Chapter 7
Soil formation on Santa Cruz Island: Influences of livestock on a developing landscape

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Abstract

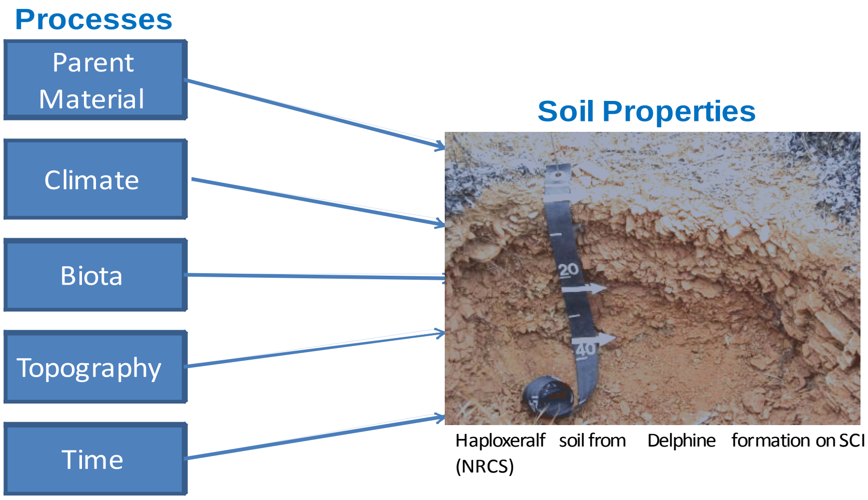
Soils on Santa Cruz Island (SCI) have developed for millennia on steep slopes in the presence of intense periods of wind and rain. These factors contributed to soil development on the island and built up a landscape that housed pine and oak woodland, shrubs and grassland. The natural processes of weathering and slope failures occurred throughout the island's history and created a dynamic backdrop for the evolution of its ecosystem. In the 1800s, ranchers introduced sheep and other non-native grazers to SCI. As the populations of these grazers exploded over the next century, they wreaked havoc on the landscape. Large feral herds denuded hillslopes and permanently removed much of the native vegetation, creating an unstable landscape populated with non-native annual grasses. Increased incidence of shallow soil slips as well as gullying and deep-seated landslides resulted. The destructive influence of these grazers was undeniable and by 1978 the Nature Conservancy bought 90% of the island with the goal of restoring a more natural landscape. The National Park Service purchased the remaining land and in 2000 all the sheep were removed from SCI. Studies have shown that sheep removal has reduced slope failure and increased vegetative cover. These studies provide hope that with time SCI can return to its historic regime of soil and landscape formation.

Introduction

Soils are a fundamental part of any ecosystem. They provide structure to landscapes, a medium for plant growth and site for decomposition of biomass and nutrient cycling. Additionally, soils and their development play a key role in hillslope evolution. Their formation requires the breakdown of parent material and the transfer of that material down slope. The unique tectonic and climatic conditions of the island have formed an environment with steep slopes and high rates of uplift, wet winters and a dry summers, high winds and exposure to intense precipitation during El Niño events and other rainstorms. Soils on the steep slopes that comprise this young landscape have always experienced erosion and slope failures. While an ongoing cycle of soil profile development and subsequent slope failure are imperative to the development of any landscape, human introductions can drive hillslope processes out of equilibrium. The introduction of grazing animals on the island in the 1840s (Brumbaugh et al., 1980) and their subsequent population explosion greatly accelerated these natural landscape processes. The large population of grazers disturbed the patterns of soil and hillslope formation on the island to which the ecosystem had adapted. In addition to the physical disturbance of the soil caused by trampling, sheep and other introduced grazers caused a shift in vegetation on the island from chaparral, coastal sage scrub and oak and pine woodlands to grassland, populated in large part by non-native annuals (Beatty, 1982). The shift in vegetation removed the root networks that in earlier times had anchored much of the island's soil, leaving it increasingly vulnerable to slope failures brought on by winter storms. The reduced soil strength associated with the changing vegetation community further propagated the disequilibrium of island hillslopes. More than a century of grazing history on SCI denuded many hillslopes and truncated soil profile development in many locales (Butterworth et al., 1993). All sheep were cleared from the island by 2000 for the first time in 140 years (Pinter and Vestal, 2005), and in this century, without the destructive force of introduced grazers, we can expect to see greater stability and re–vegetation of the landscape slopes: in sum, we should see a restoration of the past soil formation conditions.

Background

According to Hans Jenny's theory, the formation of soils is regulated by at least five factors: parent material, climate, biota, topography and time (Figure 7.1). In different locations, one or more of these state factors may display greater control over the soil expression. Soil development on Santa Cruz Island (SCI) reflects the interaction of multiple soil forming factors rather than the dominance of any one (Butterworth et al., 1993).



Haploxeralf soil from Delphine formation on SCI (NRCS)

Figure 7.1. Soil forming factors.

Over time the parent material at a site will be transformed by these fundamental factors and soil profiles will build up (Figure 7.2). At the surface, a layer of organic matter is called the O horizon. The shallowest soils, called the A horizon, will have the largest fraction of organic matter. Deeper in the soil, the B horizon is the zone of maximum leaching and clay and mineral accumulation. The deepest layer, the C horizon, contains soils that have similar properties to the parent materials from which they developed. Below the C horizon lies unweathered rock.

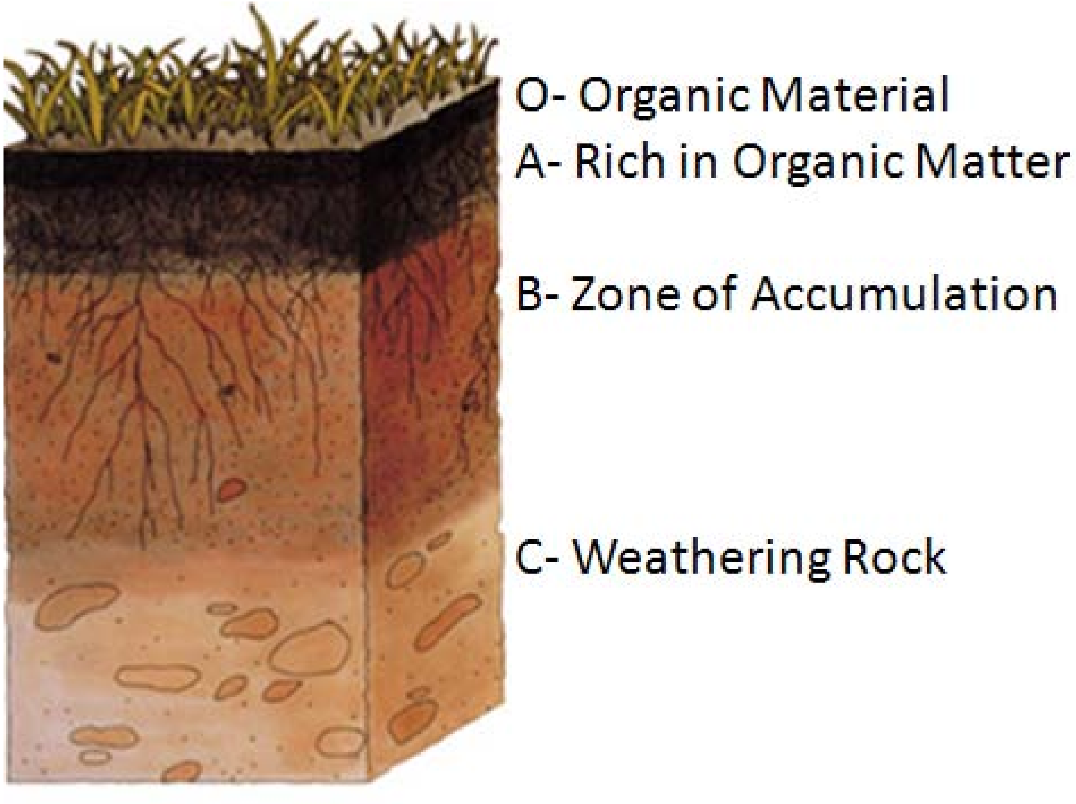


Figure 7.2. Basic soil profile with horizons (adapted from NRCS 2010).

In addition to the fundamental soil formation factors, processes such as biological or chemical transformations, translocations, additions and losses of soil and soil components at a site alter development. Physical disintegration caused by diurnal heating and cooling, resulting in expansion and contraction of soils, abrasion by wind and water and movement by plants and animals all contribute to the fate of a soil. Translocation of soils downhill by erosive forces is a natural process that forms all landscapes. Soil loss can be estimated using the Revised Universal Soil Loss Equation (Brady and Weil, 2002):

$$A=RKLSCP \tag{1}$$

where A is predicted soil loss, R is the rainfall erosivity factor, K is the soil erodability factor, LS is the topographic factor, C is the cover and management factor and P is the support practice factor.

Many areas have seen erosional rates significantly accelerated with the onset of human development. In situations of accelerated erosion, soils are often removed by winds and water at a rate faster than they build up by weathering bedrock or deposition, resulting in soil profiles that may be too shallow to be suitable for plant rooting (Brady, 2002). The loss of soil is usually greater than the volume might suggest, because erosive processes selectively remove organic matter and fine particles, leaving behind a less active, coarser soil that is less conducive to plant development (Brady and Weil, 2002).

Slope failures can occur by many mechanisms that result in different impacts to the soil profile. The dominant process found on SCI consists of shallow soil slips also referred to as slumps (figure 7.3). These slope failures expose a scarp and a toe of subsoil that has experienced limited development and create a higher level of disturbances than a rotational slump, another form of slope failure found at a lower frequency on the island (Beatty, 1988).

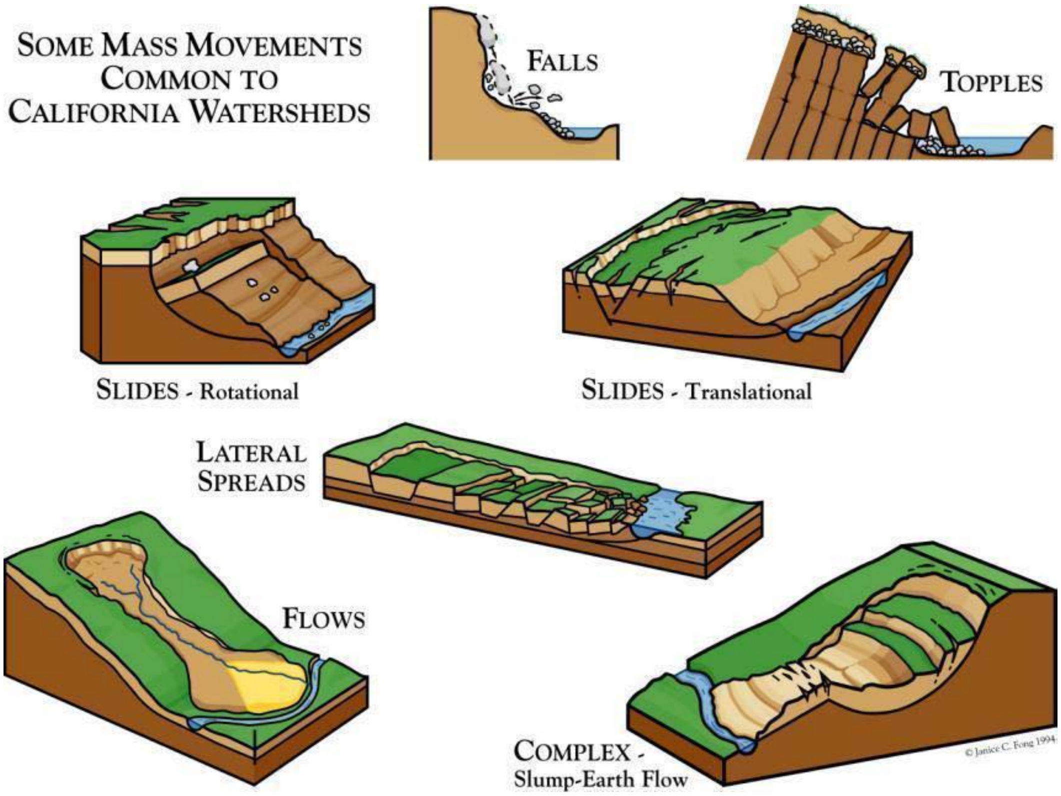
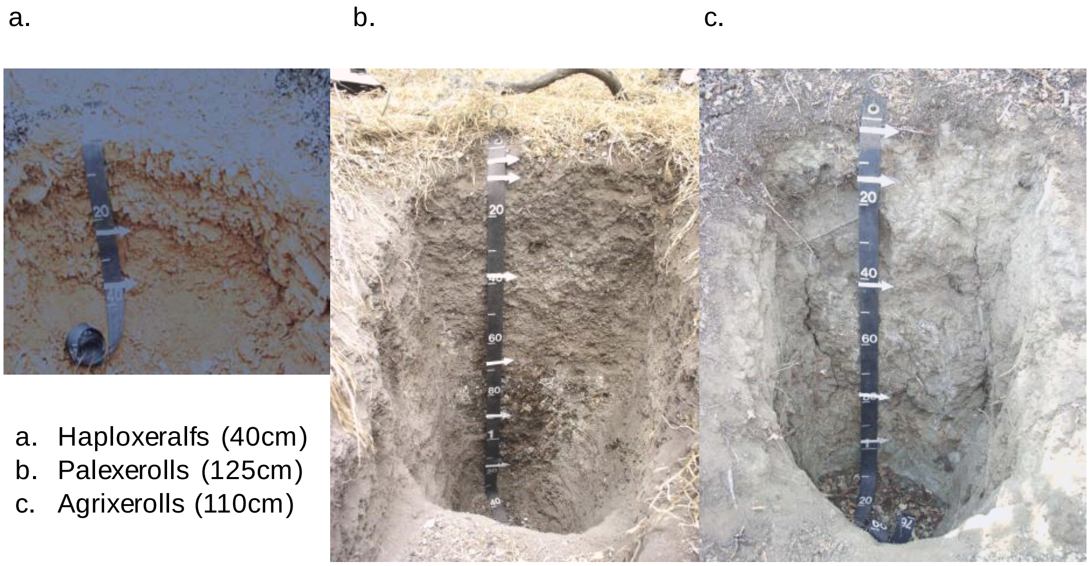


Figure 7.3. Diagram of Slope Failure Mechanisms. Complex-Slump-Earth Flow slope failures, also referred to as shallow slips are a common type of failure that occurs on SCI, which exposes undeveloped soil (Mount, 1995).

Description

Soil Development on Santa Cruz Island

Topography and Climate, two of the fundamental soil formation factors, play a particularly important role in the development of soils on SCI. The high rate of uplift on SCI has created steep slopes. Except for valley bottoms and ridge tops, most slopes on the island are greater than 20^{o} (Pinter and Vestal, 2005). High gradient slopes receive less effective precipitation and favor runoff over infiltration. Water is an important agent in many of the biochemical weathering processes that are integral to soil formation. Consequently, hillslopes that discourage infiltration and support runoff, which can carry soils off site, are often host to shallow profiles. Most soil profiles on SCI are less than 90 cm (Butterworth et al., 1993), though soils in certain locations on the island where measured to be deeper than 1m (Figure 7.4).



a. Haploxeralfs (40cm)
b. Palexerolls (125cm)
c. Agrixerolls (110cm)

Figure 7.4. Soil Profiles from the NRCS soil survey of Channel Islands National Park. Most soils are less than 90 cm deep, though some valley soils extend below 1 m (photos from NRCS 2007).

The Mediterranean climate found at SCI limits soil weathering to the winter and spring. Leaching processes are activated with the onset of rainfall, but the most intensive period of chemical weathering occurs in the spring when rainfall coincides with warmer temperatures (National Resource Conservation Service, 2007). Orographic precipitation drops more rain on the higher portions of the island, which receive 30% more water than lower elevations. Higher rainfall increases the extent of leaching and allows for more plant growth, which results in more organic matter in the soils and more rapid cycling of bases (NRCS, 2007). Prevailing winds from the northwest propel rich marine air and summer fog onto north and northwest facing slopes (Pinter and Vestal, 2005). While this increase in moisture may be advantageous to plants, studies by the National Resource Conservation Service (NRCS) showed that the presence of fog does not introduce moisture into the soil profile (NRCS, 2007). The biggest climatic effect on the island's soils may be attributed to the El Niño events, when winter storms drop unusually high amounts of rain. These events create high risk for slope failures and landslides which stunt the development of classic soil horizons and profiles (Brumbaugh et al., 1980; Pinter and Vestal, 2005).

Wind also plays a major part in removing soils from their site of development and it is a dominant climatic factor on SCI. Some of the islands ridge tops experience high winds and are stripped of soil down to the bedrock. Once the moving air picks up soil particles, its abrasive power is greatly increased and the potential for wind erosion can be even greater (Brady and Weil, 2002).

Soils on Santa Cruz Island

The earliest documented description of soils on Santa Cruz Island (SCI) was conducted by the Soil Conservation Service (1950), but concerned only farmed, valley soils. Later, Brumbaugh used the USDA *Soil Taxonomy* to describe and classify some hillslope soil great groups such as Haploxerolls (order Mollisol) and Xerorthents (order Entisol) and noted Vertisols in island valleys. Butterworth et al. (1993) mapped and described some island soils. They found that almost all island soils, when not eroded, were 30-90 cm thick, with a loam texture, massive or blocky structure and displayed pH values of 5.5-7.5. The large extent of grassland and volcanic and Monterey Formation parent material on SCI resulted in Haploxerolls covering much of the island (Butterworth et al., 1993). Except in the pine forests, these soils contained a fine loam subsoil horizon, with a redder color and translocated clays and removed carbonates. This horizon overlay a thick zone of weathered parent material. Those soils under pines experienced higher leaching (Butterworth et al., 1993). They note that high rates of erosion on the island in the past century made accurate mapping difficult; but their data confirms that geographically distinct soil subunits exist on SCI, demonstrated by the relationship between the soil great groups, geologic substrate and vegetation found in different regions of the island. Many of the island soils are overlain by a silt rich mantle that contrasts sharply with the clay and loam horizons below. This silt rich mantle is not developed on site, but is delivered by winds from the mainland. This rich soil layer provides an important medium for plant growth and should not be overlooked (Muhs et al., 2008). In 2007 the NRCS published the first full soil map of Santa Cruz Island as part of a survey of Channel Islands National Park. This survey describes 42 soil formations and addresses characteristics of soils on all parts of the island in great detail. SCI consists of soil associations and complexes that are dominated by one of 10 soil great groups. This effort demonstrated that the island is dominated by two great groups, Agrixerolls (order Mollisol) and Haploxerepts (order Inceptisols) (Figure 7.5).

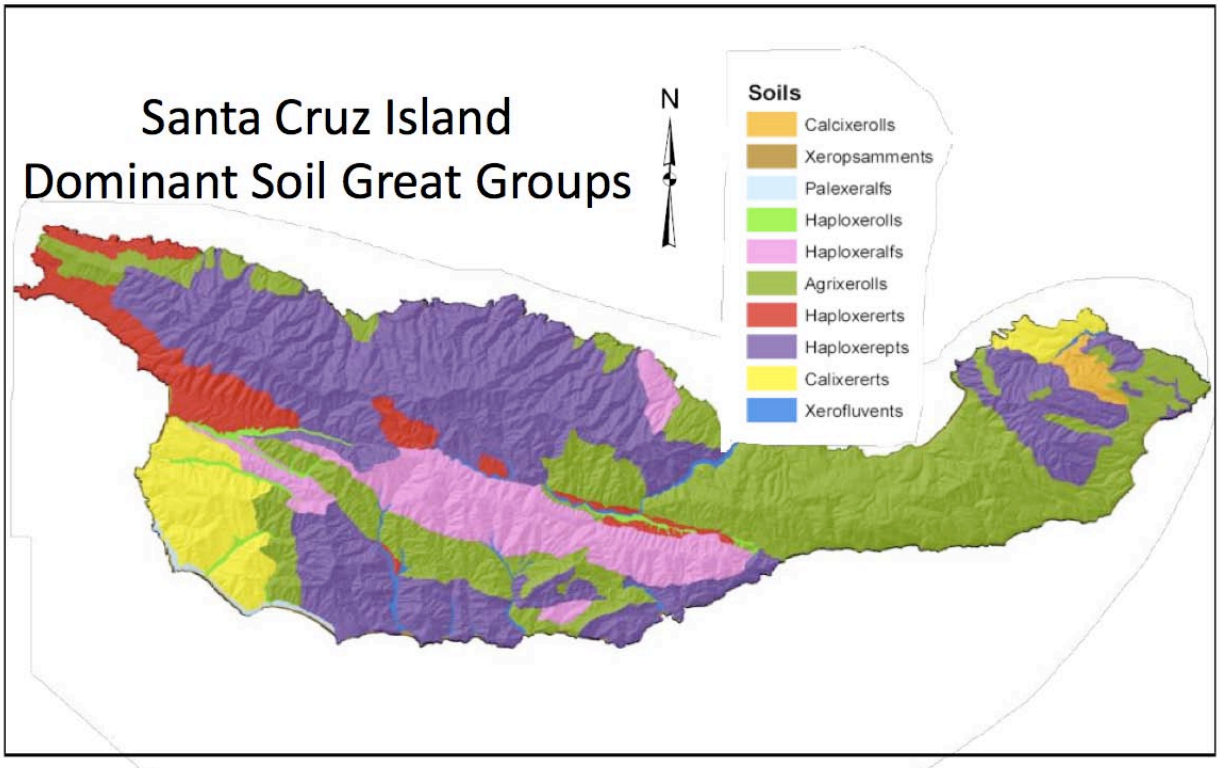


Figure 7.5 Dominant soil great groups in soil associations and complexes on Santa Cruz Island. Map adapted from NRCS STATSGO soil data for Channel Islands National Park.

Impacts of Grazing

Humans have inhabited SCI for 10,000 years, but their presence on the island did not have a significant impact on island soils and their development until European ranchers introduced sheep and other farm animals in the 1840s (Beatty, 1982). While many livestock animals were brought to the island, only two, pigs and sheep, created significant disturbance, with sheep overwhelmingly dominating. In 1857 there were 7000 - 8000 head of sheep on SCI. By 1870, the US Census of Agriculture lists a population of 45,000. Other estimates of sheep populations on SCI in the latter half of the 19th century ranged between 60,000 and 100,000 (Brumbaugh et al., 1982). Although they were originally brought over as ranch animals, the exploding population of sheep on the island became naturalized and from 1920 to the 1980s, SCI housed the largest single population of feral sheep in the world (Pinter, 2005). These populations subjected the island to soil disturbance directly from their hooves and paved the way for increased shallow erosion scarring, gullying and mass wasting by removing vegetation from hillslopes and shifting the communities away from shrubs and woodlands (Figure 7.6). Studies of the 1978 el Niño season (Brumbaugh et al., 1982; Renwick et al., 1982) demonstrated massive slope failures associated with the out of control sheep populations and, that same year, the Nature Conservancy purchased the western 90% of the island from the Santa Cruz Island Company, with a plan for restoration. By June 1989, 37,171 sheep had been eradicated from western SCI. In 1997 the Park Service acquired the rest of the island and by 2000, after removing 9270 sheep from eastern SCI, the island was sheep free for the first time in 140 years (Pinter and Vestal, 2005).

The presence of sheep, in particular, on SCI wreaked havoc on island slopes and truncated soil development across the landscape. Sheep trails alone denuded 7% of some areas (Van Vuren and Coblentz, 1987). But, the primary landscape transformation came from the change in extent and type of vegetation cover on the island. Overgrazing reduces vegetation and makes it less vigorous, causing underlying slopes to become less resistant to erosion. Semi-arid environments, such as SCI, are particularly vulnerable to the effects of grazing pressure. Soil strength is a major control of soil slippage, and plant root strength may dominate or provide a significant portion of the strength of any soil (Dietrich et al., 1995). The removal of vegetation on SCI was coupled with a shift away from chaparral, coastal sage scrub and oak and pine woodland to a landscape dominated by non-native, annual grasses. Changes in cover since the onset of grazing can be tracked via photos that show the decrease in brush and the lack of regeneration of bishop pine, *Pinus murricata* (Brumbaugh et al., 1982). Conversion of chaparral to grasses in the nearby San Gabriel Mountains resulted in a 180 to 640% (depending on storm size) increase in slip erosion, attributed to decrease of the root strength in the soil (Brumbaugh et al., 1982). On SCI, the plant community shift undeniably caused a considerable increase in erosion across the island. Measurement of the percentage of different land areas in failures suggests that grasslands have higher slippage rates than coastal sage scrub which, in turn, have higher failure rates than oak and pine woodland (Brumbaugh et al., 1982). In addition to reducing soil strength, the shift from native to non-native species can affect hydrology and nutrient cycling in soils, because different vegetation will have variable input and output traits, litter quality, quantity and seasonality, and root-soil interactions. Ecologists have long been aware that species' effects on soil regulate succession, invasions and dominance patterns in ecological communities (Yelenik and Levine, 2010).

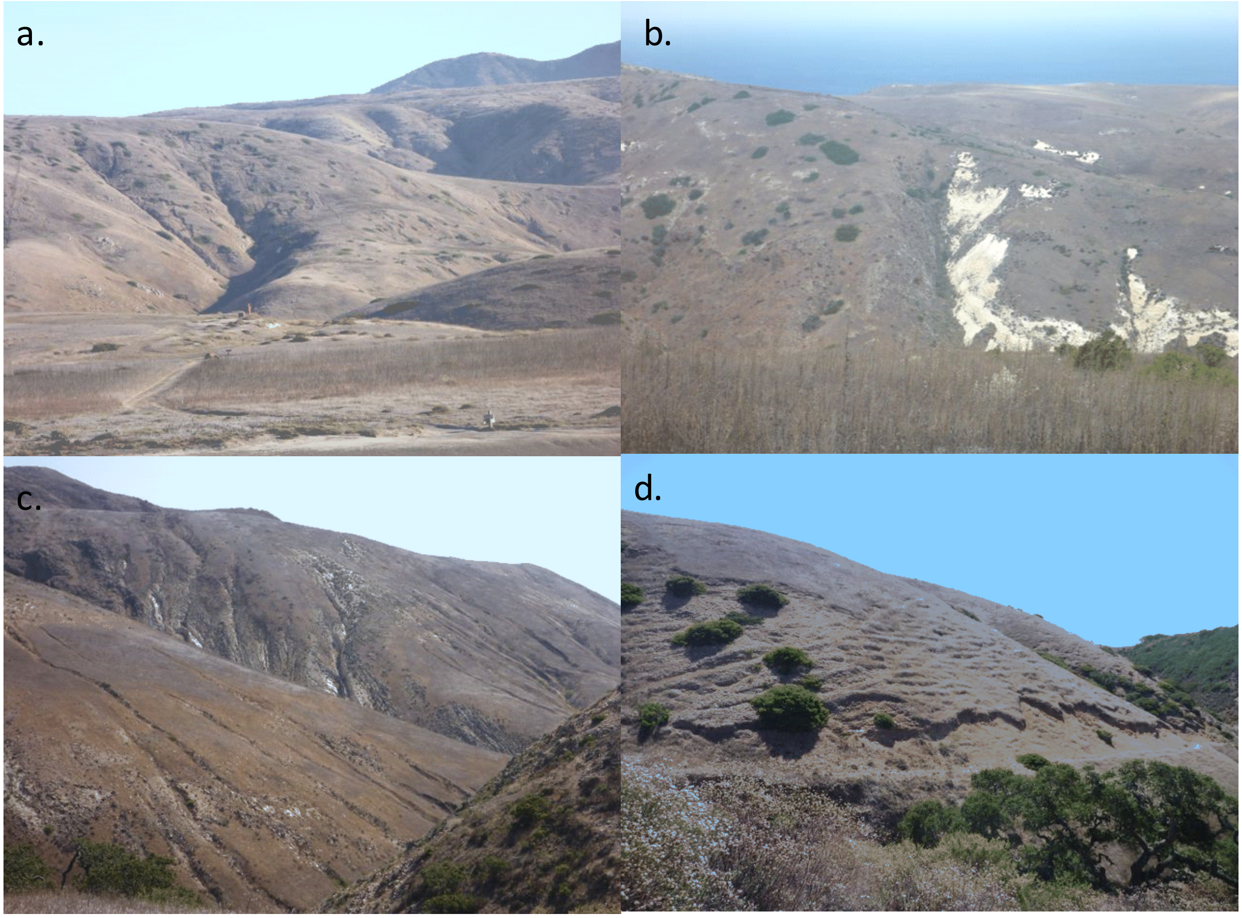


Figure 7.6. Slope Failure on SCI photographed in Sept. 2010 by GEL 230 participants, UC Davis.
[a]. Shallow slips (aka slumps) near Scorpion Cove. **[b].** Slides on the isthmus. **[c].** Gully erosion on the isthmus. **[d].** More shallow slips along the road on the isthmus.

The direct influence of grazing could be assessed the Nature Conservancy eradicated sheep from the western portion of the island. The 1997-1998 El Niño season resulted in a high incidence of slope failures, primarily small and medium-scale shallow slips, but also a smaller number of bedrock slides above steeply dipping sedimentary bedrock and two deep-seated landslides (Figure 7.6). Although sheep-grazed land comprised just 10% of the island, 80% of the failures occurred in this region (Pinter and Vestal, 2005). Additionally, slopes remained stable in western parts of the island that had experienced failures during the 1978 El Niño season, when sheep still ranged on that portion of SCI. Land-use was the primary control of slope failures. Other controls on slip occurrence included bedrock lithology, aspect, curvature and elevation (Pinter and Vestal, 2005). In should be noted that they did not include soils in their slope failure model, since no complete, field-based soil survey of SCI existed at the time. Consequently, it is impossible to quantify the relationship of soil type to slope failure based on their study.

Vegetation changes and land management practices have greatly increased the incidence of slope failure. Pinter and Vestal (2005) found that these terms showed the highest correlation with slip occurrence. However, geographically distinct soil subunits do exist on the island. These are influenced by vegetation and geologic substrate (Butterworth et al., 1993). Shallow slips usually occur when the pore water pressure reduces the strength of the soil to the point where gravity related driving forces overwhelm shearing resistance forces (Iverson et al., 2000). On SCI, failures occur by shearing soils at or near residual strength that build up critical pore water pressure. This likely occurs due to decreasing permeability with depth, resulting in a concentration of water along a soil horizon or strata, or concentration by lateral subsurface flow. When boundaries with juxtaposed permeabilities exist in the soils or the precipitation rate exceeds the deep percolation rate, soil failures will result (Renwick et al., 1982). Bedrock lithology and its influence on the overlying soil type effect infiltration rates, deep percolation rates and, therefore, slope failure potential. Low rates of landsliding over SCI schists may be attributed to the high permeability of that rock type and the extensive gullying and soil piping in the soil above. This efficient drainage network that minimizes the build-up of pore water pressure is not found on most other SCI formations, such as the Monterey Formation, composed of shale, and the volcaniclastic conglomerate and breccia composition of the Blanca formation (Renwick et al., 1982). The geologic fingerprint is further represented by the fact that 59% of the slips in 1997 and 1998 occurred over the Monterey Formation that underlies 16% of the total island, including the entire isthmus and 38% of the eastern island. Another 40% of the slips occurred over the SCI volcanics that underlie the northern half of the western island and 62% of the eastern island, though most slips occurred in the eastern region, where sheep were still grazing freely at the time of the study. Slopes on the Monterey Formation were 2.8 times more likely to fail than those over the SCI volcanics, which were 3.3 times more likely to fail than those over any other lithology (Pinter and Vestal, 2005).

Different types of slope failure have varying effects on slope soils. Some failures maintain most of the soil horizons intact, while others expose large areas of barely developed C horizons. The processes of instantaneous liquefaction and transport of material in slips, seen on SCI, selectively removed fines and left behind a proportionately higher amounts of larger particles in the disturbed zone (Beatty, 1982). Where genetic soil horizons are maintained, higher organic matter and fines also remain. The scarp and toe of a slip or larger disturbed area, created by a more destructive failure, contain a larger coarse fraction and a lower pH (Beatty, 1982), conditions less favorable to plant establishment and growth.

In 2000, complete removal of sheep from the island was achieved. This fact promises improvement in the stability and condition of hillslopes and landscape restoration. After their removal from the eastern island, Pinter and Vestal (2005) noted few slope failures in locales where they had been widespread earlier in the century, marking a dramatic rebound of soil strength after less than a decade of sheep eradication in that area. Slope failures were 67% less likely to occur with each unit of increasing Normalized Difference Vegetation Index (NDVI), which is a metric for assessing vegetation cover using remote sensing that ranges from -1 to 1. Higher NDVI values indicated more vegetative cover. This further highlights the important influence of vegetation on soil strength (Pinter and Vestal, 2005). The Nature Conservancy and the Park Service have maintained a photographic time-series of a variety of sites on the island, and most have shown an increase in density and variety of vegetation (Pinter and Vestal, 2005). Removal of destructive grazers and restoration of native plant communities should be able to restore past soil formation conditions promoting better developed soils on SCI in the future.

Conclusion

Santa Cruz Island has been intensively grazed for 140 years. This activity denuded hillslopes and shifted vegetation communities towards less stable grasslands. The pressure from grazing increased erosion and slope failures across the island. Areas with certain lithologies, i.e. schists, or plant communities, i.e. pine forest, were able to maintain high soil strength and resistance to failure. Other areas were subjected to slips and mass wasting that removed soils from their development site and retarded soil profile development. The rates of soil development and slope failure were forced out of equilibrium as a result of the damage caused by the livestock, and soil loss from hillslopes occurred rapidly. Simultaneous shifts in vegetation further weakened soil strength in these vulnerable locations. As of 2000, all introduced grazers have been removed from SCI, and in less than 10 years, vegetation cover has rebounded remarkably on previously denuded hillslopes. Increased cover and the freedom from hooves present the island with the opportunity to regain richer and more stable landscapes than those seen in the past century.

References

Beatty, S.W., 1988, Mass Movement Effects on Grassland Vegetation and Soils on Santa Cruz Island, California: *Annals of the Association of American Geographers*, v. 78(3),p. 491-504.

Brady, N.C. and Weil, R.R. (eds), 2002, The Nature and Properties of Soils. Prentice Hall.

Brumbaug, R.W., Renwick, W.H., and Loeher, L.L., 1982, Effects of Vegetation Change on Shallow Landsliding: Santa Cruz Island, California: *Gen. Tech. Rep. PSW-58. Berkeley, CA*: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture.

Butterworth, J.B., Jones, J.A., and Jones, S., 1993, Soil Forming Factors, Morphology and Classification-Santa Cruz Island, California: *Third California Island Symposium*, p. 39-44.

Dietrich, W.E, Hsu, M.-L., and Montgomery, D.L., 1995, A Process Based Model for Colluvial Soil Depth and Shallow Landsliding Using Digital Elevation: *Hydrological Processes,* v. 9, p. 383-400.

Iverson, R.M., Reid, M.E., Iverson, N.R., LaHusen, R.G., Logan, M., Mann, J.E., and Brien, D.L., 2000, Acute Sensitivity of Landslide Rates to Initial Soil Porosity: *Science,* v.290, p. 513-516.

Mount, J., 1995, California Rivers and Streams. University of California Press, Berekeley. 395 p

Muhs, D.R., Budahn, J.R., Johnson, D.L., Reheis, M., Beann, J., Skipp, G., Fisher, E., Jones, J.A., 2008, Geochemical Evidence for Airborne Dust Additions to Soils in channel Islands National Park, California: *Geological Society of America Bulletin*, v. 120, no. 1/2, p. 106-126.

Perroy, R.L., Lee, C. and Schaaf, T. (eds.), 2008, Chpt 5 Characterizing Post-grazing Change Trajectories on Santa Cruz Island, CA, with Multitemporal Landsat Data: *The Future of Drylands,* UNESCO, p. 359-371.

Perroy, R.L., Bookhagen, B., Anser, G.P., and Chadwick, O.A., 2010, Comparison of Gully Erosion Estimates Using Airborne and Ground-based LiDAR on Santa Cruz Island, California: *Geomorphology,* v. 118, p. 288-300.

Pinter, N., and Vestal, W.D., 2005, El Nino-driven Landsliding and Post Grazing Vegetative Recovery, Santa Cruz Island, California: *Journal of Geophysical Research,* v. 110.

Renwick, W., Brumbaugh, R., and Loeher, L., 1982, Landslide Morphology and Processes on Santa cruz Island, California: *Geografiska Annaler*, v. 64 A, p. 149-159.

Tierney, T.A., and Cushman, J.H., 2006, Temporal Changes in Native and Exotic Vegetation and Soil Characteristics Following Disturbances by Feral Pigs in a California Grassland: *Biological Invasions,* v. 8, p. 1073-1089.

United States Department of Agriculture, National Resources Conservation Service, 2007, Soil Survey of Channel Islands National Park, California. Accessible online at: http://soils.usda.gov/survey/printed_surveys/.

United States Department of Agriculture, National Resources Conservation Service, May 28, 2010, *A Soil Profile*, November 9, 2010, from: http://soils.usda.gov/education/resources/lessons/profile/

Van Vuren, D.V., and Coblentz, B.E., 1987, Some Ecological Effects of Feral Sheep on Santa Cruz Island, California, USA: *Biological Conservation*, v. 41, p. 253-268.

Yelenik, S. G., and Levine, J.M., 2010, Native Shrub Reestablishment in Exotic Grasslands: Do Ecosystem Processes Recover?: *Ecological Applications*, v. 20(3), p. 716-727.