part three
LITERATURE REVIEW

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INTRODUCTION TO THE LITERATURE REVIEW

The California Alpine Resort Environmental Cooperative (CAREC) came together in 2003 to develop a process for planning and implementing erosion control projects and to experiment, through field plots, with various approaches to control sediment on site. In addressing an issue as large and complex as erosion control, CAREC wanted to determine what we know, what we do not know, and what we need to learn. This is an essential element of the adaptive management cycle discussed in Part I: Guiding Principles. As part of this *Sediment Source Control Handbook,* CAREC requested a Literature Review that references appropriate information for planners, practitioners, monitoring personnel, and scientists involved in upland sediment source control projects.

The ability to return disturbed sites such as ski slopes to a high level of effective soil-plant function requires knowledge and understanding of ecological, physical, and operational processes. Too often, this information is not readily available during the planning and implementation of erosion control projects. Actual field-level or field-relevant research or other literature tends to be difficult to find or simply non existent in the case of high alpine areas. Much of the information available is produced by manufacturers and suppliers and often includes a significant bias.

This review attempts to collect as much relevant scientific information on erosion and restoration-related subjects as possible. It is intended to be a working document that will be added to over time as additional research becomes available. Information is cited on erosion control and restoration in the following sections:

Section One: Erosion – Key Concepts

Establishes a common understanding of what is meant by "erosion"

Section Two: Variables That Influence Erosion Rates

Describes types of erosion and particular variables that affect erosion rates

Section Three: Treatments for Sediment Source Control

Suggests issues to consider when applying different types of treatments to achieve sediment source control objectives

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FRAMING THE ISSUE

Definition(s) of Erosion

The entire process commonly referred to as "erosion" actually consists of two closely related processes: 1) erosion, or the detachment or breaking away of soil particles from a land surface by some erosive agent, most commonly water or wind, and 2) sedimentation, or "subsequent transportation of the detached particles to another location" (Flanagan 2002). It is important to understand the nature of these two processes, since addressing them requires quite different techniques and approaches.

Typically, controlling erosion requires keeping soil particles attached to one another and to the soil matrix. Native soils usually do this through the aggregation process (Kay and Angers 2002). Soil aggregates are combinations of soil particles that are bound together. Typically, this process is the result of physical and biological, especially microbial, processes (Horn and Baumgartl 2002). When soil is disturbed, aggregates tend to separate and are more prone to erosion. Once soil particles begin to move, it is extremely difficult to capture fine silt and clay particles, which are typically responsible for a great deal of water quality pollution and degradation. Thus, the CAREC work and this literature review focus on *sediment source control* — keeping soil particles attached and at their source.

An Introduction to Erosion

Erosion and sedimentation pose a serious problem throughout the world. Any land "improvement" or development is usually associated with the potential for accelerated erosion and associated water pollution. This is especially true in mountainous regions where steep slopes and relatively young and/or poorly developed soils create ideal conditions for accelerated erosion after an area has been disturbed.

Topsoil is an irreplaceable resource that is high in organic matter, supports healthy vegetation, and resists the erosive forces of wind and water. It also offers the most optimal seedbed for germinating and establishing vegetation, increases the water-holding capacity of the soil, contains the primary source of nutrients for plants and soil microbes, and contains seeds and beneficial soil microorganisms. Removal or burial of topsoil—a common result of development—tends to accelerate the detachment and transport of sediment. Particles of eroded sediment cause turbidity in water bodies and harm fish by clogging their gills, smothering spawning gravels, burying submerged plants, and transporting other pollutants adsorbed to the sediment (Horne and Goldman 1994). In order to take meaningful action to reduce or control erosion to acceptable levels, and thus protect water quality and topsoil resources, it is useful to develop an integrated, comprehensive understanding of what erosion is and what we currently know about controlling it.

Erosion is generally a "systemic" or functional issue rather than a two-dimensional surface issue; that is, it is the product of an entire system of environmental interactions rather than simply a function of the amount of plant cover on a site. When a system is "healthy" or operating at a high level of functionality, soil particles will stay connected to each other on site and erosion levels will generally be low. When one or more components of the system have been disturbed, erosion (the disaggregation of soil particles) coupled with sedimentation (the movement of those particles) is likely to increase.

Background or "natural" erosion tends to take place in an equilibrium with other watershed elements such as infiltration, stream flow, stream bank stability, and changes in the vegetative community. When disturbance takes place, this equilibrium is disrupted, resulting not only in increased sediment movement, but also in an increase in surface water flow, an increase in stream water volume and velocity during runoff events, a decrease in stream bank stability, and a decrease in watershed water storage (Selby 1993; Dudley and Stolton 2003). On a watershed basis, accelerated erosion and sedimentation results in removal of watershed "capital," or the carbon-rich soil organic matter that drives so many important processes within a watershed. Carbon provides energy that in turn drives ecosystem processes. Once this "capital" is diminished, the ecosystem tends to function at a lower level.

While diminished functionality may be barely noticed on small scales, when large areas such as roads or ski runs are developed, watershed function can be severely disrupted. When this happens, input and output erosion variables are no longer in balance and often result in a downward spiral of ecosystem damage or negative ecosystem impacts (Daily, Matson and Vitousek 1997). Once this damage is done, repair and restoration can be very expensive and labor-intensive; therefore, it is generally more cost-effective to implement projects properly in the first place. However, once damage has been done, repair and restoration are necessary if water quality and ecosystem health are to be reestablished. By replacing components of the larger soil-plant processes such as soil organic matter, seed, mulch, and infiltration, erosion can be reduced and water quality can be restored to background or "natural" levels.

Most of the currently accepted erosion control practices, based on models such as the Universal Soil Loss Equation, focus largely on "C," or the cover factor. Thus, emphasis is placed on plants or revegetation as the primary solution to erosion control on disturbed sites. However, processes must be put back as a complete system rather than as individual components. The Literature Review presents relevant academic research that focuses on erosion, hydrology, and soil-plant processes within the context of keeping soil particles in place on steep slopes.

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EROSION OVERVIEW

Adapted from the International Union of Geological Sciences (1996)

Erosion, or the detachment of particles of soil and superficial sediments and rocks, occurs by the hydrological (fluvial) processes of sheet erosion, rilling, and gully erosion, as well as through mass wasting and the action of wind. Erosion, both fluvial (water) and eolian (wind), is generally greatest in arid and semi-arid regions such as the American West, where soil is poorly developed and vegetation provides relatively little protection. Where land use causes soil disturbance, erosion may increase greatly above natural rates. In uplands (land at higher elevations than the alluvial plain or low stream terrace; all lands outside the riparian-wetland and aquatic zones), the rate of soil and sediment erosion can quickly approach that of denudation (the lowering of the earth's surface by erosion processes). In some areas, however, the storage of eroded sediment on hill slopes of lower inclination, in wetlands and meadows and in lakes and reservoirs can lead to rates of stream sediment transport lower than the rate of denudation.

When surface runoff occurs, less water enters the ground, thus reducing site productivity and lowering the water table. Furthermore, when surface runoff leads to soil erosion, this leads to a reduction in the levels of the basic plant nutrients available for crops, trees, and other plants and decreases the diversity and abundance of soil organisms. Stream sediment degrades water supplies for municipal and industrial use and provides an important transporting medium for a wide range of chemical pollutants that are readily absorbed into sediment surfaces. Increased turbidity of waters due to sediment load may adversely affect organisms such as benthic algae, invertebrates, and fish.

Significance: Soil erosion is an important social and economic problem and an essential factor in assessing ecosystem health and function. Estimates of erosion, including topsoil loss, sediment transport and storage in lowlands, reservoirs, estuaries, and irrigation and hydropower systems, are essential to issues of land and water management. In the USA, soil has recently been eroded at about 17 times the rate at which it forms: about 90% of US cropland is currently losing soil above the sustainable rate. Soil erosion rates in Asia, Africa, and South America are estimated to be about twice as high as in the USA. The Food and Agricultural Organization (FAO) of the United Nations estimates that 140 million ha of high-quality soil, mostly in Africa and Asia, will be degraded by 2010 unless better methods of land management are adopted.

Human or Natural Cause: Erosion is a fundamental and complex natural process that is strongly modified (generally increased) by human activities such as land clearance, agriculture (plowing, irrigation, grazing), forestry, construction, surface mining, and urbanization. It is estimated that human activities have degraded some 15% (2,000 million ha) of the earth's land surface between latitudes 72° N and 57° S. Slightly over half of this is a result of human-induced water erosion, and about a third is due to wind erosion on lands disturbed by human activity (both leading to loss of topsoil), with most of the balance being the result of chemical and physical deterioration.

SECTION 1: EROSION – KEY CONCEPTS

Section Overview

This section describes several concepts essential to a full understanding of erosion and key terms used throughout the discussion and practice of sediment source control. This section also includes general information about the state of erosion control knowledge, the extent of the erosion problem, and prediction capacity.

Sediment Source Control

The process commonly called *erosion* actually consists of both erosion and sedimentation (See Framing the Issue, page 194). Whether we address erosion or sedimentation will dictate to a great extent the overall cost and effectiveness of treatment as well. For instance, by focusing on erosion, we attempt to keep soil particles in place, an approach commonly referred to as *sediment source control.* Dealing with sedimentation, on the other hand, commonly involves *treatment* of sediment-laden water downstream or downslope from the sediment source.

An innovative program exists within the Lake Tahoe Basin in California and Nevada, where a consortium of entities has developed the "Preferred Design Approach" (California Tahoe Conservancy 2008) for planning and designing erosion control projects. The key to this approach is the order in which design solutions are prioritized and evaluated. The approach, in order of importance, is:

1) Sediment source control;

2) Hydrologic design and function; and

3) Conveyance and treatment.

This approach assumes that keeping sediment on site and in place is more cost- and ecologically effective than attempting to capture and treat it downstream. This approach is based on the understanding that the most cost-effective method of reducing sediment pollution is to ensure that sediment particles are not mobilized in the first place.

Drastic Disturbance

Drastic disturbance defines areas where "the native vegetation and animal communities have been removed and most of the topsoil is lost, altered, or buried. These drastically disturbed sites will not completely heal themselves within the lifetime of [a person] through normal secondary successional processes" (Box 1978). The term "drastically disturbed sites" describes the CAREC treatment areas discussed in the publication, including ski runs, road cuts and fills, and building sites as well as other disturbed sites outside of ski resorts that are also of interest when dealing with sediment source control. These areas must be considered as functionally and biogeochemically distinct from the pre-disturbance (native) site condition, and treatment must focus on restoring structure and function, especially in the soil, if long-term or sustainable solutions to erosion are to be implemented (Kay and Angers 2002; Torbert, Burger 1994 and 2000; Bradshaw 1992; Whitford and Elkins 1986). While some sites focused on by practitioners utilizing this Handbook may be only lightly disturbed and may subsequently support vegetation, drastically disturbed sites most often require soil amendments and tilling or loosening.

A Dose-Response (Agronomic) vs. Capitalization (Wildland) Approach

When addressing approaches to revegetation, erosion control, and restoration it is useful to differentiate between agricultural and "ecological" approaches. The two main approaches are:

1. **Dose-Response** – refers to a system in agriculture or landscaping, such as a field of corn or a backyard garden, where a specific amount of fertilizer is applied with a pre-defined output or response. These types of systems are designed for a continual dose (input) and response (output) for as long as the desired process is in place. Generally, this type of system is artificially imposed in an area and is not designed to be self-sustaining.

2. **Wildland** – refers to a one-time investment or re-capitalization of a disturbed site. The desired outcome of a wildland treatment is typically a no- or low-maintenance, self-sustaining site because continual input and maintenance are not practical or cost-effective. Adequate amounts of materials and physical manipulation must be used to "capitalize" or "invest" in the system with nutrients, organic matter, carbon, or other needed elements.

A Functional Approach

The ability to develop and apply effective erosion control techniques and materials depends to a large degree upon an understanding of the processes of erosion over time. If an erosion control practice is to be effective, it must directly address one or more of the processes involved in erosion for the long term. For many years plant cover (revegetation) alone has been used as a measure of erosion control effectiveness. While plant growth can be forced via the ongoing use of adequate water and nutrients, the literature summarized here strongly suggests that 1) an erosion-resistant landscape is the result of a robust and well-functioning soil-plant system, and 2) the effective control of erosion on disturbed sites depends largely on re-creating and re-integrating ecosystem function.

Cummings (2003) suggests that when assessing restoration or treatment "success," we look not primarily at structure (the makeup of the physical plant community) as much as essential functional elements such as nutrient cycling, infiltration (hydrologic function), and energy capture (plant growth/carbon storage) on those sites. This approach is gaining popularity since it is becoming more apparent that while a site may *look* good, visual interpretation is prone to individual bias and that bias is largely dependent upon levels of training and experience, which can vary widely between individuals. Furthermore, simple visual observations cannot discern functions such as infiltration or soil nutrient cycling, yet these functional elements are central to understanding erosion processes.

State of Erosion Control Knowledge

A great deal of information has been put forth over many years regarding erosion and its control. Unfortunately, some of this information is inadequate for planning and implementing erosion control projects. We suggest at least four reasons for this situation, based on Sutherland 1998a and 1998b and Benoit/Hasty 1994.

1. **Single variables:** Many if not most studies tend to look at one or two variables. Multi-variate studies are difficult to implement and interpret. However, restoration of a drastically disturbed site includes a wide range of variables. Therefore, single-variable studies may be misleading or difficult to understand in a multi-variate environment.

2. Site specificity: Studies and tests done in locations with different climates, soil types, and types of disturbance may not be relevant to sites in the Sierra Nevada or the arid West.

3. Inadequate experimental design: A number of erosion control studies have not been adequately designed and therefore the information derived may not be robust or dependable. For instance, Sutherland, in a critical review of rolled erosion control product studies, found that very few studies had the scientific rigor to be dependable (Sutherland 1998a and 1998b). An explanation for this lack of rigor is that many erosion control studies have been conducted by product manufacturers or suppliers, and the implementers did not set them up as scientific experiments with statistical accuracy. Further, most of these studies were not presented to peer-reviewed scientific journals, but rather were presented in trade journals.

4. Time: Most studies are not tracked over a long enough time period. Even Sutherland has only suggested that studies be more rigorous but does not consider effectiveness over time. Time is a critical consideration when designing and assessing projects, especially where soil restoration is important (Richter and Markewitz 2001; Bloomfield, Handley and Bradshaw 1982).

Extent of the Problem

How important or pervasive is erosion? One often hears the comment, "But isn't erosion a natural process?" Several sources were considered in attempting to answer this question. According to Gray and Sotir (1996), annual sediment yields for the US range up to at least two billion tons per year. Of the total amount eroded, between one-quarter and one-third reaches the ocean. The rest is deposited in flood plains, river channels, lakes, and reservoirs. They report that "siltation and nutrients (nitrogen and phosphorus) from erosion impair more miles of rives and streams than any other pollutant."

Estimates of erosion rates vary. According to an EPA study, rates range from a low of fifteen tons/mile^2/year for natural or undisturbed areas to a high of 150,000 tons/mile^2/year for highway construction sites, or a maximum difference of 10,000 times (US EPA 1973). According to Scheidd (1967), roads may be associated with erosion rates 10-50 times above background levels. According to Wark and Keller (1963), "exposure of soil during the construction period can result in sediment production equal to ten times the rate from cultivated land, 200 times the rate from a grassland, and 2,000 times that from forest land."

The California State Division of Soil Conservation found that roadways in the South Lake Tahoe area were the source of 78% of the total sheet and road erosion. Further, they noted that "ski slopes that are established by clearing mountainsides have marred the landscape and created erosion problems at the Heavenly Valley ski area in South Lake Tahoe. Erosion and land scars are noticeable, even though considerable effort has been expended to establish vegetation on the sterile granitic soil" (Resources Agency 1969). Grismer and Hogan (2005a), in Tahoe-specific rainfall simulation research, measured erosion rates on disturbed sites that were up to an order of magnitude greater than similar native areas.

Predicting Erosion

The ability to predict erosion has been important in designing and justifying many erosion control projects in the past. Erosion prediction is usually based on one or more currently used models. Many of the current models address erosion primarily as a surface phenomenon. However, commonly used models such as the Universal Soil Loss Equation (USLE) and other related models (RUSLE, MUSLE, CREAMS, GLEAMS, WEPP, etc.), have proven inadequate to effectively predict erosion in wildland settings. Therefore, these models may be misleading when used to quantify the effect of specific form-based elements such as plant cover or mulch cover on erosion rates.

While models are useful as ways to envision erosive processes, a number of researchers suggest that actual control of erosion is more likely to be enhanced by focusing on physical processes in the soil and interactions between components than by focusing on model outputs (Bradshaw 1992; Torri and Borselli 2000; Whitford and Elkins 1986; and Wilkinson, Grunes and Sumner 2000). For instance, Agassi (1996) suggests that "the successful design of soil conservation programs will be more easily achieved by studying the relationship between rainfall characteristics, sealing of the soil surface, and the ensuing decrease of infiltration rate than by studying and modeling erosion processes, as is currently being done." Section Three of this Literature Review addresses specific approaches to erosion based on ecological processes rather than model assumptions.

NOTES

> "Science does not know its debt to imagination."
>
> – Ralph Waldo Emerson

SECTION 2: VARIABLES THAT INFLUENCE EROSION RATES

Section Overview

This section describes the types of erosion and the variables that define whether, and to what extent, erosion occurs on a given site. Each variable affects the rate of erosion. An excellent description of types of erosion, and erosion processes, is provided by Gray and Sotir (1996) in "Biotechnical and Soil Bioengineering Slope Stabilization" (pp 19-30). When more than one variable is impacted in a disturbance event, erosion is likely to increase. Table 1 lists the various types of erosion, what they are caused by, and what influences them.

Table 1: Types of Erosion

Process	Cause	Variables
Splash Detachment	Raindrop impact	Amount, size of droplets
Shear Detachment	Surface flow	Amount of water
Freeze-Thaw	Water expansion upon freezing	Amount of water in soil, surface mulch cover, air temperature, cloud cover
Transport	Water velocity	Amount and speed of water
Deposition	Slowing of water; filtering of water; exceeding waters capacity to suspend particles	Velocity change, filtration mechanism
Mass Failure, Rotational Failure	Differential soil densities, sliding layer, differential pore pressure	Different infiltration levels (including over-saturation) of one layer relative to another

Types of Erosion

Erosion is generally split into two categories: water and wind. A third type of erosion that is also related to water is referred to as "frozen water" or "winter" erosion, and includes snow and snowmelt erosion and frozen soil or "freeze-thaw" erosion (McCool 2002). Additional types of erosion such as colluviation and mass failures are also important.

Water

Liquid water erosion is the most commonly cited, and possibly best understood, type of erosion. There is a strong linkage between this type of erosion and water quality. Splash detachment, transport, sheet flow, rill, and gully concepts are part of water erosion. A great deal of literature describes these processes such as Torri and Borselli (2000), Le Bissonnais and Singer (1993), Moore and Singer (1990), Wischmeier and Smith (1978), and many others.

Freeze-thaw erosion showing detached soil particles.

Freeze-Thaw

Soils subject to freeze-thaw conditions have different processes affecting erosion and runoff measurement. Edwards and Burney (1987) used a laboratory rainfall simulator to test three Prince Edward Island agricultural soils (varying in soil texture) for runoff, splash volume, and sediment loss under varying conditions of freeze-thaw, ground cover, and potential for erosion.

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With bare soil, freeze-thaw significantly increased sediment loss by about 90%. Using the same procedures, Edwards and Burney (1989) examined the effects of freeze-thaw frequency and winter rye cover. They incorporated cereal residue and subsoil compaction on runoff volume and sediment loss. Wooden soil boxes were subjected to simulated rain 1) at the end of a ten-day freezing period and 2) at the end of the fifth 24-hour freezing period of a ten-day alternating freeze-thaw cycle (freeze-thaw). Where the soil was continuously frozen for ten days, there was 178% greater sediment loss and 160% greater runoff than with daily freeze-thaw over the same period, but there was no difference in sediment concentration in runoff. Incorporated cereal residue decreased sediment loss to 50% and runoff to 77% of that from bare soil, suggesting that mulch can significantly reduce erosion in freeze-thaw conditions. Winter rye cover decreased sediment loss to 73% of that from bare soil. Simulated soil compaction caused a 45% increase in sediment loss. The loam soil showed 16.5% greater loss of fine sediment fractions >0.075mm than the fine sandy loam, which showed 23.4% greater loss than the sandy loam.

Frozen Water and Wind

Little research is available regarding the amounts and types of wind or frozen water erosion in the Sierra Nevada or other ski resort regions, even though the bulk of precipitation falls as snow in these resort regions. However, wind may represent a more insidious (and effective) erosive agent on bare, disturbed areas than water. Evidence indicates that wind erosion is significant and can have devastating effects on soil quality, soil nutrient cycling, and long-term soil productivity (Fryrear 2000; Leys 2002; Stetler 2002a). According to Fryrear (2000), "while the transport capacity of the wind is much less than that of water, wind erosion can remove the entire nutrient-rich soil surface regardless of field size or location." In other words, while wind may not move as much sediment as water, the material that is preferentially moved by wind is the lighter soil fraction, such as organic matter and fine soil particles, which have a much higher propensity for negative water quality impacts than do the coarser particles.

Thus, wind erosion is a highly important degradation variable that should not be overlooked. Furthermore, wind is less noticeable but possibly more constant than water erosion in the Sierra. Each time a gust of wind affects a bare area, the soil that is moved can be significant over time, since it is ongoing over an entire dry season. Wind erosion also has a negative impact on air quality.

This photo of the American River shows a mass failure that temporarily blocked the river. This slide was believed to be the result of lack of vegetation from a previous fire, defoliation efforts, and water associated with a 100-year precipitation event (1997).

Mass Failures

Mass failure involves a downward and outward movement of soil on a slope. According to Gray and Sotir (1996) "...mass movement [of soil] involves the sliding, toppling, falling or spreading of fairly large and sometimes relatively intact masses." Mass failure usually occurs along a failure plane, is the result of loss of shear strength, and is exacerbated by positive pore pressure within the soil itself.

Mass failures have the potential to do a great deal of damage over a short period. Mass failures include rock falls, rotational slides, translational slides, lateral spreads, flows, creep, and slumps. Mass failures can sometimes be controlled, reduced, or eliminated by plant roots when the roots are deep and strong enough.

In January 1997, a mass failure occurred along Highway 50 west of Kyburz, California, that crossed and blocked the American River. This mass failure was partly the result of a forest fire that had occurred on the upland area adjoining the river. The fire had burned very hot and removed all plant material. Several houses were completely destroyed in the mass failure. Property damage exceeded several million dollars. The ecological damage that occurred along the river has not been financially assessed, but must be considered major. Such damage is difficult to estimate.

Colluviation

Colluviation is a lesser-known type of erosion that can be significant on bare areas. Colluviation is erosion due to gravitational forces. Saprolitic granite soils are especially prone to colluviation, but all bare soils on steep slopes can be affected by gravity erosion. In fact, freeze-thaw sometimes acts as the disturbing element that can make soil particles available for transport by gravity at some later time.

NOTES

Variables Affecting Erosion in the Soil Structure

Soil structure is defined as the combination or arrangement of primary soil particles into secondary units called "peds" (Brady and Weil 1996). Soil structure may be the most important element controlling erosion in upland sites because structure depends upon many physical and biological elements and processes (Kay and Angers, 2002).

These interrelated elements include aggregate stability, infiltration, soil strength, pore space, soil density, water holding capacity, soil organic matter, plant growth, and microbial activity. Soil structure is a critical element of a site's predisposition toward erosion. According to Kay and Angers (2002), "soil structure has a major influence on the ability of soil to support plant growth, cycle C and nutrients, receive, store and transmit water, and to resist soil erosion and the dispersal of chemicals of anthropogenic origin. Particular attention must be paid to soil structure in managed ecosystems where human activities can cause both short- and long-term changes that may have positive or detrimental impacts on the functions the soil fulfills." This statement, and the research that supports it, suggest that soil structure is of primary importance to sediment source control. When soil structure is severely disrupted (see discussion of "drastic disturbance," page 197), that structure must be rebuilt if erosion is to be controlled. The following sections discuss some of the attributes and elements of soil structure.

Infiltration

To the extent that water infiltrates into and through the soil, it does not run off (Radcliffe and Rasmussen 2002). In fact, runoff can be defined as the point at which water input exceeds the soil's capacity to absorb or infiltrate water (Eagelson 2002). Infiltration is influenced by a number of factors, including antecedent soil moisture, soil texture, surface relief, restricting subsurface layers, organic matter, pore space, and soil density (Battany and Grismer 2000; Brady and Weil 1996; Radcliffe and Rasmussen 2002). High infiltration rates generally result in low runoff. Runoff rates and volumes are critical variables in the erosion process. The literature reported here, as well as rainfall simulation under way in the Lake Tahoe area, suggest that sediment source control projects will generally be successful to the extent that water can infiltrate into the soils (Arst and Hogan 2008; Schnurrenberger, Hogan and Arst 2008). A primary goal of erosion control projects is to develop a system of maximum, sustainable infiltration of water into the soil relative to a native and/or adequate reference site. This state of maximum infiltration is usually related to high organic matter, low-density soil, and a robust soil-plant community (Kay and Angers 2002).

This road cut exhibits evidence of high runoff and erosion resulting from lack of infiltration capacity and vegetation.

Infiltration is heavily influenced by soil density. Each "native" soil has a density associated with it. Generally, the more dense a given soil, the lower the infiltration rate (Frits, De Vries and Craswell 2002). When a soil is disturbed by any type of physical activity, especially when the soil is wet, that soil becomes compacted, resulting in a soil with higher density, lower pore space, and a lower infiltration rate. The terms "compaction" and "high density" are used interchangeably although they are not always synonymous. A particular soil in its native or undisturbed state exhibits a particular density (also called "bulk density") usually given in mass (or weight) per volume. A soil bulk density is usually given in g/cm^3, kg/m^3, or mg/m^3. Once a site has been drastically disturbed and/or impacted with heavy equipment, that soil's bulk density increases. This results in a loss of pore space. Lack of pore space results in increased runoff and thus increased erosion (Kay and Angers 2002; Radcliffe and Rasmussen 2002).

A compacted soil is by its nature high-density. Subsoil and parent material tend to also be high-density by nature. In cases where reconfiguration of a site results in topsoil loss and subsoil exposure, such as a road cut or deeply incised ski run, soil density may be so high that it practically precludes infiltration. In all of these cases, some type of soil loosening treatment must be implemented in order to increase infiltration to levels where plant growth can proceed and where runoff can be reduced.

Plant growth can be severely limited by compaction. For instance, Josiah and Philo (1985), in contrasting physical properties of mined and unmined soils, found that the bulk density of native and ungraded soils were both 1.3 mg/m^3, whereas graded high-density soils were 1.8 mg/m^3. Four years after planting, Black Walnut (*Juglans nigra L.*) trees were 35% taller and stem diameter was 31% greater in the ungraded versus the graded and compacted site. Torbert and Burger (1990) compared the survival rate of six commercially important tree species on soil of two different densities. The soil that had been left uncompacted demonstrated a 70% survival rate compared to the 42% survival rate for the compacted soil. For some species, height was almost double on the uncompacted site. An extensive discussion of the impacts of compaction to forest and other impacted sites can be found in *Forest Land Reclamation* (Torbert and Berger 2000), a chapter in a highly useful book *Reclamation of Drastically Disturbed Land,* edited by Barnhiesel, Darmody and Daniels (2000).

Depth to Restricting Layer

Depth to restricting layer is defined as "the depth at which a soil layer or condition severely restricts root penetration. A root restricting layer results in no greater than 'few' roots being present. Examples of root restricting layers include pans, cemented horizons, compact or high-density parent materials, chemical concentrations such as salts, bedrock, and saturated soil conditions" (Luttmerding et al. 1990). According to Torbert and Burger (2000), "depth to a restrictive layer is an especially important physical property controlling productivity of trees [and by inference, other plants as well]. In a study to evaluate the effect of various mine soil physical and chemical properties...the most important mine soil property was rooting depth." While rooting depth is seldom considered in most erosion control projects, field experience and numerous measurements of unvegetated sites clearly suggest that shallow rooting depth is often associated with lack of vegetative cover.

Two considerations connecting rooting depth and erosion are:

1) Plants need a certain quantity of available nutrients and water. Water, in particular, is associated with the volume of pore space in a soil. A restricting layer tends to limit the amount of pore space in a soil, thus limiting water availability.

2) When water reaches a restricting layer, the infiltration rate is slowed, thus tending to saturate the soil. Two things can then occur. First, more water will flow over the surface as

runoff, and second, positive pore pressure in the soil and the different soil densities can lead to mass movements, such as landslides.

Nutrient Cycling/Soil Organic Matter

Soil organic matter has been linked to both establishment and persistence of plant communities in the Lake Tahoe Basin and elsewhere (Claassen and Hogan 2002; Baldock and Nelson 2002; Reeder and Sabey 1987; and Bradshaw 1997) as well as an increase in the soil's ability to resist erosion. Torri and Borselli (2000) have found that "increasing organic matter content makes aggregates more resistant to sealing and consequently decreases runoff and erosion." Further, "...those relationships indicate that soils with good granular structure (high Fe oxide and organic matter content) are less erodible." McBride (1994) summarizes the functions of organic matter as follows: "In partnership with the clay fraction, organic matter has an extremely important influence on the chemical and physical properties of soils. Critical and beneficial functions of organic matter include:

1. Maintenance of good pore structure accompanied by improved water retention;

2. Retention of nutrients (e.g. Ca_2^+, Mg_2^+, K^+, NH_4^+, Mn_2^+, Fe_3^+, Cu_2^+) by cation exchange;

Example of a well-aggregated soil with high organic matter content. This soil was sampled from a native forested area near Mammoth Lakes, CA.

3. Release of nitrogen, phosphorus, sulfur, and trace elements by mineralization, the microbial process by which organic compounds are decomposed and carbon dioxide is released; and

4. Absorption of potentially toxic organics (pesticides, industrial wastes, etc.)."

Aggregates

According to Cambardella (2002), a soil aggregate is formed when closely packed sand, silt, clay, and organic particles adhere more strongly to each other than to surrounding particles. The arrangement of these aggregates and the pore space between them is referred to as "soil structure." Soil aggregates are held together by three classes of binding agents: 1) humic material (highly decomposed organic material); 2) polysaccharides (organic sugars); and 3) temporary elements (roots, root hairs, and fungal hyphae) (Tisdale and Oades 1982). Soil aggregate formation has been shown to be dependent upon soil organic matter content (Baldock and Nelson 2002; Blackmer 2000; Wilkinson, Grunes and Sumner 2000). Stable aggregates in the soil are closely linked to the ability of a site to resist erosion (Kay and Angers 2002).

Soil aggregate formation has been shown to be closely linked to soil organic matter content (Baldock and Nelson 2002; Blackmer 2000; Wilkinson, Grunes and Sumner 2000; Kay and Angers 2002). Soil organic matter is also the primary source of food and energy for microbial populations, whose production of extracellular polysaccharides enhances soil structure and increases soil's ability to resist erosion. These data suggest that organic matter plays a number of very specific roles in reducing erosion and is of critical importance for encouraging soil aggregation.

Surface Cover/Mulch

Soil surface cover plays a critical role not only in erosion reduction but in other ecosystem processes as well. According to Pritchett and Fischer (1987), "plant and litter cover is the greatest deterrent to surface erosion. The tremendous amounts of kinetic energy expended by falling rain are mostly absorbed by vegetation and litter in undisturbed forests. Disturbances caused by logging and other activities reduce infiltration rates and increase surface runoff and erosion."

Surface cover provides the following services:

- Reduces raindrop force (splash detachment)
- Reduces surface flow velocities (shear detachment of soil particles by both wind and water)
- Reduces evaporation (water loss reduction)
- Reduces radiation influx and efflux
- Increases soil nutrients (some mulches) (Woods and Schuman 1986)
- Increases seed germination at some levels (Molinar, Galt and Holechek 2001)
- Protects soil from sealing and pore clogging (Singer and Blackard 1978)

Raindrops exert forces that detach soil particles, which can be easily mobilized by flowing water. Mulch helps to protect soil from these forces.

Grismer and Hogan (2005b) have shown that mulches alone can reduce soil erosion from bare slopes by an order of magnitude. However, the type, age, and fiber length of the mulch material are important.

Plants

Plants play an important role in erosion processes. Plants are closely linked to the elimination or reduction of erosion and have commonly been employed as the chief line of defense against surface erosion. Gray and Sotir (1996) describe the various services provided by plants including surface protection, surface and subsurface reinforcement of the soil, and influence on subsurface hydrology. They describe differences between woody and non-woody plants as well as provide limited shear strength values for some plants. The role of plants cannot be overstated. Since these roles are so complex, we refer to Gray and Sotir as well as other references where these roles are discussed in detail. Plants provide an indirect service by providing surface protective mulch. According to Torri and Boreselli (2000), "...the most effective action (of plants) is due to dead leaves and branches lying on the soil surface (mulch)." This mulch, as well as senescent plant roots, plays a major role in establishing and maintaining the soil nutrient cycle (Baldock and Nelson 2002; Pritchett and Fisher 1987; Paul and Clark 1989). Plant roots are a host to soil microorganisms and provide some of those organisms with a source of energy and nutrients (McBride 1994; Paul and Clark 1989; Reeder and Sabey 1987; Smith, Redente and Hooper 1987).

While plants do play a number of essential roles in stabilizing soil and reducing erosion, plants alone do not always limit erosion to acceptable levels (Elliot 2002; Zhang 2002). In recent rainfall simulation experiments on a range of cover types and amounts throughout the Tahoe region, Grismer and Hogan (2005b) found that plant cover did not always correlate with sedimentation rates, and in fact found that some sites with extremely high levels of plant cover produced extremely high erosion rates, similar to adjacent bare plots (Grismer and Hogan 2005a).

Soil Microbial Communities/ Mycorrhizae

Microbial activity is the chief driving force behind most soil function (McBride 1994; Paul and Clark 1989; Reeder and Sabey 1987; Huang and Schnizer 1986; and Whitford and Elkins 1986). Microbial populations are closely linked to and dependent on soil organic matter and soil quality. Microbes contribute to nutrient cycling and availability, aggregate formation, erosion resistance, water-holding capacity, disease resistance, etc. A number of microbial types coexist in the soil. While a great deal is known about soil microbes, an even greater amount remains to be discovered. Soil microbes are grouped into broad categories of *bacteria, actinomycetes,* and *fungi.* Soil microbial communities are known to convert most nutrients from an organic form into a plant-available form (Blackmer 2000; Killham 1994; Paul and Clark 1989; Tisdale and Oades 1982; Tisdale et al. 1993; Buxton and Caruccio 1979). In some cases, specific fungi are known to enhance uptake of both nutrients and water (Killham 1994 and Allen 1991). These fungi are categorized as *mycorrhizal.*

Mycorrhizae, which means "fungus roots," are an important element of the soil ecosystem. Mycorrhizae have received a great deal of attention with respect to their function and potential for use in disturbed site revegetation (Allen 1992). Mycorrhizae are a specific type of fungi that form a symbiotic relationship with plants. They are just one part of the incredibly complex ecosystem of soil microbes.

Surface Roughness

Surface roughness is often overlooked as a significant variable in erosion (Torri and Boreselli 2000; Battany and Grismer 2000). Surface roughness helps determine the velocity at which overland flow can occur, thus influencing both flow velocities and infiltration. Further, surface roughness is often associated with soil clods or aggregates and thus suggests soil stability, at least in an undisturbed and/or stable soil.

Soil Surface Sealing/Pore Clogging

Surface sealing and pore clogging are two potentially related processes. When infiltration of water occurs, fine clays, silts, organic matter, and other elements entrained in downward or interstitial flow can contribute to the clogging of pores. This process is especially related to splash detachment of fine sediments and subsequent redistribution. In some cases, these fine sediments are redistributed across the soil surface and subsequently dry into a hydrophobic layer called a soil crust. In other cases, this material makes its way into the soil and fills soil pores. In either case, the result is loss of infiltration and subsequent increase in overland flow and related erosion (Moody 2002). Over time, pore clogging and surface sealing may reduce infiltration to a level similar to highly compacted soil. This is an insidious issue in settling ponds.

SECTION 3: TREATMENTS FOR SEDIMENT SOURCE CONTROL

Section Overview

This section describes various functional tools that can be used to develop a sustainable, robust erosion control program. The term "functional" refers to the various functions that exist in an ecological system. Many planners attempt to establish grasses and other plants on a highly disturbed site much as one would plant a lawn or pasture. However, recent research has clearly indicated that vegetation alone may not always be adequate to control erosion (Grismer and Hogan 2004; Grismer and Hogan 2005a; Grismer and Hogan 2005b). To create a self-sustaining soil-vegetation community, this section addresses the restoration of actual functions that have been disturbed or destroyed during disturbance.

A great many erosion control projects are designed and implemented with the project proponent assuming that specific BMPs (Best Management Practices) have been tested and "proven" or that information gathered from various publications or conferences will actually perform as indicated across a range of site conditions. Unfortunately, that is not usually the case. The following section discusses tools used in site-specific erosion control and restoration treatments.

Refer to the Toolkit (Part Two) for complete descriptions of tools.

Defining Success as Improving Functions

All erosion control treatments define success either implicitly or explicitly. How project success is defined will determine a project's approach. For instance, if we envision a successful erosion control project outcome as primarily a well-vegetated area, then we are likely to focus on revegetation as our primary treatment. We will seed, fertilize, possibly mulch, and irrigate to establish that vegetation. Erosion itself may actually take on a secondary level of importance. As an example, some erosion control projects have actually *produced* erosion (sheet erosion or rills) as an outcome of irrigation that was used in an attempt to establish vegetation on treated areas. Some of these sites have been considered "successful" because grass had been established (Arst and Hogan 2008; Schnurrenberger et al. 2008).

If we define success in terms of *function* (such as hydrologic function, nutrient cycling, or energy capture), rather than *form* (how a site looks), it is likely that we will be much more accurate in assessing "success." In other words, we will be able to determine how a project is working rather than simply how it looks. According to Cummings (2003), the ability to restore function within the soil-plant ecosystem is likely to be the most powerful approach we can take to control sediment at its source. Cummings suggests that restoration of function within a disturbed system should be a primary goal. The usefulness of this concept can be seen in some projects where surface treatments are aimed at plant growth as a primary objective. Recent research on ski runs and highway road cuts has shown that, while it is possible to actually force plants to grow, these plant-dominated projects do not automatically equate to greater erosion control because runoff can still be quite high (Grismer 2004).

According to Cummings and others, the main functions of concern are:

1) Hydrologic function (infiltration, storage, transfer of water into and through the soil);

2) Nutrient cycling (cycling of nutrients within and through the soil); and
3) Energy capture (processing, storage, and transfer of energy from the sun as well as capture and transfer of water energy within and through the watershed).

For example, if water infiltrates into the soil, it will move through the watershed more slowly, resulting in a lower runoff rate as well as lower volume and velocity of water in the streams. This attenuation of energy will lower overall erosive forces. Without restoring soil hydrologic function, including infiltration, the goals of erosion control are not likely to be met, even though a site may support plant growth (for as long as fertilizer and irrigation are applied).

Energy capture may be described in two contexts: 1) energy captured and stored in the biota, or living things such as plants and soil flora and fauna; and 2) energy stored as water within the soil. Energy capture describes the plant community as well as links to the hydrologic function within a project area. Beyond simply describing plants as a "form," this approach recognizes the plants' function within the ecosystem—they store and then transfer energy to the soil and to animals as food.

This approach also discusses the energy function of the water within an ecosystem as well. For instance, a storm and/or runoff hydrograph represents an energy distribution graph. A hydrograph with a large peak early in the runoff cycle indicates a much higher probability of erosion than a lower peak later in the runoff cycle. This is also known as peak flow attenuation. A high-peak hydrograph describes a much more erosive runoff force than a low-peak hydrograph. Water that is stored in the soil as energy is available for plant growth throughout the growing season.

We therefore focus on three main functions: *hydrologic function, nutrient cycling,* and *energy capture* for planning and implementing treatments. By maximizing these three functions, soil will tend to remain in place and water within the watershed will tend toward a more natural or background behavior.

Three Common Treatment Indexes

While most sediment source control efforts focus on liquid water erosion, many of the same processes used to control liquid water erosion are also effective for wind and frozen-water-caused erosion (McCool 2002; Fryrear 2000; Tibke 2002). According to Reichert and Elemar (2002), "Water erosion is caused basically by raindrop impact and runoff of excess water, thus erosion and sedimentation control strategies must be based on covering the soil against raindrop impact, increasing water infiltration to reduce runoff generation and increasing surface roughness to reduce overland flow velocity."

The same techniques that are used to protect the soil surface against raindrop impact, namely mulch and live plants, are also effective for protection against wind erosion (by deflecting wind from the soil surface) and for protection against frozen-water erosion (by insulating soil against freeze-thaw and by providing additional surface roughness for snowmelt). Traditionally, live-plant cover has been considered of primary importance in erosion control. However, a great deal of research has shown that total ground cover, especially mulch, provides the most critical short-term impact or protection against erosion (Zhang 2002; Elliot 2002; Grismer and Hogan 2005b).

There is an extremely large number of attributes that define a site's ability to resist erosion, such as the extent of the microbial community, particle size distribution, plant type, and so forth. However, the three most accessible attributes that we often choose to serve as indices or site indexes for erosion resistance, given that they increase sediment source control in areas with water and wind pressures, are:

1) Cover (plant and mulch);
2) Soil organic matter and associated nutrients; and
3) Levels of infiltration.

Soil Nutrient Treatment Issues

Nutrients are critical for both plant and microbial growth in the soil. There are a broad range of both macro (N,P,K), secondary (Ca, Mg, S) and micro (Zn, Fe, Mn, Cu, B, Mb, Mo, Cl, Ni) nutrients. Typically, in the Sierra Nevada and other western mountain ranges (in non-mined sites), most macro and micro nutrients may be adequate, even on disturbed sites, with the exception of nitrogen. However, this is not always the case. Further, in disturbed sites, nitrogen (N) and carbon (C) are often deficient. Therefore, the ability to gather soil nutrient data from surrounding "reference" sites and comparing that to data from the disturbed site is an important step in understanding what is required in a native or self-sustaining system.

N is clearly recognized as the most important or generally most limiting nutrient involved in plant growth on disturbed sites (Marrs and Bradshaw 1993; Palmer 1990; Reeder and Sabey 1987; Bradshaw et al. 1982; Bloomfield, Handley and Bradshaw 1982; Wilkinson, Grunes and Sumner 2000; Palmer 1990; Claassen and Hogan 2002; Cummings 2003). N is used in the greatest quantities by plants and can be very mobile in mineral form.

While N is known to be limiting, caution should be exercised when determining which material may be needed to replace N or other nutrients. Many water bodies, such as Lake Tahoe, are known to be phosphorus (P) limited. If a fertilizer or amendment contains relatively high levels of P and the soil contains adequate P, additions may result in loss of P from the soil into nearby waterways, becoming a water body pollutant. Therefore, knowledge of both existing soil nutrient conditions as well as release characteristics of the fertilizer or soil amendment itself is important for effective use that minimizes runoff-pollution prevention.

N can be a limitation in both agricultural and wildland ecosystems. An important difference between these two types of ecosystems is that agricultural systems ("dose-response") are designed to receive an input (fertilizer) that is then removed from the system after producing a response (plant growth). The following season, the same cycle is repeated. Wildland systems, on the other hand, are self-sustaining. That is, they cycle most of their nutrients internally. In a pine forest, for instance, pine needles fall to the ground, are broken down by microbial activity, and eventually turn into nutrients for plants, microbes, and macrobes. Therefore, when planning and implementing an erosion control project, an understanding of the soil nutrient content (load) is critical.

In preparing project plans, it is important to understand three things:

1) The amount of nutrients and organic matter that are presently in the project site soil;
2) The amount of nutrients and organic matter that should be in the soil (measuring a reference site and/or using data from similar sites); and
3) The amount and what type of nutrients and organic matter need to be added to assure a self-sustaining system.

Several studies suggest that a certain level of nutrients, especially N, must be present in the soil before an adequate plant cover can be established and maintained (Claassen and Hogan 2002; Bradshaw 1997; Li and Daniels 1994; Reeder and Sabey 1987; Bradshaw and Chadwick 1980). Research on disturbed sites in the Lake Tahoe Basin shows a correlation between certain nutrient pools, especially nitrogen, and plant cover on previously disturbed sites (Claassen and Hogan 1998). Therefore, knowledge of current soil nutrient conditions allows the planner to specify amendments and fertilizers with the appropriate amount and type of nutrients.

Bradshaw et al. (1982) discuss the development of N cycling on mined land. They suggest that a pool of at least 1,000 kg/ha N must be accumulated, after which N cycling by mineralization, plant uptake and litter fall will support a self-sustaining ecosystem. This is comparable with Claassen and Hogan (2002), who found that well-vegetated, previously disturbed sites in the Lake Tahoe Basin are located at sites where there is a pool of at least 1250 kg/ha total N.

While N is understood to be a critical limiting nutrient in most terrestrial semi-arid ecosystems, and N is largely derived from organic matter in those ecosystems, the capacity for the total N contained in that organic matter to mineralize is not consistent or well understood (Baldock and Nelson 2002; Blackmer 2000). Reestablishment of nutrient cycling on disturbed sites is seen as a primary cornerstone in the successful re-creation of a sustainable terrestrial ecosystem capable of resisting erosion, improving water quality, enhancing wildlife habitat, and improving other beneficial uses (Haering, Daniels and Feagley 2000; Macyk 2000; Marrs and Bradshaw 1993; Palmer 1990; Reeder and Sabey 1987; Dancer, Handley and Bradshaw 1977; Cummings 2003; Bradshaw et al. 1982; Bloomfield, Handley and Bradshaw 1982; Dodge 1976). Woodmansee et al. (1978) report that N deficiency can affect the long-term stability of a site by limiting plant growth, thereby increasing erosion from that site.

Organic Matter Treatment Issues

Soil organic matter drives a number of processes in the soil, as discussed in previous sections. Powers (1990) suggests that a decline in forest productivity is linked directly to losses of soil organic matter. It thus may be one of the most important elements of soil function. Noyd et al. (1996) report that compost has a primary impact on reestablishment of both plant communities and mycorrhizal fungi colonization on taconite mine spoils in the Mesabi Iron Range in Minnesota while arbuscular mycorrhizae (AM) inoculation played a secondary role. Johnson (1998) suggests that manipulating edaphic factors through additions of soil organic matter may be more cost-effective on low P sites than large-scale mycorrhizal inoculation. These edaphic factors include adequate organic matter in the soil and many of the connected elements, as mentioned above.

The inclusion of organic material in a depauperate (low-nutrient) soil may provide additional benefits beyond nutrient additions, such as increased water-holding capacity,

Tub-ground wood shreds ("tub grindings") can be used as a soil amendment to add organic matter to disturbed soils. Tub grindings and other woody amendments support critical soil functions such as microbial activity, water infiltration, and water storage.

increased microbial activity (enhanced cycling of pre-existing nutrients), increased infiltration rates, and a higher cation exchange capacity (Brady and Weil 1996). Soil organic matter has been linked to establishment and persistence of plant communities in the Lake Tahoe Basin and elsewhere (Claassen and Hogan 1998; Baldock and Nelson 2002; Bradshaw 1997; Woodmansee, Reeder and Berg 1978) as well as to an increase in the soils ability to resist erosion. There are a number of types of organic matter including compost, wood chips, manure, and others. Each has its own strengths and weaknesses and should be considered carefully before use, especially for amounts and release rates of nitrogen and phosphorus.

Fertilizer Treatment Issues

The use of fertilizer for erosion control projects has been a standard practice for many years. Essentially, fertilizer is used to make up for inadequate amounts of nutrients in the soil (Soil Improvement Committee 1998). Much of the information on and the approach to fertilizer use comes from agricultural research. Much less research has been done on wildland system restoration. However, some work has been done by Bradshaw and others in mine reclamation to focus on rebuilding and re-capitalizing the nitrogen cycle in "derelict" or drastically disturbed sites. These researchers generally found that adequate N cycling was directly linked to organic matter in the soil (R. D. Roberts et al. 1980; Bradshaw, Marrs et al. 1982; Bloomfield, Handley et al. 1982; Marrs and Bradshaw 1982; Woodmansee, Reeder et al. 1978). Further, Classen and Hogan (2002) found that adequate organic matter and mineralization of the N in organic matter was directly linked to plant growth. While some of this research has been available since 1980, few findings have been incorporated into ski area work.

Bradshaw and others (1982) suggest that rebuilding of the nitrogen cycle is the underpinning of most reclamation or restoration on drastically disturbed land. Reeder and Sabey (1987) and many others support the importance of this approach. Their findings clearly suggest that fertilizers alone are unlikely to rebuild these soil-plant systems to adequate levels of N in a reasonable time unless a very careful application regime is instituted. Yearly applications may increase nutrients to the point of self-sustainability, as Ray Brown was able to show on a mine site in Idaho. However, 25 years were required to do so. In this project, cost was not evaluated, but estimates of labor alone could be as high as $25,000 (Brown and Johnson 1978).

When using fertilizers, it is essential to understand their strengths and limitations and not expect fertilizers alone to completely regenerate self-sustaining nutrient cycling (Tisdale et al. 1993). Fertilizers will be seen as part of an overall package of treatment. It is also critical to understand what type and how much fertilizer is actually needed in any particular situation so that under- or over-application does not become a problem (Tisdale et al. 1993; Soil Improvement Committee 1998).

Fertilizers come in many forms and nutrient amounts. The two most common fertilizers are the mineral and the organically based fertilizers. Some mineral fertilizers are coated so that the nutrients are released more slowly. Specific information on fertilizers can be found in Tisdale et al. 1993 and Soil Improvement Committee 1998.

Mycorrhizae Treatment Issues

Mycorrhizal fungi play an important role in most ecosystems. Mycorrhizal fungi are a group of fungi that have the ability to form a relationship with certain plants that is mutualistic.

Mycorrhizae can be considered an important subset of soil microbial components. A broad range of information about mycorrhizal physiology, morphology, and classification can be found in Walling, Davies and Hasholt 1993; Paul and Clark 1989; and Killham 1994.

In terms of the benefits of mycorrhizae, there is little doubt that these types of fungi play a critical role in the life cycles of many plants. Paul and Clark and Killham discuss the myriad of benefits associated with the range of mycorrhizal fungi. The two types of mycorrhizae that are of chief concern in wildland systems, especially relative to restoration, are the vesicular-arbuscular subgroup of the endotrophic mycorrhizae and the ectotrophic mycorrhizae, which form relationships with temperate trees and shrubs (Paul and Clark 1989). Endotrophic mycorrhizae are found on about 90% of the world's plants (Israelsen 1980) and thus are of critical concern.

The microbial community within a soil is known to drive conversion of most nutrients from an organic form into a plant-available form (Paul and Clark 1989; Killham 1994; Tisdale et al. 1993; Buxton and Caruccio 1979; Killham 1994; Buxton and Caruccio 1979). In some cases, specific fungi are known to enhance uptake of both nutrients and water (Killham 1994). A great deal of attention is currently being placed on mycorrhizal fungi and specifically on use of commercial, non-native or non-indigenous inoculum. Noyd et al. (1997) and others reported that compost had a primary impact on reestablishment of both plant communities and mycorrhizal fungi colonization on taconite mine spoils in the Mesabi Iron Range in Minnesota while arbuscular mycorrhizae (AM) inoculation played a secondary role.

Johnson (1998), in studying plant response to mycorrhizal inoculation across a phosphorus gradient, reported that inoculation with AM fungi reduced growth at high soil P levels. This finding is relevant to Tahoe and Sierra Nevada soils that tend to be high in P (Rogers 1974), suggesting that AM inoculation may not play an important role and may in fact reduce plant growth on some revegetation sites. This finding is further supported by an unpublished study of a variety of treatments (Longenecker, senior thesis) on Tahoe granitic soil, including inoculation with non-native (cultured) mycorrhizae. Measurement of growth rates in a sixty-day experiment showed that soil inoculated solely with mycorrhizae resulted in a growth rate lower than the control, while soil with compost and organic fertilizer resulted in growth rates over twice as high as either the control or the inoculated plots.

Further, Johnson (1998) suggests that manipulating edaphic factors through additions of soil organic matter may be more cost-effective on low P sites than large-scale inoculation. In support of this approach, Sylvia (1990) reported that after initial infection by vesicular arbuscular mycorrhizae (VAM) on plants used in a mine reclamation site in White Springs, Florida, there was no plant effect at 18 months and that VAM inoculation had no effect on transplant survival. These soils were low in nutrients, thus supporting the nutrient-addition findings of Noyd, Pfleger and Norland (1996), Johnson, and others.

In another study, Noyd et al. (1997) reports that adequate rates of compost added to taconite mine tailings produced biomass equivalent to or surpassing a native tallgrass prairie in three years. At the same time, organic matter accrual increased and the litter breakdown rate decreased, implying long-term plant community sustainability. In a greenhouse study, Stahl et al. (1998) discuss the greater capacity of VAM-inoculated Big Sagebrush to withstand drought than non-inoculated plants. However, the substrate used was collected from an undisturbed, nutrient-adequate site, further supporting the adequate-nutrient concept. Weinbaum and Allan (1996), in a reciprocal transplant study between San Diego and Reno, showed that non-local mycorrhizal inoculum always declined at the exotic site and with exotic hosts, arguing for both locally collected inoculum and locally sourced plants.

Native plants, such as this Penstemon newberyii, can thrive and grow vigorously in low-density, high-nutrient soil conditions.

Plant Treatment Issues

Plants play an extremely important role in practically all ecosystems. Plants are linked to and supported by the soil community. For many years, researchers and erosion control writers and practitioners have emphasized the plant or vegetative component of erosion control projects and have in fact referred to erosion control projects as "revegetation," with the assumption that vegetation controls erosion (California Tahoe Conservancy 1987; US Department of Agriculture 1982; Nakao 1976; Leiser et al. 1974). Plants play many roles in restoration and erosion control, especially on disturbed sites. Plants are closely linked to the elimination or reduction of erosion and have commonly been employed as the chief line of defense against surface erosion. However, while plants play an essential role in stabilizing soil and reducing raindrop impact, they do not always limit erosion to acceptable levels (Elliot 2002; Zhang 2002). We suggest that by linking the plant and soil elements, a more effective outcome can be produced.

A healthy, robust soil will be a critical issue for planting of any kind. Drastically disturbed soil will have very different attributes from a slightly or non-disturbed site. Reestablishment of a sustainable plant community on severely disturbed upland sites in the Sierra Nevada has proven difficult (Erman et al 1997; Leiser et al. 1974).

Aside from surface stabilization, plants also contribute to subsurface stabilization. An increase in root biomass typically results in an increase in physical soil stabilization due to shear and tensile strength (Gray and Sotir 1996). This fact is useful in ski areas to counter some county ordinance interpretations that may require ski runs to be compacted in order to provide soil strength. However, when soil is compacted, infiltration is decreased and plant roots cannot penetrate easily, thus reducing plant growth to minimal levels. (For discussion of soil density, see "Infiltration" page 204). Further, plants have been used successfully in the Lake Tahoe and Truckee areas to successfully hold loose soils on up to 1:1 slopes (Hogan 2005). One additional consideration for plant use is that claims made by suppliers may not live up their billing, given that site conditions vary widely.

Mulch Treatment Issues

A great deal of information exists regarding the effectiveness of mulch to control erosion. Agassi (1996) states that "mulching is a very efficient means to dissipate raindrop impact and to control the ensuing soil surface sealing, runoff, and erosion. Mulching can also reduce evaporation of rainwater and overhead irrigation water. Therefore, mulching can be a vital factor in improving water use efficiency." Mulch provides a number of "services." These services are listed in Table 2.

In the Lake Tahoe Basin, an ongoing study by Grismer and Hogan (2005b) found that mulches can reduce sediment delivery by an order of magnitude. Edwards and Burney (1987) found that mulch minimized the effects of both compaction and freeze-thaw on a range of soils (silt, sandy loam, fine sandy loam). Battany and Grismer (2000) showed that in a California vineyard, soil loss was linked to soil cover.

Pine Needles

Pine needles have been used in the Lake Tahoe Basin and elsewhere as a surface mulch since 1992. However, little research has been done on pine needle effectiveness. Pannkuk and Robichaud (2003) studied pine and fir needle cast following fires on both volcanic and granitic soils and found that a 50 % cover of Douglas fir needles reduced interrill erosion by 80% and rill erosion by 20%. A 50% cover of Ponderosa pine needles reduced interrill erosion by 60% and rill erosion by 40% (Wright, Perry and Blaser 1978).

Pine and fir needles offer advantages over some short-lived mulches such as straw because

Table 2: Mulch Services

Service	Description	Notes
Surface Protection - Rain	Protects soil surface from raindrop splash detachment	
Surface Protection - Wind	Protects soil surface from detachment and transport of soil particles by shear forces	
Overland Flow Reduction	Reduces overland or surface flow of water by creating a maze of "mini-dams"	Longer fiber length provides a higher level of protection. Blown-on mulch results in greater soil surface contact.
Temperature Protection	Reduces solar input to the soil by reflecting solar energy	The color of a particular mulch plays an important part in this process. Darker mulch absorbs more heat energy, for instance.
Evaporation Protection	Reduces evaporation by reducing surface temperatures as well as by creating a physical barrier	
Nutrient Addition	Organic mulches contain carbon and other organic nutrients that can enhance both organic matter and nutrients in the soil	Nutrient and energy additions are variable and depend upon the material. For instance, straw is known to contain very little C and N while pine needles can be much higher. Wood chips may lock up N but contain high amounts of C.

they last anywhere from two to ten times as long, thus providing services over longer periods of time. Grismer and Hogan have been assessing pine needle mulch effectiveness since 2003. Several reports and publications have quantified the positive effects of pine needles on both plant growth and erosion reduction at a wide range of sites (Grismer and Hogan 2005b; Arst and Hogan 2008; Schnurrenberger, Hogan and Arst 2008). These reports have shown that some of the highest infiltration rates, as well as the highest levels of plant cover on restoration sites, have been measured at sites where pine needles were applied as the mulch material. Modeled after native forest surface cover, the use of pine needles has shown very promising results. Pine needle mulch has the additive benefit of being native and locally-sourced throughout the Sierra Nevada, thus reducing both transportation costs and the risk of importing weeds.

Tilling Treatment Issues

Removal of compaction and/or reduction of soil density is a critical component of restoring hydrologic function to soil. Froehlich and McNabb (1984) show that compaction may last up to 30 years and can reduce stand growth in

Tilling has proven to be a highly effective method for loosening dense soil and incorporating organic matter.

Pacific Northwest forests by up to 15%. Tillage of compacted soil can be effective in reversing compaction. Luce showed that on a highly compacted road that had been ripped, saturated hydraulic conductivity can be up to 35 mm/hr, or approximately half of the natural background. However, Luce (1997) also suggests that this rate represents a significant increase in infiltration and would effectively reduce runoff and thus erosion during rainfall events of over one inch per hour.

Grismer and Hogan (2005b) measured infiltration rates of more than four inches per hour on a Tahoe area ski run where wood chips had been tilled into a highly compacted soil. Torbert and Burger (2000), reporting on research by Larson and Vimmerstedt (1983), state that compaction is likely the most important mine reclamation problem in need of solution. They state that compaction is caused during several steps of reclamation construction such that soil bulk density is reduced to root-limiting levels.

Economic Considerations in Treatments

An extremely important consideration in designing and implementing a restoration, erosion control, or revegetation project is cost. One approach that needs further study is the cost over time or cost per unit time aspect.

The cost of implementing an erosion control project is often measured as the cost of applying material to the project area. However, if we regard the replacement of function to that site as a primary goal and add the element of time, the question becomes, "How well does this project function and for how long?" For instance, if straw mulch is used and lasts two seasons and costs $1000/acre compared to pine needle mulch which may initially cost $2500/acre but lasts five seasons, then the actual cost would be exactly the same per year effectiveness. More cost-effectiveness assessments will be critical to determine the actual costs of projects, not just the application cost. Many projects in the Lake Tahoe Basin have been re-treated using the same relatively inexpensive techniques (hydroseeding, no soil preparation) two and three times and still have not performed adequately (personal communication, Jason Drew—NTCD; Joe Pepi—California Tahoe Conservancy; Larry Benoit—Tahoe Regional Planning Agency). This raises the question, "How many times do you apply something that doesn't work before realizing that resources are not being spent effectively?"

> "Equipped with his five senses,
> man explores the universe around him
> and calls the adventure Science."
>
> – Edwin Powell Hubble, The Nature of Science, 1954

CONCLUSION

Disturbance and erosion need to be considered in a holistic, systemic, and functional context to develop effective strategies to reduce or control that erosion (Dudley and Stolton 2003). If the *system* within which erosion takes place is ignored, erosion control measures are unlikely to succeed over the long term. It is useful to present information and techniques that clearly show how to stop erosion successfully. The paucity of this information has led to the implementation of a wide range of CAREC test areas.

While a great deal of information has been published regarding the control of erosion, little of the information provides a complete picture of what is required at each site. Furthermore, most erosion-related research tends to be single-variable manipulation studies such as mulch, seed, fertilizer, plant type, etc. (see "State of Erosion Control Knowledge," page 198). Beyond the single-variable consideration, most studies are also point-in-time studies, and thus do not typically measure results over a multi-year period. This type of information can be incomplete at best and misleading at worst. Field practitioners must deal with multiple variables and do so over several seasons.

Based on this Literature Review, the following information gaps have been identified as key areas for additional inquiry, research, and documentation in alpine areas:

- Direct measurement and quantification of treatments versus modeling or guesswork
- Long-term trends
- Runoff (overland flow) simulation
- Aging wood chips for use as a soil amendment
- Tilling depths and amendment concentrations
- Seeding rates and plant response
- Shrub seeding response and timing
- Effects of different irrigation types and cycles on plant establishment and rooting depth
- Measurements of shear and tensile strength provided by plant roots
- Effectiveness of biological and soil-based BMPs
- Direct measurement of temporary BMP effectiveness
- Freeze-thaw protection with mulch and organic matter
- Improved calibration of the runoff ("C") coefficient for erosion models
- Low-impact ski run construction techniques

This situation presents us with both restrictions and opportunities. We are restricted by a lack of complete knowledge on effective erosion control treatments in disturbed alpine areas. However, we are offered the opportunity to gain missing knowledge on our own projects through the use of an adaptive management approach (see Guiding Principles). CAREC has been committed to improving the understanding of effective sediment source control treatments in and beyond ski resorts. This Handbook contains a large amount of information that has been gained through the cooperative CAREC process. We encourage others to expand this important work so that we can continue to improve our collective understanding of erosion processes, sediment source control techniques, and restoration of disturbed ecosystems.