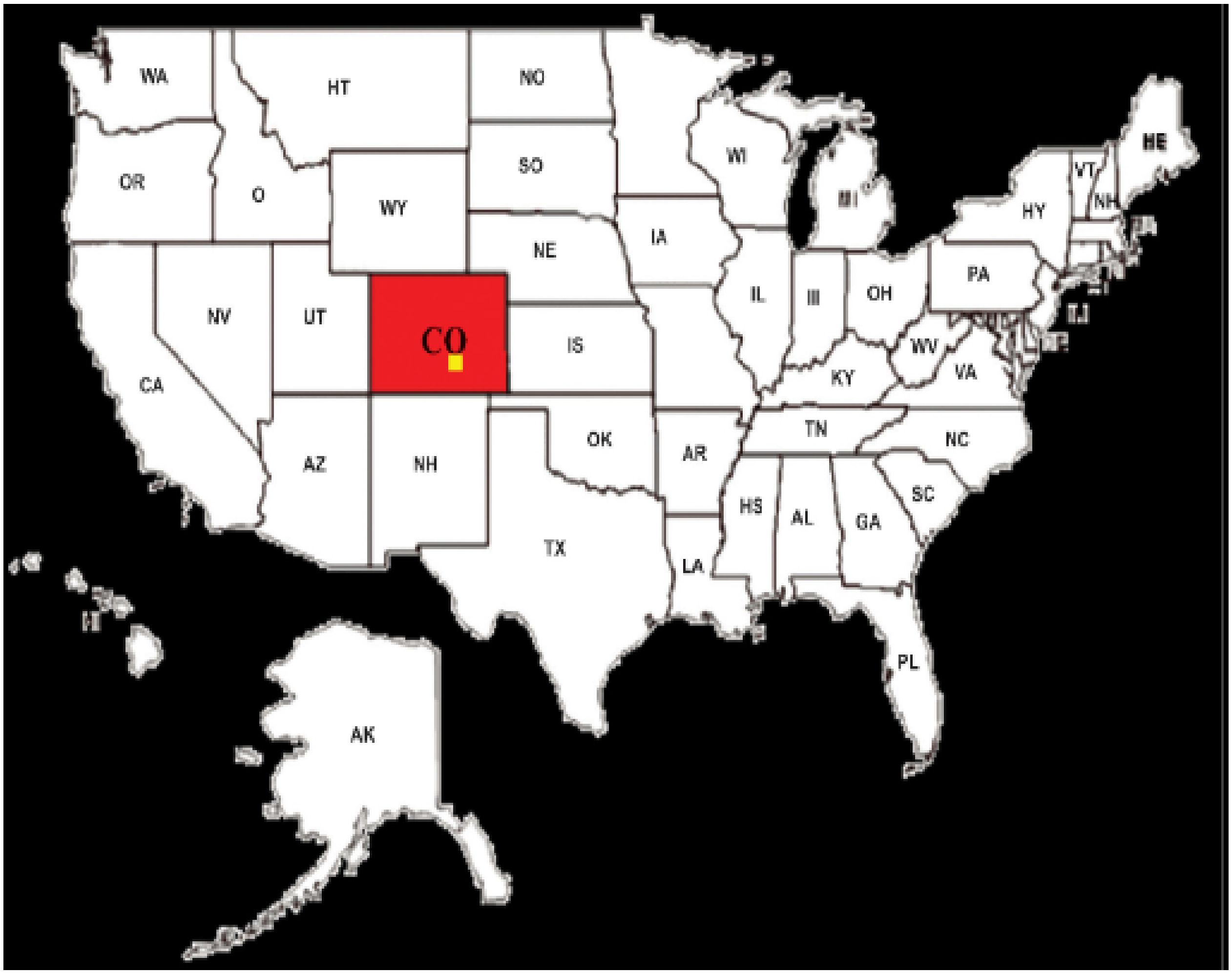

Fig. (2). Location of the study areas in southern Colorado, in the United States of America.

The northernmost site is on a ridgetop at treeline on private land south of the Old La Veta Pass Road, south of U.S. Highway 160 (Fig. **3**). Sites 2 and 3 are in the San Isabel National Forest above Bear Lake, near the village of Cuchara. Site 2 (Fig. **4**) is positioned similarly to Site 1, on a ridgetop at treeline, whereas Site 3 is in a subalpine meadow about 50 meters below and to the west of Site 2 (Fig. **5**). All three sites are gently sloping (< 10º). Sites 1 and 2 face west to northwest, and Site 3 faces to the east. Forest vegetation at all three sites was characterized by typical southern Colorado tree species such as Colorado blue spruce (*Picea pungens*) and Douglas-fir (*Pseudotsuga menziesii*), with grassy understory. Gopher micro-landforms were located in the grassy, open areas just above treeline (Sites 1 and 2) or in a grassy meadow (Site 3).

Each study site is heavily bioturbated by Northern pocket gophers (*Thomomys talpoides*). Gopher eskers (Fig. **6**) are widespread. Gopher mounds are also common at all three sites (Fig. **7**). Sites 1 and 2, the ridgetop sites, seemed to have more eskers than mounds, whereas the meadow site (Site 3) was characterized by more mounds and fewer eskers. Site 1 was visited in the field in 2005 and 2008, and Sites 2 and 3 in 2008 and 2009.

METHODS

At each of the three sites, slope angle and aspect in the field were measured with a Brunton compass/clinometer. Elevation, latitude, and longitude (Table **1**) were extracted from images of the sites outlined on Google Earth. These values were extracted from the approximate center of the outlined study sites.

The mounds and eskers at each site were closely examined, comparing them on initial photographs taken in 2005 (Site 1) and 2008 (Sites 2 and 3) with subsequent photographs taken in 2008 (Site 1) and 2009 (Sites 2 and 3). It was not possible to identify any individual eskers or mounds that survived the span of time between the two visits, *i.e.* each visit revealed only fresh deposits attributable to the year of the visit.

In order to characterize the particle size and color of soils excavated by gophers versus those unaffected by gophers, two soil samples from gopher mounds, gopher eskers, and undisturbed soil were collected at each of the three study sites, for a total of 18 soil samples (6 mounds, 6 eskers, and 6 undisturbed soils). These samples were transported to the laboratory for particle size analysis. Munsell dry soil color [16] was determined for each of these 18 soil samples.

Fig. (3). Old La Veta Pass study site.

Fig. (4). Bear Lake Upper study site.

The effects of gopher pedoturbation on soil compaction were determined by collecting triplicate penetrometer measurements from the surface of 30 gopher mounds, from 30 gopher eskers, and from 30 adjacent undisturbed soil sites at each of the three study sites. A standard metal pocket penetrometer was used to collect compaction data, which were recorded in kg cm^{-2}. All penetrometer measurements were taken within a five-day period in late July, 2008, to minimize any variations attributable to seasonal changes.

The triplicate penetrometer measurements from each sample location were subsequently averaged, to produce a single value for each of the 30 mounds, eskers, and

Fig. (5). Bear Lake Lower study site, viewed from Bear Lake Upper site. Arrow points to study site.

Fig. (6). Typical fresh gopher "eskers", lens cap for scale, Old La Veta Pass Site.

undisturbed soils at each of the three study sites. These 30 values for each soil type were subsequently averaged for each of the three study sites. ANOVA statistics were calculated to determine if soil compaction varied among soil types and among study sites.

Hydrometer analyses were employed to determine the sand, silt, and clay fraction of each soil sample. Because of the limited number of samples (6 from each landform type), statistical analysis was not used to examine the results. Percent sand, silt, and clay were calculated for each landform type at each site, and landform-type data from the three sites were combined in order to produce landform-type averages across the study area.

RESULTS AND DISCUSSION

As noted above, gopher microlandforms (mounds and eskers) did not survive from year to year at the study sites. The mounds broke down more quickly than those reported from Niwot Ridge [5]. Eskers were entirely new each

Fig. (7). Typical gopher mounds with entrance, lens cap for scale, Old La Veta Pass site.

season, confirming the rapid breakdown of these micro-landforms suggested (but not dated) elsewhere [10].

Soil colors at the three study sites were very similar at a site, and were not drastically different among sites. Site 1 had soils ranging in color only from Munsell 10YR3/2 to 10YR3/3. Site 2 also had soils with very little color difference, with the six soils from that site ranging only from Munsell 7.5YR4/3 to 7.5YR5/3. Site 3, the meadow site, had the greatest color variability, Munsell 5YR5/3 to 7.5YR4/2 to 10YR5/2; nevertheless, these are subtle differences and do not suggest any trends between gopher-affected soils and undisturbed soils. Overall, the limited ranges of color variability probably only reflect site-specific variations in underlying bedrock across each site. No apparent differences existed between eskers, mounds, and non-gopher soils, either at an individual site or from site to site.

Textural data were similarly unremarkable, with no obvious differences between gopher mounds, gopher eskers, or undisturbed soils (Tables **2-5**). Each site showed rather remarkable similarity in the textural breakdown, with sand dominating each sample. Silt occurred in amounts 2-3 times lower than sand, and clay was remarkably low in almost all samples and never higher than 10-13% of the total. This trend echoes results from Niwot Ridge [5], namely, that clay amounts are strikingly low, especially on mound soils. These soils are subjected to surface wash and deflation to a greater degree than gopher eskers, which are smaller and lower to the ground surface. Combined amounts of silt and clay were especially low at Site 1, where exposure to the potential for eolian deflation was especially pronounced; to the west of that ridge, slopes dropped off dramatically to the west so that winds hitting the ridge are powerful. At Sites 2 and 3, a higher ridge (the main ridge of the Culebra Range) is immediately to the west, reducing the impact of eolian deflation.

Table 2. Textural Data, Site 1 (Old La Veta Pass)*

Soil Site	% Sand	% Silt	% Clay
Esker	67.5	26.5	6.0
Mound	70.5	27.0	3.0
Undisturbed	76.5	22.5	1.0

*Due to rounding, values may not = 100%; all values rounded to nearest 0.5.

Table 3. Textural Data, Site 2 (Bear Lake Upper)*

Soil Site	% Sand	% Silt	% Clay
Esker	60.0	30.0	10.0
Mound	63.5	31.5	5.0
Undisturbed	58.5	28.0	13.5

*Due to rounding, values may not = 100%; all values rounded to nearest 0.5.

Table 4. Textural data, Site 3 (Bear Lake Lower)*

Soil Site	% Sand	% Silt	% Clay
Esker	63.5	26.5	10.0
Mound	76.5	21.5	1.5
Undisturbed	63.0	30.0	10.0

*Due to rounding, values may not = 100%; all values rounded to nearest 0.5.

Soil compaction data (Table **6**) illustrate Site 1 soils were in general less compacted than the soils at Sites 2 and 3, which were similar to each other. These differences may reflect the aforementioned greater deflation of fines from the soils of Site 1, in both gopher-affected and unaffected soils.

Table 5. Composite Textural Data, All Sites*

Soil Site	% Sand	% Silt	% Clay
Esker	63.7	27.7	8.7
Mound	70.2	26.7	3.2
Undisturbed	66.0	27.2	6.7

*Due to rounding, values may not = 100%.

Table 6. Soil Compaction Data, kg cm^{-2} *

Soil Site	Site 1	Site 2	Site 3	Mean
Esker	0.48	1.48	2.18	1.38
Mound	0.41	2.04	1.89	1.45
Undisturbed	1.81	3.42	3.27	2.83

*Values represent the average of the thirty eskers, mounds, and undisturbed soils at each site.

Eskers and mounds were significantly less compacted (ANOVA, $p < 0.05$) than surface samples taken from locations unaffected by gopher digging, and not significantly different from each other (Table **6**) (eskers and mounds 1.38 and 1.43 kg cm^{-2} average compaction; unaffected soils, 2.83 kg cm^{-2} average compaction). These results, although measured differently, echo the results for gopher mounds versus undisturbed soils at Niwot Ridge [5]. The results for gopher eskers are the first such published data. The pedoturbational activities of gophers have substantial impacts on loosening treeline soils. Although mounds are larger micro-landforms, and perhaps more susceptible to deflation as mentioned above, soils from mounds are statistically indistinguishable from esker soils in terms of compaction (Table **6**). These results again suggest the overarching importance of gopher bioturbation and excavations in loosening treeline soils and distinguishing such soils from soils unaffected by gopher digging, regardless of whether the resulting loosened material is deposited in mounds or eskers.

Loosened soils in the treeline ecotone are sites that should allow easier tree seedling establishment, due to the greater ease of penetration of the soils by the incipient seedling, than do undisturbed tundra and meadow soils. Gophers therefore may, through their zoogeomorphological activities, assist tree seedling establishment and the upward migration of treeline that is occurring regionally as a result of climate change.

CONCLUSIONS

Soils affected by gopher pedoturbation and excavation, as measured from gopher mounds and gopher eskers, are significantly less compacted than soils unaffected by the digging actions of gophers. Other measured characteristics of gopher mounds, gopher eskers, and undisturbed soils varied little in the study area, and probably simply reflect local site variations in geology and exposure to wind deflation. Gopher eskers and mounds disintegrate in less than one year in this environment, replaced each year by fresh ones.

At alpine treeline, where soils tend to be dry and compacted during much of the season when potential seedling establishment can occur, the geomorphic activities of gophers may be of importance in facilitating tree seedling establishment through the creation of sites (gopher mounds and eskers) with significantly lower compaction levels. This soil is rapidly distributed around the landforms as they disintegrate, offering loose soils that are amenable to seedling establishment. Future work needs to concentrate on monitoring tree seedling establishment in environments where gopher activity exists at treeline, to determine if establishment is actually occurring on soils affected by the geomorphic actions of gophers.

ACKNOWLEDGMENTS

We thank Michael Butler, of the greater La Veta-Walsenburg metroplex, for field assistance and logistical support. Comments on earlier versions of this paper by Dr. Don Huebner and this journal's referees were greatly appreciated. This paper, which is a Contribution of the Mountain GeoDynamics Research Group, is dedicated to the memory of Ray Butler, who brought La Veta into our world.

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Received: August 31, 2009 Revised: September 14, 2009 Accepted: September 15, 2009