SOIL RESOURCE EVALUATION

a stepwise process for regeneration and revegetation of

of drastically disturbed soils

Introduction Expert System Soils Course Case Studies Application Examples

California Department of Transportation, Office of Stormwater Prevention and Headquarters Landscape Architecture

Federal Highways Works Administration

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SOIL RESOURCE EVALUATION

1. Introduction

2. Site Map

Introduction

1. Project information, objectives and rationale

The Soil Resource Evaluation (SRE) Project (RTA # 43A0073, Task order 20) was funded by the California Department of Transportation's Stormwater Protection group and administered by the Caltrans Headquarters Office of Landscape Architecture, Jack Broadbent, Project Coordinator. The purpose of the project was to more efficiently evaluate barren road shoulders and rights-of-way for plant growth limiting conditions, and to generate effective treatments to reestablish revegetation on barren, erosive sites.

Project objectives were 1) to organize a suite of appropriate soil tests into a systematic evaluation system for barren slopes and 2) document the ability of appropriate treatments to support and sustain perennial plant growth on previously barren sites.

The rationale for this intensive, soil-focused program is that while plants provide excellent erosion control, they often cannot grow or survive on the harsh sites that are created after roadway construction. The sites remain sparsely vegetated for decades and many are chronically erosive. Regeneration of soil resources helps infiltrate rainfall during storm events, and it facilitates plant growth that provides erosion protection for the soil surface. Decreased overland flow and a reduction in sediment yield are overall goals of soil regeneration on harsh, drastically disturbed sites, and of the establishment of a sustainable revegetation cover.

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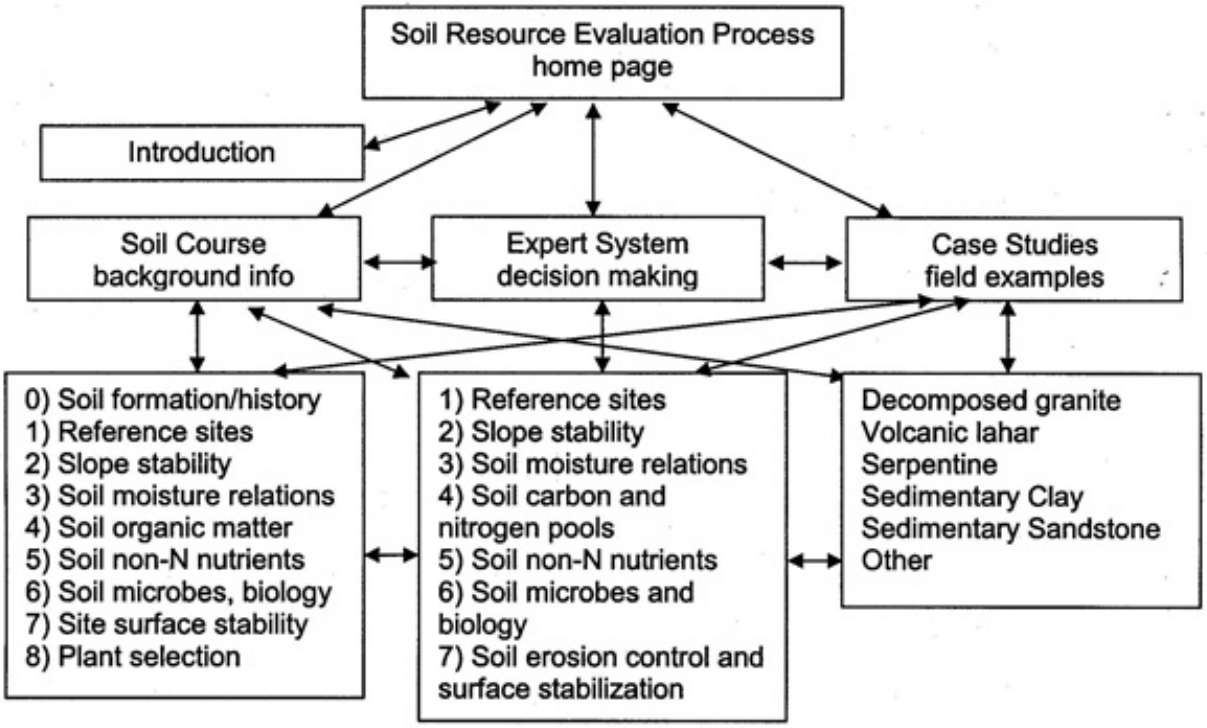
2. Site Map



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SOIL RESOURCE EVALUATION

Introduction

I. Visual Flowchart Key

II. Tabular Key

III. Technical Question Key

1. Reference sites

2. Slope stability

3. Soil moisture

4. Soil organic matter

5. non-N nutrient

6. Soil biology

7. Surface stabilization

Expert System for Soil Resource Evaluation and Treatment

Objective: Using a visual flowchart, table or set of guided, technical questions, evaluate a site or substrate to predict whether it will support sustainable vegetative cover. If one or more soil characteristic is deficient, evaluate potential treatments or amendments to assure successful revegetation.

Three versions of the expert system are provided to facilitate either a brief or a thorough technical evaluation of the soil resources involved:

The "Section I. Visual Flowchart Key" is a overall view of the various components of the Soil Resource Evaluation Process.

The "Section II. Tabular Key" is a more detailed list of the components, and some target values to look for.

The "Section III. Technical Question Key: provides the most detailed description of the measurement tests and target values for soil resource evaluation. Parts or all of this key should be used for difficult or unusual field situations.

All three versions of the soil resource evaluation have the same general format and arrive at the same result, just in a different level of detail. To keep the keys brief, pictures and explanations are included in the Soils Course rather than in the key. Numerous terms are highlighted by links to explanations or examples in the Soils Course.

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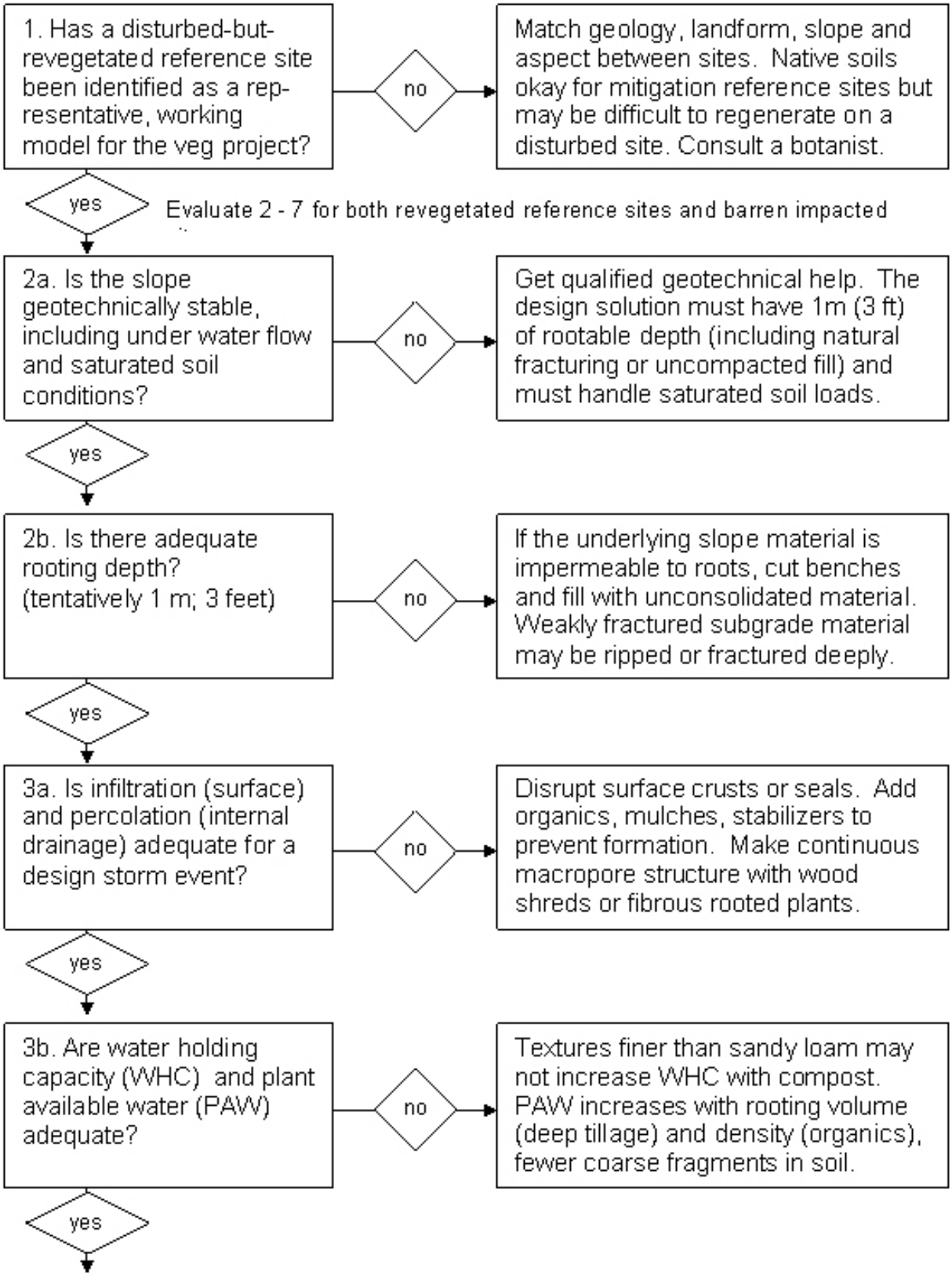
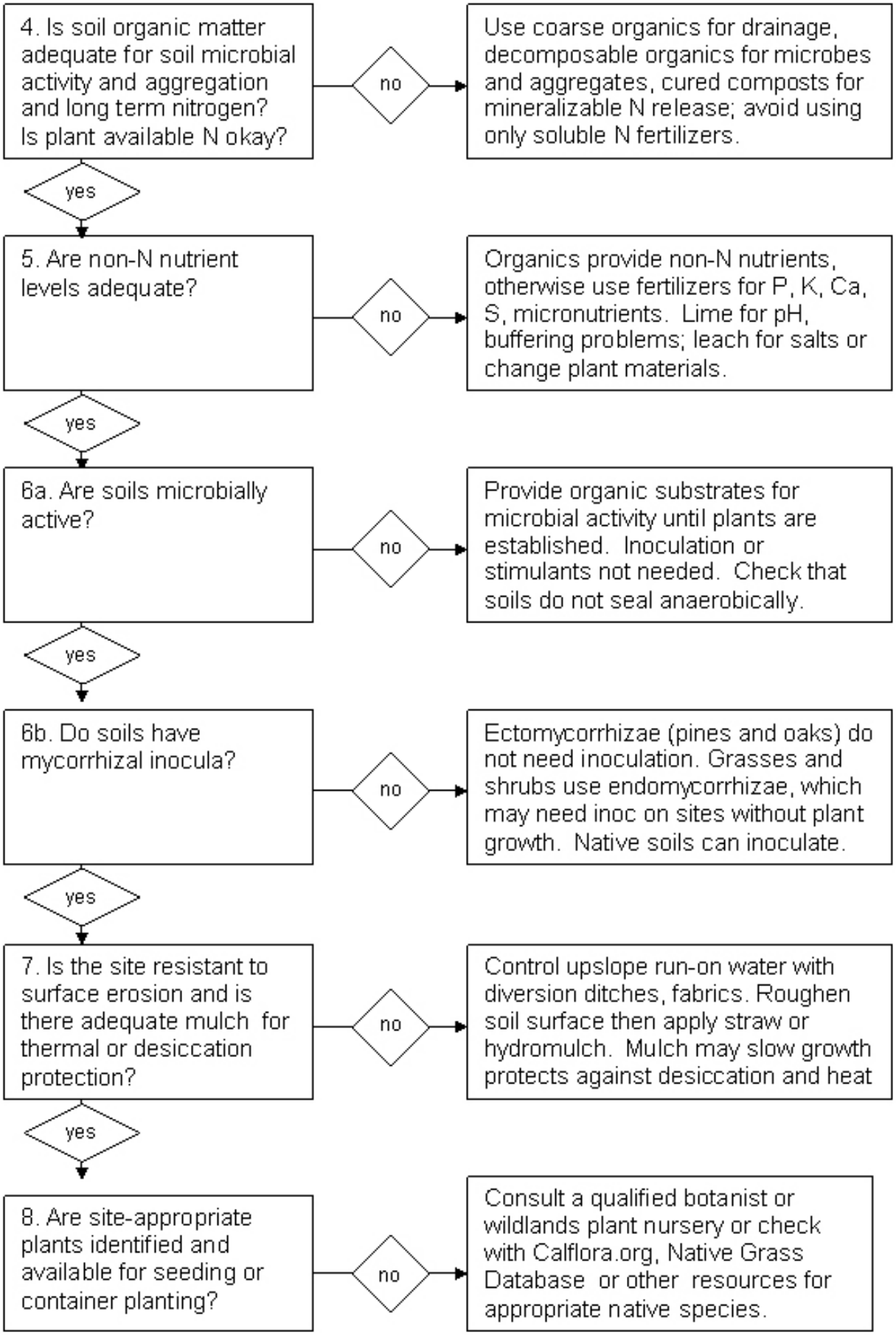
Expert system evaluation keys for soil resources.

Section I. The Visual Flowchart Key:

The first key format is as a visual flow chart. This is the quickest to review, but also the most simple. Be aware that some conclusions obtained through this key may be

inaccurate due to oversimplification.





Section II. Tabular Key

Evaluation question:	Indicators / response / treatment:
1. Has a disturbed-but-revegetated reference site been identifiedas a representative, working model for the reveg project?	If the impacted site already exists, then match geology, landform, slope and aspect between sites. If the project is in design, then check the local area for slopes that are similar to the proposed project slopes. How steep do slopes remain stable on this geological material and in this climate? If well vegetated slopes are hard to find, what would need to be changed on the undervegetated sites that are observed? If the impacted site is planned but not built, can a freshly cut slope be found to indicate what the substrate will be like after the project is built? A botanist or revegetation specialist will help identify suitable plants for local conditions. Native soils are okay for mitigation reference sites, but may be difficult to regenerate on disturbed sites. Would topsoil be available for harvest and reapplication to the constructed slope?
Evaluate each of the following soil resource conditions for both the reference site and the impacted or planned site.	
2a. Is the slope geotechnically stable, including under water flow and saturated soil conditions?	Look for signs of slumping (rotational failures) or sliding (translational failures). Slumps often occur where drainage is poor. Slides may occur because of slippage planes, steep slopes, water flow or textural discontinuities. For deeper failures get qualified geotechnical help. The solution must handle saturated loads of unconsolidated soil. Are there upslope drainage issues that would overload a slope that would be stable if in isolation? Shallow failures (< 0.3 m deep) can be stabilized by root and soil development, providing lateral drainage with strength to hold soil.
2b. Is there adequate rooting depth? (tentatively 1 m; 3 feet)	Dig pits or look at existing roadcuts for examples of rooting depth. For perennial grasses, shrubs or trees, a minimum of 1 m (3 feet) of rooting depth is needed, more if rocks dilute the fine soil. Fractured geology allows deeper rooting in the cracks, but rocks may decrease water holding capacity of rooting volume. Fine soil that overlays coarse sand (textural discontinuity) may stop root growth. Compacted fill slopes are often non-rootable except near the surface. If the underlying slope material is impermeable to roots, cut benches and fill with unconsolidated material. Weakly fractured subgrade material may be ripped or fractured deeper.

3a. Is infiltration (at the soil surface) or percolation (internal drainage) adequate for a design storm event and local climatic conditions?	Infiltration is measured with rainfall simulators. Use design storm event data for target values. Empirically, look for evidence of overland flow (from inadequate infiltration), including rills, surface crusts, soil sealing, or waterflow paths carrying duff and plant litter to mini-terraces, pedestalling under gravels. Clayey, silty or sandy soil textures and low organic content substrates are prone to sealing. Disrupt surface crusts or seals with tillage. Add organics, mulches, stabilizers to prevent re-formation. Create continuous macropore structure with wood shreds or fibrous rooted plants. Constant head permeameters can be used to test percolation at depth, but use low head devices to avoid piping.
3b. Are water holding capacity (WHC) and plant available water (PAW) adequate?	Plant available water (PAW) is measured as the soil water holding capacity of the wet soil minus the content when plants wilt. The amount of PAW must exceed plant water use target values for various plant types and climates. WHC can be measured by commercial labs for crops but wildlands plants can dry soils further, extracting additional water. Empirical signs of low PAW are widely scattered plants, shallow root distribution, high rock contents and sandy or silty textures. Composts can increase WHC of coarse, sandy soils, but soils finer than sandy loam (with PAW > 10 %) may not be improved by compost amendment. PAW increases with greater rooting volume (deep tillage) and fewer coarse fragments in soil.
4. Is soil organic matter adequate for soil microbial activity and aggregation and long term nitrogen? Is plant available N adequate?	Organic matter content can be observed in the field by darker color, horizon position (deeper horizons have less) or by tilthyness (granular soils have more, hard chunks have less organic matter). Total carbon (C) levels for soil organic matter should exceed 1.5 % in the top 150 mm (6 inches). Carbon of composts is more decomposable, so less is needed to support microbes, perhaps 5 to 10 Mg C/ha. Nitrogen (N) should exceed 1500 kg total N/ha in top 150 mm if measuring natural soil organic matter. Mineralizable N (organic, but decomposable to ammonium or nitrate) should provide 30 to 70 kg N/ha per year, less if atmospheric deposition is over 10 kgN/ha/yr. Well cured composts release N sooner than fibrous composts. Extractable N (soluble, inorganic) is inconsequential. Organics should have correct amount and proportions of C and

	N, so check for a C:N balance of 15 to 25. Aggregation is a long-term process requiring stabilized organics and plant and microbial activity.
5. Are non-N nutrient levels adequate?	Standard agricultural tests work well for non-N nutrient evaluations. Cation exchange capacity (CEC) indicates the ability of the soil to hold cation nutrients and should exceed 10 cmol/kg. pH should be between 5 and 8. Salts should be less than 2 dS/m unless salt tolerant plants are used. Organics can provide non-N nutrients that are combined with substrate for microbial activity. Chemical fertilizers can be used as supplements, individual elements can be balanced, have less volume than organics, but can produce salt effects. Sample target levels are: K > 1 % of CEC, and over 100 ppm. Extractable Ca > 25 % of CEC. P > 10 ppm extractable, especially on reddish clays or alkaline soils.
6a. Are soils microbially active?	The earthy "soil" smell is indicative of microbial activity. In the lab, microbial activity is measured by respiration. Activity can be inferred from organic levels and tilth. Provide organic substrates for microbial activity until plants are established. Inoculation or stimulants are not needed. Check that soils do not seal anaerobically. Excessive pH and high metals reduce microbial activity.
6b. Do soils have mycorrhizal inocula?	Ectomycorrhizae (pines and oaks) do not need inoculation. Grasses, forbs and shrubs form endomycorrhizae, which may need inoculation on sites without previous plant growth. Sample fine roots and clear and stain to observe colonization. Native soils can be used as inoculant.
7. Is the site resistant to surface erosion and is there adequate mulch for thermal or desiccation protection?	Control upslope run-on water with diversion ditches, fabrics for overland flow. Roughen soil surface then apply straw or hydromulch. Good infiltration eliminates need for most temporary erosion control. Check for mulch covering from 25 % cover to 20 mm thick. Mulch protects against drying and freezing as well as rain drop impact. Mulch protects plants and soil but may slow plant growth.

8. Are site-appropriate plants identified and available for seeding or container planting?	Check reference site for examples of adapted species. Check seed source. More extreme environments may require more specially adapted plant sources. Consult a qualified botanist or wildlands plant nursery or check with Calflora.org, Native Grass Database or other resources for appropriate native species.

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Section III. Technical Question Key

Instructions:

Each question should be answered with a "yes" or "no." If the question is not clear, refer to the [Soils Course] or click on a highlighted [link] to the term that needs explanation. The Soils Course is arranged in the same manner as this Technical Question Key, but has longer explanations plus more photos and charts.

"Yes" means you may have identified a problem condition in the soil or substrate. Answer all questions in that specific section and proceed to the "response" options.

"No" means "no problem" with this soil characteristic. If a main point (ends in "0") has a "no" answer, you can skip to the next question whose number ends in zero.

If the question is clear but the answer is unknown and requires a test, more analytical information on the site needs to be obtained.

REFERENCE SITE SELECTION (Step 1)

Step 1. Select reference site

Objectives:

The reference site should 1) provide an example of a local site with an acceptable vegetation community and 2) give a working example of the soil conditions needed to support this type of vegetation.

The conditions are qualified individually (Steps 2 through 7), both to evaluate the reference site and to provide target values for treatment or amendment of the barren, impacted site to support an equivalent level of revegetation.

If the project involves mitigation plantings on intact, relatively undisturbed soils, the reference site selection provides an example of soil resources needed for better ecological management (species type and density) rather than general revegetation of a barren site. This process only evaluates soil characteristics and not other potential controlling factors such as climate, herbivory, fire, etc.

Step 1 emphasizes primarily observational clues, so that a reasonable example for a

reference site can be quickly selected. The more detailed measurement of soil characteristics will be done later in Steps 2 through 7.

Questions:

1.0 Select reference site.

1.1.0. Does the [reference site] have unacceptable [plant types] or species?

Evaluation: Plant composition evaluation can range from observational (species lists) to numerical (transects, density by species, frequency) depending on objectives for the site. Methods for [plant monitoring] are summarized in the Soils Course. Broad groups of plant types (and some general examples) are:

Central Valley / Coast Range

1. annual grasses and forbs (grow in winter and spring season) (wild oats, annual rye, foxtail barley, erodium/filaree, mustards, vetch)
2. perennial grasses and forbs (grow in winter, spring and early summer becoming dormant in late summer (needlegrass, blue wildrye, lupines, xx)
3. exotic forbs (summer active) (yellow star thistle, perennial pepperweed, turkey mullin)
4. perennial forbs (summer active) (grindelia, milkweeds)
5. shrubs and trees (coyote bush, oaks, mountain mahogany)
6. specific listed (threatened, endangered) species

Sierra / East side

1. annual grasses and forbs (grow in winter and spring season) (xxwild oats, annual rye, foxtail barley, erodium/filaree, mustards, vetch)
2. perennial grasses and forbs (grow in winter, spring and early summer becoming dormant in late summer (xxneedlegr,blue wildrye, lupines, xx)
3. exotic forbs (summer active) (xxyellow star thistle, perennial pepperweed, turkey mullin)
4. perennial forbs (summer active) (xxgrindelia, milkweeds)
5. shrubs and trees (xxcoyote bush, oaks, mountain mahogany)
6. 6) specific listed (threatened, endangered) species

Response: If plant types are not appropriate for the revegetation project, locate other similar landforms on similar geology and elevation for a site with acceptable plant type and density.

Note: Annual species may indicate shallow or droughty soils, although rank growth of the same annual species can occur on deep, fertile soils due to lack of seed source for perennials, or due to management practices. Acceptable perennial communities can be used as examples for treatment of the impacted site. In general, perennial plant communities require deeper rooting volume, greater overall water availability, and slow nutrient availability from large, stable pools, while annual grasses may survive on shallower, droughtier soils. Because of lack of fire, however, many grasslands are currently dominated by annuals even though rooting depths are great enough to support perennials.

1.2.0. Does the proposed [reference site] have different [landscape position] or [geology] compared to the impacted site?

Evaluation: Compare the reference and impacted sites for characteristics of:

- + landform position (summit, shoulder, slope, erosional, depositional)
- + slope angle
- + slope aspect
- + construction type (cutslope/ fill slope)
- + hydrologic characteristics (run-on water flow from upslope, seeps, water collecting/spreading slope shape)
- + geological underlayment (deep soil, rocky soil, shallow soil over bedrock, solid bedrock, weatherable bedrock, fractured bedrock)
- + mineralogy (mineral type and weathering state)
- + substrate texture (physical weathering) state

Response: Matching landscape position is a priority, since the impacted site cannot be moved once it is established. For mitigation purposes, the reference site should match the area to be potentially used for mitigation plantings, but may have varying degrees of disturbance.

1.3.0. Is the reference site new enough that construction effects (tillage, fertilizer) or lack of a range of weather conditions are biasing the plant response on the site?

Evaluation: If the site is new enough, plants may still be growing on fertilizer stimulation rather than nutrients obtained from the substrate. If the site was tilled within the last year or two, it may not have settled or developed a compaction layer yet, which will reduce plant growth. The site may have acceptable plant cover, but it may be growth from a wet winter, and will not continue into the summer, or during multi-year climate shifts. Has weather been unusually favorable in recent years? Has an extreme drought killed plants on an otherwise acceptable site? Are new recruits of young plants of appropriate species colonizing the site? Is the site appropriately vegetated in both winter and summer conditions?

Response: Interpret the site conditions with respect to site age or climate information.

1.4.0. Does the vegetative community of the reference site (or the impacted site before construction) need to be numerically documented for plant species and density? Is a photographic record needed?

Evaluation: For some sites, [plant monitoring] of species type and cover are needed to document revegetation or establishment of mitigation species. The suggested methods are in the category of point [transects] off of a baseline transect that runs along a roadway. Transects are aligned along the road edge, shoulder, swale and backslope, or they can be oriented through a larger area of interest for a mitigation project as needed to [block] the site (measure different locations separately). Examples of [plant monitoring] methods are included in the Soils Course.

Response: Plant evaluation methods are described in the Soils Course that range from brief to detailed.

SITE EVALUATION (Steps 2 - 7)

The previous step involving Reference Site Selection (Step 1) is intended to be predominantly observational, to generally and quickly identify a functioning example of a successful site. The subsequent Steps 2 through 7 are intended to be more analytical, to

describe and quantify the soil characteristics are inherent in the selected reference site example, as well as in the drastically disturbed impacted site that needs amendment, or the potential mitigation site that would have to achieve some "natural" level of ecological functioning.

Step 2. Evaluate slope stability

OBJECTIVES:

The slope must 1) be geotechnically stable to prevent mass failures and safety hazards at the site and 2) the geotechnical design of the site must provide adequate rooting depth for growth of vegetative cover, which protects against chronic surface erosion.

QUESTIONS:

2.0. Evaluate slope stability

2.1.0. Is the slope unstable for geotechnical reasons on the reference or impacted sites?

2.1.1. Are there signs of rotational failures or translational slides that are too large to be controlled by vegetation? (the depth of the failing (moving) mass is greater than 0.3 m (1 foot) for grasses, greater than 0.5 m (1.5 feet) for woody plants)

> **Evaluation:** Estimate the depth of the failure relative to the ability of roots to stabilize the soil.
>
> **Response:** Get geotechnical assistance for potential failures. Emphasize woody plants for physical reinforcement, but use fibrous rooted grasses for rapid development of soil structure and drainage.

2.1.2. Are there geological structures that may promote failure?

> **Evaluation:** Look for textural discontinuities (soils over sandy or gravelly layers, sedimentary layers inclined toward road, seeps, intrusions (large white veins of rock intruded though granite).
>
> **Response:** Get geotechnical assistance.

2.1.3. Is there less than 1 m (3 feet) of rooting depth through fractured parent material or uncompacted fill?

> **Evaluation:** Observe a local road cut to evaluate if the underlying geology permits root growth. If it is impermeable, require rooting volume greater than 1 m (3 feet) at the deeper part of the bench. Effective rooting volume also depends on the coarse fragment (rock) content of the substrate. More rocks means a greater depth of fine soil is needed to provide adequate moisture (Step 3).
>
> **Response:** Redesign slope with adequate rooting volume. Blast to fracture rock in place.

2.1.4. Is the slope new enough that it has not successfully withstood a wide range of weather conditions?

> **Evaluation:**Check weather records, but suspect that a newer slope may not have

been tested through extreme weather.

Response: Be more critical in evaluation of the slope, and design in greater factors of safety.

2.2.0. Is the slope unstable for surface erosion reasons on the reference or impacted sites?

2.2.1. Are there rills that can be controlled by drainage structures?

Evaluation: If rills start from the top of the slope or above, control slope run-on with diversion ditches. If rills start randomly mid-slope, work on infiltration (Step 3) and surface erosion control (Step 7). If rills start from seeps, integrate erosion control and geotechnical treatments.

Response: Get assistance from a certified erosion control specialist. Design the impacted slope to be less steep than the observed reference site.

2.2.2. Is there less than 1 m (3 feet) of rooting depth through fractured parent material or uncompacted fill?

Evaluation: Observe a local road cut to evaluate if the underlying geology permits root growth. If it is impermeable, require rooting volume greater than 1 m (3 feet) at the deeper part of the bench. Effective rooting volume also depends on the coarse fragment (rock) content of the substrate. More rocks means a greater depth of fine soil is needed to provide adequate moisture (Step 3).

Response: Redesign slope with adequate rooting volume. More vigorous plant cover will increase erosion resistance.

2.2.4. Is the slope new enough that it has not successfully withstood a wide range of weather conditions?

Evaluation: Check weather records, but suspect that a newer slope may not have been tested through extreme weather.

Response: Be more critical in evaluation of the slope, and design in greater factors of safety. Is the slope new enough that it has not successfully withstood a wide range of weather conditions?

Evaluation: Check weather records, but suspect a new slope may not have been tested through extreme weather.

Step 3. Evaluate soil water relations

OBJECTIVES:

The site must have 1) a high enough [infiltration rate] to avoid overland flow and surface erosion and 2) it must provide enough [plant available water] (PAW) in the rooting profile to support adequate plant growth.

QUESTIONS:

3.0. Evaluate soil infiltration capacity rate.

3.1.0. Is soil infiltration inadequate for the site and location on the reference or impacted sites?

3.1.1. Does the soil surface have evidence of overland flow?

Evaluation: Signs of overland flow includes bare soil surfaces without accumulation of plant litter and duff, eroded rills (< 5 cm (2 in)), gullies (cannot be covered by tillage), pedestalled pebbles or plants, lag gravels (fines removed, leaving gravel pavement)?

Response: Apply mulch to protect against sediment detachment, increase infiltration rate. Go to 3.1.9. for measurement and amendment methods.

3.1.2. Does the soil surface have a dispersion crust, slurry crust or settling crust?

Evaluation: Dispersion [crusts] are fine, close packed, somewhat hardened layers on substrate surfaces that can decrease infiltration.

Response: Apply mulch to decrease raindrop impact, gypsum to reduce dispersion, apply a temporary soil stabilizer, increase infiltration rate to reduce surface saturation. Go to 3.1.9. for measurement and amendment methods.

3.1.3. Does the soil have a compacted surface layer?

Evaluation: Dig a soil pit and determine compaction layer depth. Roots penetration and proliferation are a good indicator of rootability. Penetrometer measurements should (generally) be less than 20 kg/cm2 (Hemsath et al, 1974).

Response: Till to depths greater than the compaction layer, add organics to keep soil pores open. Soil stabilizers are not useful for this type of compaction. Go to 3.1.9. for measurement and amendment methods.

3.1.4. Does the soil surface have low organic matter content, so that individual particles settle and pack and plug pores?

Evaluation: Measure total carbon of the 0 - 2 cm depth (0 to 1 inch). Carefully scrape off this surface layer without contamination from underlying layers. Compare numbers between reference and impacted site. Specific target values are not available because of the different effects of various carbon and particle types.

Response: Add fibrous organics at volumes approaching 25 % for packed soils. Go to 3.1.9. for measurement and amendment methods.

3.1.5. Has the slope been recently constructed, so that tillage activity artificially increases the infiltration rate?

Evaluation: Get information on construction activity. Look for formation of crusts and silt deposits in local depressions. Look for evidence of tillage (ripping lines, large cavities between clods, etc.).

Response: Look for older slopes with longer exposure to weather, re-evaluate. Apply fibrous organics, even if initial porosity is high. Go to 3.1.9. for measurement and amendment methods.

3.1.6. Does the slope have a concave slope shape that will concentrate water from upslope to volumes greater than the slope's infiltration capacity?

Evaluation: Look for concave slope shapes, with erosion forming in the low point. Infiltration on the slope in general may be adequate, but swale areas need reinforcement.

Response: Construct armored conveyance structures for concentrated flow paths, construct water spreading structures upslope to disperse water, control and divert on-slope water flow, plant mat-forming, densely rooted plants in the swale or drain. Go to xxxx. for Erosion control methods.

3.1.7. Does the slope surface have a fluffy surface layer from recent frost heave, but that will settle with the first rains?

Evaluation: Probe the soil surface and see if individual grains from a frost heave crust collapse to the surface. These are formed when ice lofts the particles up, but then evaporates and leaves the particles in an open lattice of particles. Freezing also breaks small particles into finer parts, accelerating the sealing of the pores when the frost heave layer settles.

Response: Mulch to reduce heat loss and ice formation, and be aware that the soil may reseal against water infiltration after it settles. Go to 3.1.9. for measurement and amendment methods.

3.1.8. Do any of the above conditions indicate that [soil infiltration rate] is less than the design-intensity storm event?

Evaluation: The substrate can be measured for infiltration using a rainfall simulator or permeameter. Measurement with the rainfall simulator requires specialized equipment. Rainfall simulators provide more accurate estimates of infiltration because permeameters and ponded ring infiltrometers can give excessively high values on wildlands soils due to water flow down cracks, root channels and burrows. Alternatively, an arbitrary incorporation of organics may be made, based on indications of infiltration limitations on the site, plus the need for a suite of other benefits a compost amendment provides. This arbitrary amendment is listed in the following section.

A) First, estimate what level of infiltration is required for your site location (Table 1). This involves the location of the site, but also defining the intensity of the storm you want to withstand without generating overland flow. The left hand column lists Return Frequency Interval for various storm intensities. Follow down under the column headed by your location and identify the intensity predicted for that location. This does not include rain-on-snow events in which warm rains melt accumulated snow pack.

Table 1. Table of return frequency storm intensities by site location (mm/hr for 15 min interval).

Return Frequency Interval (yrs)	Buckhorn SHA 299 DG	Colusa COL 20 serp	Willits MEN101 clay	Willits MEN101 sand	BlueCyn PLA 89 vol lahar

station location	Whiskytown data	Clear lake data	Willits data	Willets data	Blue Canyon data
2	38	19	28	28	23
5	51	25	38	38	32
10	60	29	44	44	37
25	70	34	52	52	43
50	78	38	57	57	48
100	85	41	62	62	52

B). Second, check the amended or ambient infiltration rate of your site. As an example, Table 2 lists infiltration measured at various sites with various treatments.

Table 2. Example infiltration values attained by different amounts of coarse, unscreened yardwaste compost incorporation (v/v) at various locations in Northern California. An asterisk indicates treatments that were not tested at these locations.

compost incorp % (v/v)	Buckhorn SHA 299 granite	Colusa COL 20 serpentine	Willits MEN101 clay	Willits MEN101 sandstone	Tahoe PLA 89 moraine
non-tilled	*	42	26	42	44
0	34	50	38	52	*
6	34	*	*	*	*
12	46	*	*	*	*
24	60	53	39	51	50

C). Third, determine if tillage or amendment required to be able to infiltrate design storm events at your site. If so, continue to the following Response section.

Response: (general case, for drastically disturbed substrate)

Infiltration amendments should be incorporated to the top 300 mm to account for storm water infiltration functions, but this considers only single-storm events. Multi-day storms deliver more water to the slope, which percolates to deeper depths and becomes an engineering concern. The Buckhorn Summit design had porous surface horizons over compacted DG fill of low permeability, meaning surplus water was forced to the surface and ran down the face over heavy coir fabric blankets.

Compost amendment specification:

Unscreened compost shall be used which is produced from tub grinding (75 x 125 mm (3 x 5 inch) grate) of yard waste materials according to US EPA regulations (40 CFR, Part 503c), and which including no biosolids or municipal or food wastes or toxic substances that are harmful to plant or animal life, and which was produced with a minimum internal temperature of 57 C for at least 15 continuous days during composting and which was turned a minimum of five times during composting and which has completed a minimum of 90 days of aerobic curing after the 15 days thermophilic composting process is completed.

Incorporation specification:

Unscreened compost material shall be mixed with sub-grade (regolith, unconsolidated geological) material in a ratio of 1 part unscreened compost to 3 parts fill. Amended substrate shall be placed to a depth of xx mm on flat benches, not inclined slopes.

Note:

Individual short-duration high-intensity rainstorms can generally be infiltrated into a 300 mm amendment depth. Multiple days of heavy rains will provide more water than this soil depth can hold. Over sub-surfaces with impermeable geology, greater depths of amendment are needed for real-world storm events or rain-on-snow events. In these conditions, amendment of benches to 1 m at the notch are useful and produce more robust plant growth as well.

Surface tillage specification:

Unscreened compost material shall be added to a depth of 50 mm (2 inches) and tilled to 300 mm (1 foot) using an incorporating ripper shank. If a standard ripper shank is used, two separate passes at 30o angles shall be made.

Note:

A 50 mm application typically provides about 3 Mg total N/ha, which is appropriate for a completely nutrient and organic matter depleted, drastically disturbed substrate (roughly equivalent to 225 Mg/ha; 500 m3; 650 cu yd).

For sites with good soil nutrient properties, but with limited infiltration resulting from compaction from traffic, amendment with coarse woody fragments produced by screening yard waste compost through a ½ inch screen ("overs") can be used to provide soil porosity with less nutrient amendment (particularly N).

After treatment, restrict traffic on site substrates. Throughout the project, do not till soil when wet unless compaction is beneficial (construction of impermeable wetlands or roadways).

3.2.0. Is plant available water (PAW) inappropriate for target plant community on the reference or impacted sites?

3.2.1. Is summer season plant water use greater than plant available water held within the substrate?

Evaluation: A generalized table of summer season plant water use is presented in Table 3. These data are measured by water depletion of a profile during the summer dry season. Data on plant water use needs from wildlands environments is difficult to obtain, but plant water use needs from different areas of the state are being measured as part of a current Caltrans project from 2004 through 2007 (Alternatives to Irrigation for Plant Establishment, RTA # 65A0182). Note that this is for summer season water use, since the soil profile is repeatedly re-wet during the winter seasons, recharging the soil water holding capacity.

Table 3. Generalized target summer season water use from literature review information from California and other arid environments.

plant life form	Water Use Needs
annual	30-40 mm[1]
perennial	100-200 mm[2]
shrub	200-300 mm[3]
tree	400 mm[4]

Source notes: [1]Annual grass summer season water use estimated from data and observation on harsh roadway sites. [2]Perennial grass summer season water use data from constructed plots from SRE I plots. [3]Shrub water use data estimated from literature values. [4]Tree water use data estimated from literature values.

Response: Use plants that are summer dormant to reduce water use. Providing too little water, however, promotes annual plant growth.

3.2.2. Is soil plant available water less than the target summer season plant water use needs?

Evaluation: Read Table 4 for various tillage depths to see if there is enough water in the profile to grow the plant type listed in Table 3.

PAW in the soil is measured as the difference between soil [moisture content] at field capacity (0.001 to 0.03 MPa, (tenth to third bar) down to either 1.5 MPa (15 bar) moisture content (the limit of moisture uptake for agricultural plants or cool season forbs) or to 5 MPa (50 bar) moisture content (mid-summer drought) for very drought-tolerant species.

Table 4 lists examples of PAW contents in two amended soils when tilled to different rooting depths. These values are for the tilled depth only. Determine whether the underlying geological strata permit deeper rooting for additional plant available water.

Table 4. Target PAW values for different rooting depths. These values are measured to 1.5 MPa dryness, and are 20 to 25 % greater when plants use water down to 5.0 MPa (50 bar) dryness. All treatments use 24 % v/v unscreened yardwaste compost amendments.

tillage depth	Buckhorn SHA 299 1.5MPa	Colusa COL 20 1.5MPa	Colusa COL 20 5.0MPa
mm	14.5% PAW	9.3%PAW	11.3%PAW
150	22	14	17
300	44	28	34
600	87	56	68
1000	145	93	113

Response: A. Measure PAW of representative substrates. Sample different horizons down to the maximum rooting depth, measure WHC at field capacity and dry conditions, measure bulk density and coarse fragment (rock) content. Along with WHC samples, get enough material to sample for total nitrogen (N) (Step 4), which also needs to be sampled by horizon.

B. Determine if compost addition will increase PAW, according to ambient WHC values. (Is the PAW of a soil more than 10 % of its weight? If so, compost addition may not increase moisture availability, although several other soil qualities will be improved.)

C. Determine if compost addition will improve rooting depth and distribution. (Compacted soils benefit most from compost addition)

D. Determine the depth to which compost should be added to provide target PAW levels using Table 4.

E. If PAW is too low, provide deeper rooting volume (backfill benches deeper, rip deeper, fracture). On very sandy soils, clay minerals can increase WHC and PAW.

Step 4. Evaluate soil organic matter and carbon and nitrogen pools

OBJECTIVES:

The site must provide adequate soil organic matter (SOM) for three main functions: 1) [infiltration] is provided by pores along coarse organic fragments, as outlined in Step 3; 2) microbial activity and [soil aggregation] is provided by decomposable carbon; and 3) [nitrogen] (N) for plant growth and community development is provided by organic matter decomposition.

QUESTIONS:

4.0. Evaluate soil organic matter (SOM) and carbon and nitrogen pools

4.1.0. Does the soil provide inadequate organic carbon on the reference or impacted sites?

4.1.1. Are coarse organic fragment levels too low?

Evaluation: Coarse fragment organics are naturally produced roots and small branches or are large composted fragments produced by tub grinding. These coarse organic fragments do not have a short-term nutrient or chemical function, but they do create large pores for infiltration and drainage. There is not a soil test for coarse carbon levels specifically, but it would be accounted for by infiltration measurements in Step 3. Application rates should approach 25 % (v/v) to positively impact soil structure (Brandt and Hendrickson, 1991).

Response: Amendment of erosive, decomposed granite with coarse (unscreened) Redding Municipal Compost Facility yardwaste compost (tub grinder through a 75 x 125 mm (3 by 5 inch) grating, at 24 % v/v amendment) brought infiltration to reference site levels. At sites having adequate soil N and fine organic matter contents, consider using only the coarse "overs" fraction produced by screening to 1 cm (3/8 inch) size for a finished fine compost product. Use of the "overs" material provides soil porosity without applying excessive N. Shredded wood from a tub grinder gives a long wood fragment size, which is more beneficial than the shorter, round wood chips. Coarse wood fragments may persist in the soil for an estimated 3 to 5 years (Tietjen and Hart, 1969) before decomposition reduces their effectiveness.

4.1.2. Are fine (decomposable) carbon levels too low?

Evaluation: This fraction is defined as coarse particulate carbon between 120 mm (1/2 inch) down to 250 um (1/10,000 inch), containing mainly shreds of wood with visible cell wall structure. This represents the bulk of most finished compost products. In natural or revegetated ecosystems, this material comprises the fine, powdery duff and shredded plant litter materials on the soil surface.

Response: Although microbial activity is absolutely important for revegetation sites, no baseline measure of activity, or of the amount of substrate of a given quality that is needed to induce a useful amount of microbial activity, has been studied on drastically disturbed slopes. Substrates with greater danger of compaction would need more microbial activity (and carbon substrate) than soils with coarser texture or more structure. Clay and iron rich soil soak up more organic matter before an effect is developed than do sandier soils.

In spite of the lack of analytical data for fine carbon content on soil, plant growth effects occur with 24 % (v/v) compost amendments that are not directly attributable to water or nutrient additions. Therefore, compost applications of this volume are assumed to be adequate to stimulate microbial activity and to enhance root and plant growth.

4.1.3. Are stabilized (humified) carbon levels too low?

Evaluation: Analyze soil carbon, amend if xxx (Munshower). To calibrate the amount of organic to add, analyze total carbon on the fine (9.5 mm, 3/8 inch) compost fraction, multiplying by soil bulk density in the field and dividing by fine soil fraction (soil volume minus rocks).

Response: Minimum total carbon levels in soil associated with moderately revegetated sites in the Tahoe Basin were approximately 21 Mg C/ha for 30 cm depth of soil, compared to 54 Mg C/ha for native soils. These are soil organic matter materials were predominantly aged, stabilized, and humified. To achieve infiltration levels similar to reference sites, the impacted decomposed granite sites required total C levels of approximately 135 Mg C/ha (30 cm depth) in a total compost amendment of 337 Mg compost/ha (dry wt). Because compost is plant-based (cellulosic), the decomposition will be faster than with humified SOM carbon, and the materials will not last as long on site. Recent research indicates that charred carbon (charcoal) may be an important component of soil to sorb carbon from plants and microbes so that it does not decompose away to carbon dioxide. Newly constructed sites may well be missing this stabliizing component, since they are often constructed out of deep subgrade material.

4.2.0. Does the soil provide inadequate nitrogen (N) on the reference or impacted sites?

4.2.1. Are short term, extractable nitrogen (N) levels too low?

Evaluation: Short-term N (the measured supply lasting for hours to days) is measured by salt extraction and is called "extractable ammonium" (NH_4^+) or "extractable nitrate" (NO_3^-). One or both of these N forms will commonly be reported on most commercial soil tests. The practical use of these test results is limited to agricultural crops, which need quickly available N for rapid growth, or as an indicator in an undisturbed natural ecosystem, with stable and constant nutrient pools, nutrient cycling, plant growth and weather. In general, these test results are not useful for disturbed wildlands soils and cannot be used to predict future plant growth.

Response: On disturbed sites, disregard laboratory estimates of extractable N, since the significance of these N pools are too short term for revegetation projects. To provide N for plant growth, provide 20 kg N/ha if some low amount of residual soil material exists, or up to 70 kg N/ha if the site is drastically disturbed, but rapid plant growth can occur to take up the N (Munnshower, 1994). Resin or sulfur coated fertilizers can break open in hydroseeders and lose their "slow-release" characteristic (become all available at once). Polyurethane coated urea is durable and has longer N release. Organic forms of fertilizers have more complex release patterns: fungal byproduct-type soil amendments release about half of the contained the first year and lesser amounts subsequent years. (Claassen, 1998). See the [Soils Course] for calculations and fertilizer data. Urban areas may receive as much as 36 kg N/ha/yr adjacent to major highways as atmospheric deposition (Rusmore, 2004), eliminating any need for fertilization. Rural areas range from 2 to 8 kg N/ha/yr across the state (NADP website, 2003 data).

4.2.2. Are mineralizable nitrogen (N) levels too low?

Evaluation: Mineralizable N (the measured supply lasting weeks to months, (Campbell, et al., 1993)) is difficult and conditional to measure. Various aerobic and anaerobic tests are done in research labs, but none are commercially available. Further research is needed for disturbed and amended wildlands soils. An alternative, black-box approach is to assume that a given amount of organic matter is available in the soil of the site, and that a given amount of N is mineralized (released) out of the site each year. For existing, functioning soils, this assumed amount is 1 - 2 % of the total N content that is released each year. As sites become more disturbed, these assumptions are less and less likely to be true.

Response: For empirical approach, measure total N (next section) and multiply times 1 to 2 % to get estimated annual N mineralization. Make sure that most of the total N measured is soil humic material with small proportions of fresh amendments.

4.2.3. Are long-term nitrogen (N) levels too low?

Evaluation: Measure total N concentrations for the whole rooting profile, including bulk density and coarse fragment (rock) content.

Response: If substrate has not been recently amended, the general figure of 1 - 2 % of the total N can be assumed to be mineralized each year to be available for plant growth. Literature values from around the world commonly indicate that 1000 to 1500 kg total N/ha to 30 cm depth is a threshold for growing sustainable vegetation on disturbed sites.

Some sedimentary rocks can have appreciable amounts of nitrogen in the geology, but the availability of this N to plants is unknown.

Step 5. Evaluate non-N nutrient availability

OBJECTIVES:

The site must provide adequate nutrient availability and soil chemical conditions to support revegetation on the site.

QUESTIONS:

5.0. Evaluate soil nutrient availability and soil chemical conditions

Nitrogen nutrition is primarily cycled by organic processes and is treated in Step 4. Non-N nutrients (P, K, S, Ca, Mg, micronutrients) and soil chemical conditions are primarily non-organic cycles, and are evaluated and treated in this section. These soil test levels are from commonly available soil nutrient availability tests using Bray or bicarbonate P extract, neutral ammonium acetate cation extracts, hot water sulfate-S extracts, and 1 M neutral DTPA micronutrient extracts. Know which tests your lab uses and know what their thresholds are for nutrient sufficiency for dryland crops such as wheat or barley.

5.1.0. Does the soil have inadequate soil chemical conditions on the reference or impacted sites?

5.1.1. Is soil pH greater than 8 or less than 5?

> **Evaluation:** Soil pH (acid or base intensity) should be between 5 and 8, and ideally between 6.5 to 7.5. Plants are quite adaptable and can be found growing in extreme soil pH conditions in spite of our perception of these materials as toxic, but growth is typically much slower under these conditions and ground cover will decline. The intensity of pH (acid or base reaction) is not the same thing as the amount of acid or base in the soil (buffering capacity). This must be determined by a separate buffering test.
>
> **Response:** Lime (calcium carbonate) applications for acid soils require buffering tests for each soil. Gypsum does not increase soil pH. Alkaline soils can be acidified by application of elemental sulfur, which slowly oxidizes to acidify the soil. This may take several years to accomplish. Gypsum does not increase soil pH. At extreme pH levels, consult a soil scientist.

5.1.2. Is salinity or electrical conductivity (EC) greater than 2 dS/m?

> **Evaluation:** Electrical conductivity indicates the salt of a saturated soil solution. A few sensitive plants may be impacted at EC levels less than 2, especially at seedling stage. Most will not be impacted until 4 and above. A spinoff of high salt content occurs if the salinity comes from sodium, which disperses the soil and forms crusts.
>
> **Response:** In the absence of leaching treatments for the soil, select salt tolerant plant species. Temporary high salt levels can occur after compost or fertilizer amendment.

5.1.3. Is cation exchange capacity (CEC) less than 10 cmol/kg soil?

> **Evaluation:** CEC indicates the capacity of the soil to hold onto nutrient cations (ammonium, potassium, calcium magnesium, micronutrients). If it is less tha 10 cmol/kg soil and organic matter levels are low, cations could leach away with rainfall.
>
> **Response:** Organic matter has appreciable CEC, which increases with decomposition state. Amendment with xx kg/ha increased a decomposed granite from xx cmol/kg to xx.

5.2.0. Does the soil have inadequate soil nutrient availability on the reference or impacted sites?

The following tests in section 5.2.0. are based on soil samples in the main rooting zone, commonly the 15 to 20 cm (6 to 8 inch) depth. A recommended practice is to take four separate samples from the 15- 20 cm depth, that are evenly spaced around the area of interest. Dry the samples, composite (mix) together, sieve to < 2 mm and submit one sample to the lab for a cost effective analysis. No site variability would be known, which can be determined using greater sample number.

5.2.1. Is extractable phosphorus (P) less than 10 ug/g using weak Bray extract or 5 ug/g using bicarbonate extract?

Evaluation: Plant available P is measured on acid soils with acid (Bray or double acid) extracts and on alkaline soils by alkaline extracts (Olsen; bicarbonate) extracts. On soils with neutral pH, acid extracts tend to dissolve more P out of granites than bicarbonate extracts do. On soils with neutral pH, alkaline extracts tend to dissolve more P out of organic matter than do acid extracts do.

Response: Request the appropriate available P extraction test from the analytical lab. P can be added by fertilizers (superphosphate, 9 % P; triple superphosphate, 20 % P) or by compost (typically xxx % P) or by organic soil amendments (xx % P). Typical application amounts are 30 to 100 kg P/ha. Excess applied P is rapidly sorbed onto mineral surfaces, where it is held against leaching, but may erode as small particles. Clays and reddish soils are the most likely to sorb large amounts of P and still allow low levels of plant available P. Excess P is not toxic to plants in reasonable amounts, and may forestall the time when P is again limiting. P application should be limited when mycorrhizal colonization needs to be high.

5.2.2. Are extractable cations less than the amounts on Table 5?

Evaluation: Extractable cations all hold onto the soil by ion attraction between the positive cation and the negative exchange site on the soil (CEC). Their suitability is determined by their total amount in the soil (in ug/g) and also by their ratio of percentages on the CEC.

Table 5. Exchangeable nutrients in soils.

nutrient	ug/g in soil	min % of CEC
K	at least 100	at least 1 %
Ca	at least 200	at least 20 % of Mg level
Mg	at least 100	at least 10 %
Na		at most 20 %

Response: Compost is a high source of K (xx %). Potassium-containing fertilizers are also inexpensive and easy to apply, but may increase short-term salt levels. Application calculations are listed in the Soils Course.

Calcium can be applied in compost, gypsum or lime. Magnesium (Mg) is commonly not limiting, but may be excessive in serpentine and ultramafic materials. Even on these materials, Mg levels are not the focus for plant growth, it is maintaining at least a minimum level of Ca. Excessive application of Ca can increase the invasibility of serpentine plant communities by annual weeds.

5.2.3. Is extractable SO4-S less than 3 ug/g?

Evaluation: Sulfur as sulfalte (SO4-S) is measured as a hot water wash of the soil. Clear minimum numbers for this element are not well known. A very high level of S is not toxic to plants, but often indicates acid generating potential in the soil and often the possiblilty of metal toxicity.

Response: Gypsum and elemental sulfur are easily added to a slope to provide S. Common amendment levels may be xx kg/ha.

5.2.4. Are available micronutrients less than those listed on Table xx (when extracted by the methods/solutions accompanying each element)? In the case of B, numbers listed are maximums.

Evaluation: Compare soil micronutrient fertility analysis data from lab to values on Table 6.

Table 6. Critical soil extractable nutrient levels for selected micronutrients.

essential micronutrient	nutrient level ug/g	extraction method
Zinc (Zn)	at least 0.5	1 M neutral DTPA
Manganese (Mn)	at least 4.0	1 M neutral DTPA
Iron (Fe)	at least 5.0	1 M neutral DTPA
Copper (Cu)	at least 0.3	1 M neutral DTPA
Boron (B)	5 to 8	water
Molybdenum (Mo)	at least 0.1	water

Response: Amendment of specific micronutrients with separate fertilizers is a difficult task, since the difference between deficiency and toxicity is small. Amendment with a bulk material such as yard waste compost accomplishes the task with out danger. Also, several fertilizer and forestry supply manufacturers make fertilizers with micronutrients, including "teabag" doses that can be dropped in planting holes.

Step 6. Evaluate soil biology

OBJECTIVES:

The site must support adequate biological activity for nutrclass="question_text"ient decomposition and cycling, nutrient uptake and to generate soil aggregation.

QUESTIONS:

6.0. Evaluate soil biology

Because most soil microbes are widely distributed and continuously blown around by wind and distributed by animal and water movement, inoculation is not a primary concern for soil microbial activity on disturbed sites, possibly exceptions of endomycorrhizal fungi and nitrogen fixing actinomycetes and bacteria. What is critically important is providing habitat and substrate for microbes on these previously barren substrates. Sections on inoculation are included for endomycorrhizal fungi.

Macrobiology of organisms colonizing newly revegetated sites is poorly known. Some burrowing organisms (worms, ants, gophers) provide rapid benefits to the site. Other

organisms that graze on revegetation plant species may have important influences that are not well understood at this time. These effects may include reducing plant biomass production by herbivory, increasing nutrient cycling or increasing plant community diversity.

6.1.0. Does the soil have inadequate soil microbiological activity on the reference or impacted sites?

6.1.1. Is the soil have excessively toxic chemistry or extreme conditions so that saprophytic (organic matter decomposing) microbes will not grow?

> **Evaluation.** Plant litter can accumulate salt crusts on excessively salty or metal contaminated sites, which eliminates microbial activity. Check pH, salt and metal contents from Step 5.
>
> **Response:** Amend soils as if for plant growth. In addition, provide carbon substrate to increase microbial activity if plant litter is low on the site (Step 4).

6.1.2. Do roots of grasses, forbs and shrubs lack endomycorrhizal colonization?

> **Evaluation:** Collect fine roots from actively growing plants, clear and stain and count mycorrhizal structures in cortical region of roots.
>
> **Response:** Mycorrhizal colonization of plant roots is widespread and predominant in functioning soils. Drastically disturbed soils may lack inocula for the first several years, which may critically delay plant establishment and soil regeneration. Little benefit has been observed from use of commercial inocula on drastically disturbed sites, and some studies cite a negative effect compared to native mycorrhizal fungal inocula. If any previous plant growth has occurred on the site, including annual weeds (but excluding mustards, Russian thistleclass="question_text" and pigweed), the site probably has more inocula than can be obtained from commercial application. Link mycorrhizal evaluation to P availability and amendment in Step 5.

6.1.3. Do roots of N-fixing species (ceanothus, purshia, legumes, lupines) lack nodules?

> **Evaluation:** Dig up fine roots of host species and check for small 1 - 5 mm nodules.
>
> **Response:** Inoculate new container plants in the nursery. Amend planting holes with 250 mL (1 cup) of soil recently harvested from under other colonized plants of the same species. Some legumes form symbioses with microbes from cross inoculuation groups (same microbial species on different, closely related plant hosts) in commercial production. The efficacy of these microbes on wildlands sites is not known. Link N symbiosis evaluation to amendments for organics, N and C in Step 4.

6.1.4. Is there lack of other members of the biological community, or an excess of one member?

> **Evaluate:** Are plants grazed severely without signs of predators? Is infiltration being increased by burrowing animals (worms, ants, vertebrates)?
>
> **Response:** Provide habitat for other species needed for community development, such as stone cover, slope heterogeneity, host species.

Step 7. Evaluate site surface stabilization (erosion control)

OBJECTIVES:

The site must be adequately stable against surface erosion and desiccation that plants can germinate, grow and cover the site before erosion resumes.

QUESTIONS:

7.0. Evaluate site surface stabilization

Because plant growth of native species is slow for the first several seasons, a surface erosion control is often needed to protect against the return of soil erosion from the barren surface There are many well developed erosion control methods available for this component. The only additional element that may be requred is to add a thicker mulch than required for raindrop erosion control, that will protect the soil and seedlings against desiccation and thermal extremes.

7.1.0. Does the soil have inadequate surface erosion control on the reference or impacted sites?

> **Evaluation:** Is water flow onto, through and from the site controlled? Is rain drop splash detachment controlled with a surface mulch? How thick is the mulch layer on the reference site?
>
> **Response:** Integrate these findings with activities in Slope Stability (Step 2) and the Soil Water Relations (Step 3). Follow standard temporary erosion control procedures.

7.2.0. Does the site have inadequate thermal protection?

> **Evaluation:** In mid winter, check for frozen soil and ice heave. Mulched areas in the Tahoe Basin were not frozen in mid winter, while barren areas were frozen to 30 cm. In mid-summer check for hot and desiccated surface soils. Compare barren or impacted site to the reference site.
>
> **Response:** Add thicker mulch layer than required for raindrop erosion control.

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SOIL RESOURCE EVALUATION

1. Reference sites

2. Slope stability

3. Soil water relations

4. Soil organic matter

5. non-N nutrient

6. Soil biology

7. Surface stabilization

8. Site Appropriate Plant Materials

SRE Soils Course

Regeneration of Drastically Disturbed Substrates into Vegetated Erosion Resistant Soils.

Objective:
This Soils Course section will provide explanation of soil processes, along with pictures, examples and testing methods. This section provides information, but it is not a decision-making process. That is provided in the Expert System section. In many cases, links can be used to move the reader between the Expert System evaluation process and the Soils Course information pages.

A History of Soil Science
The development of soil science is a story of identification of the component parts of a complex system, so that adjustments can be made effectively on functioning soils, and so that non-functioning soils can be regenerated and made to work again.

For thousands of years, people have evaluated soils for their ability to grow food, fiber or forage crops. Over 2000 years B.C., the Chinese used a soil map as a basis for taxation rates. Over 1000 years B.C., Homer wrote in the Odyssey about use of manure amendments on fields. Agricultural practices continued for centuries with little knowledge of why the practices were necessary.

In the 1600's A Flemish chemist Jan Baptista von Helmont grew a willow for five years to 164 pounds in an earth-filled tub. When he did not detect any loss in weight from the earth, he concluded that the plant biomass was generated from air and water alone. A short time later, however, John Woodward, in Britain, found that muddy water grew plants better than rain water, helping him to identify the importance of the "fine earth" component. Jethro Tull, in the 1700's, advocated tillage of the fields to break up soil so that more of the fine earth and humus "components" could be adsorbed into the plant. But the nutrient elements in these components remained unknown.

A chemical basis for plant nutrition started in 1834, when a Frenchman, J.B. Boussingault, and a German, Julius von Liebig, were able to show that the amount of "minerals" in manures were related to plant growth responses. This led directly to the concept of fertilizers as nutrient elements. The United States Department of Agriculture was established in 1862, partly to address the problem of decreasing crop yields on land that was not properly cared for. Still, the concept of a "soil" was that of a passive storage medium that fertilizers or organic amendments were added to, rather than of a functioning system of its own.

In the late 1860's, E.W. Hillgard, from Mississippi, and V.V. Doukachaev, in Russia, began to describe that the horizontal layerings in a soil profile were related to climate, vegetation and geology. They began to predict that similar conditions would produce similar soils at other distant locations. These preliminary findings were assembled by C.F. Marbut with the USDA, who used them for the first soil classification system. Hans Jenny (pronounced "yen´ny"), at the University of California, Berkeley, traveled on the Russian steppes and on the North American prairies, added concepts of carbon and nitrogen accumulation to the components that drive soil formation and function. This body of knowledge now allowed field people to predict where different types of soils would occur, based on the knowledge that soils are the combined effects of many processes at the earth's surface. Instead of viewing soils as random occurances on the landscape, the type of soil that formed was now seen to reflect the environment in which it was produced, as a product of the "factors of soil formation."

Soil formation is now understood to be a function of the different effects contributed by *climate, organisms* and *organic matter, topographic relief, parent material* and *time.*

Each effect operates in an interactive fashion with the other effects, producing the wide variety of soils we see across the landscape. This discovery allows us to see that each soil-forming effect works independently. This concept also shows the mechanics of how soils are formed and how they work. The utility of this information for revegetation on harsh sites is that if the soil is *not* working adequately, an understanding of the various components can allow the deficient component to be more easily identified and fixed.

The Soil Resource Evaluation system was developed with a similar structure. The objective is to define the main soil functions that are required by plants for growth, but that may be missing or deficient on barren, non-vegetated areas. The list of five "factors of soil formation" is modified so that they describe the soil components that plants need to live at any given point in time rather than as a long process of soil formation.

The soil resources needed for plants to grow on sites include *slope stability, plant available water, nutrients, biological activity* and *erosion protection.*

When these processes are regenerated on a drastically disturbed site, revegetation is expected grow as well as if the site had not been disturbed.

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A brief overview of soil structure.
As a soil develops, a typical pattern of horizons form at different depths. These horizons are defined by the changes in the soil layers in comparison to the relatively unaltered geological, or C horizon, material. C horizon material is defined as unconsolidated rock (regolith) that is broken up, but is otherwise little affected by soil forming processes. It is the parent material on which the soil forms.

The A horizon forms on top at the earth's surface by accumulation of organic matter, root growth and microbiological activity. The accumulation of organics gives the A horizon a darker color and a structure more like small bread crumbs rather than like large clods. The term "clod" refers to a volume of soil that is artificially molded by shovels or equipment, rather than as part of natural soil formation. Vigorous plant growth can start to form an A horizon in as little as a decade of time.

The B horizon forms below the A, and is distinguished by an accumulation of clay, iron or aluminum, carbonate or gypsum. These accumulations give the B horizon a coarser, blockier structure (bigger chunks of soil) and either a redder color (with iron) or a lighter color (with carbonate or gypsum). B horizons take a much longer period of time to form than the A, taking centuries to millennia to develop.

As mentioned before, the C horizon is the unconsolidated regolith formed by disarticulation of the rock matrix, but having little other soil development. If the soil is relatively young, it may have an A/C profile, meaning some organic accumulation has occurred, but a B horizon has not developed. The depth of a functioning soil is often defined by the lower extent of plant root growth.

[scporfKirk]
Mormon Immigrant Trail near its junction with state route 88.
In this soil profile, an A horizon is well developed (darker surface 300mm) to where the roots stop, but a B horizon is not clearly evident. The rest of the soil is a C horizon because it is little altered from the original geological material. The soil overlays a finer pinkish gray ash below, which is not really considered a soil since roots do not penetrate. Roots from the shrubs hit this lower layer and trace along the boundary of the coarser overlying layer and the ashy underlayer. This rooting depth defines the depth of soil at this location.

Topsoil harvesting
An organic rich A horizon is a valuable resource to harvest, stockpile and reapply to the site. The A horizon has more fertility than the C horizon that may be exposed following construction. The A horizon has more organic matter and soil structure, which will keep the soil particles from settling and reducing infiltration. Even if the A horizon is stockpiled for a period for several years, and the biological activity is stopped, the material still is a valuable growth medium. The biological activity will re-activate as soon as plant start putting carbon back into the soil.

The degree of soil development on a site prior to disturbance can partly determine how well a site recovers after disturbance. A site with a well developed, clayey B horizon may support plants (usually shrubs or trees) that can use the water in this horizon during the summer. Excavation and removal of this horizon means these plants would have to grow on a C horizon, which may hold less water. In another example, vernal pools rely on standing water during the spring. Disturbance may increase drainage and decrease the residence time of water, which is the cue for various vernal pools species. On the other hand, soils with very little horizon development may revegetate easily after disturbance, because the remaining substrate is not very different from the initial coarse, sandy soil.

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Soil Resource Evaluation Steps

The process of evaluating these processes at a site have been organized into the various steps listed in the Soil Resource Evaluation expert system. For each step, the objective of that component is identified, an evaluation method is proposed, and target levels for sufficiency are suggested. Because soils are complex and interactive systems, and because drastically disturbed sites are widely and wildly variable, a prudent approach is to identify a disturbed-but-revegetated site that is similar to the impacted or degraded site. This provides a working example of the soil properties that are appropriate for regenerating plant growth on sites that have been impacted by construction or other disturbance.

Soil Resource Evaluation Expert System organization:

The (current) steps of the SRE expert system include evaluation of:

1. Reference site selection
2. Slope stability and rooting depth
3. Soil water relations
4. Soil organic matter, carbon and nitrogen pools
5. Soil fertility (non-nitrogen)
6. Soil biology
7. Surface stabilization and erosion control
8. Special plant materials, information, if needed

The steps in the Soil Resource Evaluation system are also arranged in a generally chronological pattern. The Reference Sites can be envisioned years ahead of time, when route locations are still being discussed. The Slope Stability issues are established during heavy construction of the site and are difficult to change afterward. The Soil Water Relations and Soil Organic Matter steps involve (at this point in treatment development) semi-truck loads of compost or other amendments. Soil Fertility, on the other hand is much smaller in scale, consisting of bags of fertilizers. Soil biology is at the scale of inoculation of microbes. Surface stabilization is the well known step of temporary erosion control. Planting on the amended slope is one of the last steps, in conjunction with erosion control. Not only are the steps in general first-to-last order, but they are also separated according to sampling and testing methods and amendment methods.

Although the steps as proposed are intensive and detailed, a smaller number of generally applicable amendment combinations is expected to become apparent after a few years of treating common types of disturbed sites along California roadways. At that time, revegetation specialists should be able to selected a suitable treatment based more location and a brief site evaluation, without the intensive measurement steps proposed here to identify the problem and appropriate amendments.

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SRE step 1). Reference Site Evaluation

OBJECTIVES:
The reference site should 1) provide an example of a local site with an acceptable vegetation community and 2) give a working example of the soil conditions needed to support this type of vegetation.

A [reference site] is defined as an example ecosystem that serves as a model for planning a revegetation or restoration project, by providing examples of levels of physical or biological soil attributes that are sufficient for the observed plant growth and diversity at the site (adapted from SER, 2004). These attributes are measured through direct comparison of soil resources at the time of sampling. The trajectory of the soil and plant community regeneration process can be inferred, but not actually known unless the site is resampled at a later time.

The process of selecting a reference site forces planners to reconcile the type of community they imagine attaining on a site with the conditions (slope, aspect, rooting depth, amendments) needed to regenerate that type of plant community on the site.

The analysis of soil resources on reference and impacted sites (Steps 2 through 7) forces soil scientists to evaluate whether the soil tests they use actually represent the conditions that plants require to revegetate the sites.

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1.1.0. Acceptable plant cover, plant types or species

Central Valley / Coast Range

"Acceptable" plants (in general)
1) native annual grasses and forbs (grow in winter and spring season)
(Six weeks fescue, xxx, ReGreen, barley from straw application)
2) native perennial grasses and forbs (grow in winter, spring and early summer becoming dormant in late summer
(needlegrass, blue wildrye, lupines, xx)
3) perennial forbs (summer active)
(grindelia, milkweeds)
4) shrubs and trees
(coyote bush, oaks, mountain mahogany)
5) specific listed (threatened, endangered) species

"Unacceptable" plants (in general)
1) exotic annual grasses and forbs (grow in winter and spring season)
(wild oats, annual rye, foxtail barley, erodium/filaree, mustards, vetch)
2) exotic perennial grasses and forbs (grow in winter, spring and early summer, becoming dormant in late summer) (pubescent wheatgrass,xx)
3) exotic forbs (summer active)
(yellow star thistle, perennial pepperweed, turkey mullin)
4) exotic shrubs, trees (woody, summer active) (tree of heaven, scotch broom, tamarisk)

Sierra

"Acceptable" plants (in general)
1) annual grasses and forbs (rare at high elevations)
2) perennial grasses and forbs (grow in spring and early summer (squirreltail, California brome, blue wildrye, yarrow)
3) perennial forbs (summer active) (Mules ears)
4) shrubs and trees (buck brush, manzanitas, mountain mahogany, oaks, conifers, willows)
5) specific listed (threatened, endangered y)

"Unacceptable" plants (in general)
1) annual grasses and forbs
(cheatgrass)
2) perennial grasses and forbs (grow in winter, spring and early summer
becoming dormant in late summer)
(orchard grass)
3) exotic forbs (summer active)(yellow star thistle)

4) woody shrubs and trees

Great Basin / Mojave Desert

"Acceptable" plants (in general)

"Unacceptable" plants (in general)

Relationship of plant type and soil resource levels
Annual species may indicate shallow or droughty soils, although rank growth of the same annual species can occur on deep, fertile soils due to lack of seed source for perennials, or due to management practices. Acceptable perennial communities can be used as examples for treatment of the impacted site. In general, perennial plant communities require deeper rooting volume, greater overall water availability, and slow nutrient availability from large, stable pools, while annual grasses may survive on shallower, droughtier soils. Because of lack of fire, however, many grasslands are currently dominated by annuals even though rooting depths are great enough to support perennials.

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1.2.0. Landscape position
Conditions to consider during reference site selection:

1. *landscape position*: Landforms (hills, slopes, valleys, fans) have consistent effects on soil formation because gravity consistently moves materials down-slope. This means that soils on hill top, ridge line and shoulder positions are shallower than on side slope, foot slope or fan positions, all other factors being equal. The landscape position can be the single most important indicator of the ability of a soil to support revegetation, mainly because it controls depth, and depth controls water holding capacity.

A related effect occurs with landscape position, however, and that is *landform stability*. Different from slope stability (geotechnical failures), landform stability refers to the ability of a site to stay at the earth's surface. Depositional sites are often buried under more material coming from upslope. Erosional sites often steadily lose material to various forms of erosion. Stream channels can alternate between "erosional" during scouring high flows and "depositional" during less energetic flows. Plants are well adapted to move into these changing conditions, but it is critical to obtain appropriate plant species. Much of Caltrans effort comes in changing erosional landforms into stable ones. The oldest soils (several hundred thousand years old) are on stream terraces that are low enough they are not getting eroded away, but are high enough to avoid stream scour. Deep soil development occurs on these sites, and plants can be dependent on the soil strata for their lifecycles. The more erosional sites have less soil development, and so there are fewer plant growth restrictions other than growing faster than the competition.

[photo of well developed soil vs entisol] Figure caption with phrases on illuviation

2. *slope angle*: Deviation of a land surface from horizontal, measured in degrees, ratio of horizontal:vertical, or percent.

3. *aspect* (slope direction): The compass direction of the fall line of a slope. Significant for vegetative growth because north and east slopes are cooler than south and west slopes. North and east slopes may also stay frozen longer, thereby reducing plant growth.

[photo of n/s slope veg cover]

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1.3.0. Geology

parent material: Parent material refers to the unconsolidated (not solid rock; regolith) geological material underlying a site. Soils form on these materials and derive most of their nutrient content (other than N) from the minerals in the rock. Parent materials influence plant growth because of water availability and nutrient availability.

[scprofserp1]
COL 20 2.0. The areas of chaparral are underlain by serpentine parentmaterials while the areas with grasses and oaks are underlain by Franciscan sediments. Note how the soil is red in areas where it is exposed but not eroded (iron rich serpentines weather to brown-red colors) but it is gray-blue where erosion is active (lower left and center along the fire road).

Strategies to consider when selecting reference sites. Because soil development is slow (decades to centuries for organic matter accumulation, B horizon development takes millennia), be realistic about the soil that is expected to develop in the next few years of revegetation on the site. Vigorous plant growth can quickly cover the site with plant litter for erosion protection, but increases in organic matter content are decades away. Compost application can jump start this component. If the substrates are gravelly and unweathered, do not expect large changes in fine soil development unless the substrates show the potential for rapid weathering, such as occurs on some crumbly volcanic or sedimentary parent materials. Sites on parent materials that don't weather quickly may require greater rooting depths, or more drought tolerant plant types.

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1.4.0. Site history

The recent years that a site has been existence may have been atypically dry, reducing the chance for erosive processes to develop. Alternatively, if a recent, 500-year return frequency storm has eroded the site, should the site design be upgraded to handle this condition? Or, should a less expensive, routine design be reinstalled that is adequate for a 20 year event, for example.

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1.5.0. Site documentation

Plant cover and diversity monitoring method Objective: measure plant cover and diversity of a reference site so that success criteria can be established for the revegetation site. Method based on *Measuring and Monitoring: Plant Populations* (Elzinga, et al., 1998).

1. Set precision level
Measurement of changes in a population is a more rigorous task than measurement of the coverage of a species at a given time. Perhaps an acceptable management question is not actually about a species, but about the general life form of plants at the site (annual vs perennial; native vs exotic). Select a numerical goal, and reevaluate this goal with consideration of time for measurement of each plot, or other constraints.

A common example objective would be to sample the population so that the confidence level is 80% that the sample estimate is within 20 % of the true population mean. (pg 92, Elzinga et al., 1998)

2. Delineate area of interest
Make a sketch of the overall field setting. Distinguish landforms (fans, slopes, drains, differences in parent material) or management units (previous treatments, road edges, different, establishment times) so that you can delineate the area that you want to sample. In the case of road rights-of-way, segregate the road edge (subject to frequent vehicle impacts or construction effects) versus the shoulder (sloping away from the plane of the road toward a drain) versus the swale (local drainage conveyance) versus the backslope (slope on the side of the drain away from the road excavation/fill that transitions into the existing topography (hingepoint). These roadway environments will be long in the direction parallel to the road, but will vary in width perpendicular to the road.

3. Tentatively ID most plant species to be observed before running the transect
Identification of most species prior to measuring will speed measurement, without interrupting the numerical process. Temporary ID numbers or labels may be used; samples may be saved for ID later. Do not trample the area to be used for the transects.

4. Establish baseline transect along long axis of area of interest and position measurement transects. Baseline transect:
Select an area of interest, and lay a 30 to 50 m tape on the long axis of the area. The start of the baseline transect should be randomly oriented along the long axis of the area of interest. The baseline transect length should be divided into 10 equal sections. Determine 5 evenly spaced baseline transect intervals for the start point of the measurement transect. (Example, at 1, 3, 5, 7, and 9 m).

5. Measurement transect:
Smaller measurement transects will be located starting at each of the baseline transect intervals. Orient each of the measurement transects parallel to the baseline transect (as long as they don't overlap each other) or perpendicular (to cross drill rows of young plants) or an some angle to the baseline transect.

Select a measurement transect length and intervals between measurement points that will provide 100 counts (sampling points) that do not hit an

individual plant of average size more than once. For example, with young grass seedlings having a canopy diameter of 10 mm, a 2 m measurement transect length that is measured at 20 mm intervals will provide 100 hits. For larger average plant sizes, counting at an interval of 100 mm between sampling points will require 10 m of measurement transect length before 100 hits are obtained. If the area of interest is small, reduce the number of hits (to 50? 25?), but do not reduce the measurement transect intervals to the point that multiple hits occur on the same average sized plant.

Common formats include:
A. Multiple 2 m transects perpendicular to the baseline transect with measurement points at each 10 or 20 mm, providing 20 or 10 measured points per measurement transect (for long, narrow bands along road rights-of-way, or to measure across drill rows).
B. Multiple 10 m transects parallel to the baseline transect with measurement points at each 20 or 50 mm intervals, providing 50 or 20 measured points per measurement transect (for long narrow bands along road rights-of-way with uniform plant cover).
C. Multiple 10 m transects perpendicular to the baseline transect with measurement points at 10 cm intervals, providing 100 measured points per measurement transect (for averaging slope cover perpendicular to the roadway alignment).

6. Measure plant composition along the measurement transects.
Vertical observation of plant cover and type at the measurement point is critical. Some observers use point frames to remove bias. Ocular sampling devices are available. Multiple "hits" at a particular point may be recorded for various canopy levels, surface mulch, etc. The objective is to measure the plant cover, plant biomass, ground cover or soil at the point directly adjacent to each measurement point.

Count canopy cover, ground litter cover, bare ground or stone, as they occur. More than one hit from these categories may occur per measurement point.

7. Calculate adequate sample number for measurement transects

After a preliminary sampling along the measurement transects, use the mean and sample variance to estimate adequate sample number (141 - 154 (Chapt 7) (Equation A below) and Appendix 7 (345-350) Elzinga et al, 1998; or pg 89 (Newton and Claassen, 2003)). If sample number of the measurement transects is adequate, proceed to the next plant type or location.

If additional samples are required to obtain the numerical sampling objective, randomly select the appropriate number of additional measuring transects and locate additional measurement transects along the baseline transect.

Note: Adequate transect sample number for a commonly occurring species will probably be lower than adequate transect sample number for a species that occurs infrequently. Calculate required sample number for one of the dominant or co-dominant species.

8. Compile a frequency of occurrence list of plant species for the site.(optional)
Point transects may miss plant species that are infrequent at the site. Compile a list of all species at the site. Relevance of this information requires that the size of the area of interest be identified, so that a frequency per xx area can be reported. Often, a meter square quadrat is located at each of the baseline transect intervals or along the measurement transect. All species within the quadrat are noted and the size of the quadrat is recorded. (Morrison et al., 1995). (NPS method)

Equation A. Sample size calculations.

$n = ((Z\alpha)^2 (s)^2 / (B)^2$

1. Get "$Z\alpha$."

Table of standard normal deviates ($Z\alpha$) for various confidence levels

Confidence level	Alpha (α) level	($Z\ \alpha$)
80 %	0.20	1.28
90 %	0.10	1.64
95 %	0.05	1.96
99 %	0.01	2.58

2. Get "*s* ."
Enter counts from each measurement transect on hand calculator and press "*s* " for standard deviation.

3. Get "B."
Multiply the mean of the measurement transect replicates times the alpha level (within ± 30 % = X times 0.30, within ± 20 % = X times 0.20; within ± 10 % = X times 10 %, etc)

4. Calculate uncorrected sample size "n" using Equation A.

5. Consult table from Elzinga pg 439. Find uncorrected sample size "*n* ", and read off the corrected sample size value. This is the number of samples needed to get the confidence interval and confidence level you initially established.

<u>Photos of pairs of impacted and reference sites</u>

Objective: Give visual examples of impacted sites and a reasonable reference site. Ideally, the reference site is disturbed-but-revegetated, but often the best available site is one that is relatively less disturbed. A potential error may occur when a less disturbed site is selected for a reference because the soil may be better (more developed, deeper, more fertile) than that attainable by amendment of impacted site, and plants may never perform as well as expected.

[screflp3][screflp1]

ELD 89 1.8. Reference slope at Luther Pass. Cut slopes have a south aspect and coarse glacial granite substrate. They are inherently droughty. The general area is vegetated with coniferous forests, mostly with overstory cover or shading. The reference site needed to be exposed, not shaded, since the first years of a vegetation project are without much cover. A site was selected that had more south exposure and sun to serve as a example of appropriate soil resources. The site turned out to be very rocky, possibly accounting for some of the open canopy and smaller plant forms.

[screfbh1][cs1p01]

SHA 299 0.06. Reference slope for Buckhorn Summit. The impacted slope was southfacing and hot, given the high elevation of the site. Most of the surrounding terrain was covered by dense forests. An old logging landing had been regraded 1.6 km west in Trinity county in 1986. The flat landing was excavated to locate the previous drainage path and elevation, which had enough rock structure to carry waterflow. Then the loose

material from the landing was pushed up against the cutslope to make a south-facing, in a 2:1(H:V) slope (left photo). This material was disturbed, but revegetated with an erosion resistant plant cover, qualifying it as an example of an adequate reference soil example.

[screfserp][cs2p5]

COL 20 1.5. The conceptual reference site for the barren slope at is the smaller area of chaparral above the white car. Note the change in vegetation cover from blue oaks and annual grass (on sedimentary Franciscan geology) to the shrubby serpentine tolerant plants (on the area of gray-blue soil exposed by an old road cut). The soil on the reference site, however, was more developed was possible to regenerate on the face material. Because the face material was an engineered fill unlike any surrounding substrate, a plausible reference site was not available for comparison. On the face material (right photo) note the seep lines resulting where compaction of the engineered fill brings water to the surface of the fill. While infiltration on this site was almost acceptable, rooting depth was shallow because of compaction during construction.

[cs2p2]

COL 20 1.5. In this photo, the serpentine site is viewed from the ridge to the northwest of the site. Note the difference between the Coast range vegetation on the sedimentary Franciscan geology in the foreground (grasses and blue oaks), compared to the serpentine tolerant (chaparral) vegetation surrounding the site. The left third of the top bench on the fill slope received a 10 to 20 mm overlay of serpentine topsoil that was salvaged from the top of the slope before it was excavated. The patches of vegetative cover in the center of the site (third and fourth slopes up from bottom) are located on small areas of sandstone rather than serpentine. The study plots were located at the far lower right of the impacted slope. Note that the engineered fill on the bottom two slope sections is much more uniform in parent material than the upper slopes, which are cut back into the native rock. This will make vegetation response more variable on the residual materials than on the lower fill.

[screm1]

MON 203. This excellent example of revegetation is on the spur road to Mammoth Lakes west of 395. The duff and some topsoil was windrowed back from the site before the road was widened. A shallow slope was cut. The crushed material was re-spread on the slope. Without seeding or fertilizer, a good stand was obtained. The revegetation success probably occurred because of the duff and topsoil harvesting and reapplication, a shallow slope angle and the use of plant seeds, roots and inocula. Also helping was a deep rooting volume in these unconsolidated soils, high ambient infiltration rate due to coarse soil materials, a drought tolerant plant palette, and a lack of extensive soil development in this arid area, allowing the replaced substrates to be roughly similar to undisturbed soils. Saving and reapplying topsoil can be more effective and less expensive than intensive substrate amendment. And, you don't have to learn all the soil science jargon.

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SRE step 2). Slope Stability and Rooting Depth

OBJECTIVES:
The slope must 1) be geotechnically stable to prevent mass failures and safety hazards at the site and 2) the geotechnical design of the site must provide adequate rooting depth for growth of vegetative cover, which protects against chronic surface erosion.

2.1.0 Geotechnical stability of reference and impacted slopes (failures)

Translational failures

[cs3p3]
MEN 101 38.4. This shallow translational failure (slide) could be controlled with perennial grass roots or by woody shrubs. The lobe of an older slide is visible above the lower tree tube. The bare scoured area exposed by the slide will weather and 'fluff' up by wet/dry cycles, weed growth etc, until it is porous enough to hold more water than it has soil strength to keep on the slope. Because the underlying slippage plane is at an angle, it will fail downhill. Porous, unconsolidated soil materials must be placed on nearly horizontal benches, with slight (2 º) outslope to drain water out of the slope. In this case, the upper area where the slide originates is composed of fractured sandstone while the lower area that is slumping is more clayey. This combination of a well drained material and a poorly permeable material commonly generate failures.

[scslide1]

MEN/SON 101. These shallow slides occur when the smooth bladed surface of the cutslope becomes more porous by wet/dry cycles or root growth. Because the root growth does not tie into a lower soil horizon, and because the porous horizon is on an inclined plane, the slope fails when it becomes saturated. The scoured surfaces will subsequently become more porous by the same processes of drying and root growth. Eventually a rain event will fill the porous surface horizon with water and the surface will fail again, repeating the cycle in several-year intervals. In time, a well developed over-steepened slope section will form at the top where roots hold the soil together.

Rotational failures

[cs3p1]
MEN/SON 101 xxx. This larger rotational failure occurred when fractured sandstone infiltrated rapidly, building up behind an area of poorly draining clay. The small rills all start where the geology transitions from sandstone (above the rills) to clay (rills). While this rotational failure is larger than most plant roots could stabilize, including oaks, the matrix of roots may be able to flow water downhill through a porous soil rather than shunting it to the surface, where it gathers energy and cuts surface rills.

Dry ravel

[granite fans]

2.2.0 Surface erosion stability of reference and impacted slopes (surface erosion)

Although many of these problems will be addressed in Step 7 Erosion control, it is important to verify that the site surface is not moving away as well as the slope structure as a whole. Many slopes that are judged to be "stable" have chronic erosion, and this must be dealt with in conjunction with overall slope treatment, including compaction and rootable volumes.

Visual Clues for Evaluating Erosion Erosion is caused by the impact of raindrops on bare soil, by the force of running water on the soil surface, and by wind. Erosion is a natural process, influenced by climate, soil type, slope, and vegetation type. Loam and silt loam soils are more erodible, than clay or sand dominated soils. Sandy granitic soils, however, are highly erodible. Steep slopes are more erodible than gentle slopes. And well vegetated slopes, especially with a variety of root forms and above ground biomass, are less erodible than areas with sparser vegetation.

Plant cover, surface debris, and biological crusts stabilize the soil, with bare soil between plants being most susceptible to erosion. Certain factors will increase erosion to an unnatural rate. Soil compaction allows for increased runoff. In addition, poorly located or maintained trails funnel water

into erosion channels, and sloped campsites lose soil in a downhill flow. Additional factors contributing to erosion include soil surface stability, soil aggregate stability, water infiltration, and organic matter content, all of which can be evaluated against suitable reference communities. Sites with a history of heavy grazing or weed establishment will increase the risk of erosion.

Assess the site compared to reference sites for the following visual indicators of erosion: 1. bare soil Unless the soil has been recently disturbed as by a burrowing animal or tree throw, the soil should either have a crust or have a thin layer of organic duff or an armoring layer of gravel or stones. 2. lag gravels or plants or rocks on a "pedestals" If the surface has many more gravels or stones than the soil profile, the fine soil may have been eroded away, leaving the heavier rocks to "lag" behind. If the process is very slow such as in a desert, the rocks may have a dark oxidized patina, showing that although erosion has occurred, it is not a rapid process. If the soil is actively moving away from the local area by raindrop impact, soil may be protected under bits of wood or rocks and pedestals may form, with the protective object at the top.

[scpedestal2][scpedestal3]

COL 20 1.5. Raindrop splash detachment carries away soil fines except where a stone protects the soil. These gravels are about 10 or 20 mm across, meaning this volume of soil has been eroded away. Exposed gravels, lath stakes and concrete edges suggest that the slope has lost 50 to 80 mm of surface material since construction. On a flat bench, a loop of bailing twine has protected a small area from raindrop impact (bottom photo).

[scpedestal1]
Gravels protect decomposed granite soil from raindrop splash detachment.

3. exposed roots If soil has moved since a tree or shrub grew roots into the soil volume, the exposed roots will show the old soil levels.
4."terracettes" which are level benches of soil deposited behind obstacles
5. an increase in the number, size and connectivity of waterflow patterns (rills) between plants
6. soil deposition at slope changes. Where a steep slope transitions into a shallow slope, the speed of water flow decreases and sediments will deposit in a fan.
7. changes in thickness of topsoil Thick topsoils in depositional positions (swales, lower on slopes) mean soil has been lost from upslope (shoulders, mid-slope positions)
8. exposure of subsoil at the surface Subsoils are marked by higher clay content, redder color, or larger blocky or massive soil structure. On larger scales, these subsoils can form small cliffs, with the softer surface soils and deeper subsoils weathering away and the subsoil protruding prominently.
9. rills, headcutting, and/or downcutting in gullies Rills (only a few centimeters deep) are formed by water movement that has enough energy to suspend and move sediment.
10. reduced plant vigor As topsoil is removed, less moisture and nutrients are available for plant growth and plant size decreases.
11. long unsheltered smooth soil surfaces (wind-blown sites)

<u>Methods for providing rooting depth on slopes.</u>

Adequate rooting depths for plants on harsh sites are critical. Plants require water for moving nutrients, expanding their tissues, cooling leaves, and for cellular processes. Water deficits can quickly reduce growth and can easily become fatal. Tillage of existing slopes, meanwhile, is difficult. Existing slopes with insufficient rooting volume must be treated to increase porosity, but at the same time, the amended volume must be placed on a horizontal or only slightly outsloping (2 º) bench. Otherwise, the porous soil will sooner or later fill with rainwater and its weight will exceed the strength of the soil or the friction at the interface with the underlying slope and the amended

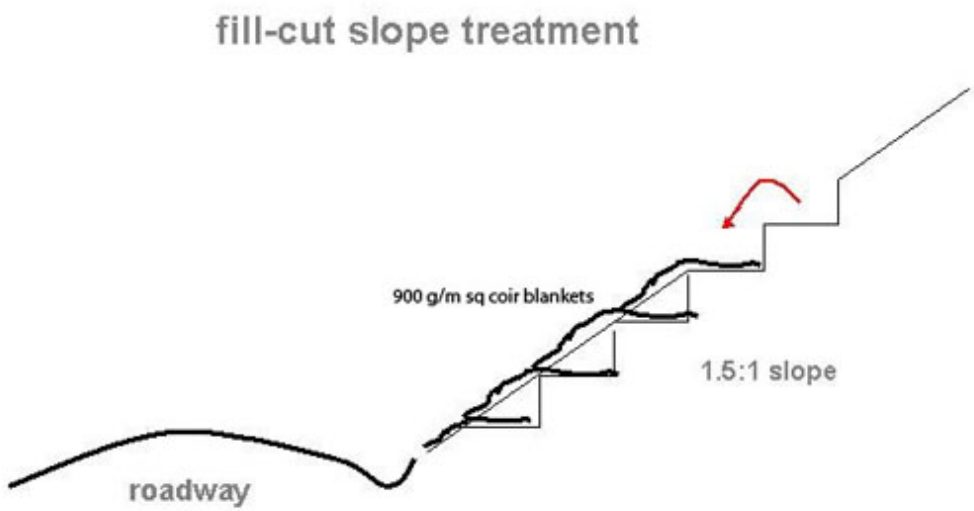
portion will fail as a translational slide. Despite these difficulties, a non treated slope can become a chronic source of sediment production, and will eventually destabilize the slope above if it is not stabilized. Some potential methods to till the soil and potentially to incorporate composts are to till with an excavator bucket, rip, spade the slope with tines, construct benches and backfill, dig augered holes, or shatter the underlying material with explosives.

Bucket tillage **with an excavator bucket has been done from the top of the slope reaching down, or from the bottom up. In either case, substrate and amendments are lifted and replaced from the same volume. Mixing the amendment may be difficult. The base of the excavated volume should be more or less horizontal so that the tilled substrate volume is replaced on a flat, horizontal surface to avoid lateral sliding when it gets saturated. The slope underneath the tilled material should resemble a series of small level steps.**

Ripping **behind a crawler tractor is commonly done to loosen the surface soil, but incorporation of surface amendments occurs only to shallow depths, such as 0 to 10 cm (0 to 4 inches)(ref). Deeper ripping is not possible with current equipment suitable for slopes. Ripper shanks often are limited to the top 50 cm (18 inches) and steeper slopes may restrict tillage to vertical passes. This should be avoided because the ripping channels may pipe water rapidly to the bottom of the slope. One suggested option is to create a cross hatch ripping pattern with two passes oriented at 30 º left or right of vertical, thereby avoiding a direct path for water flow.**

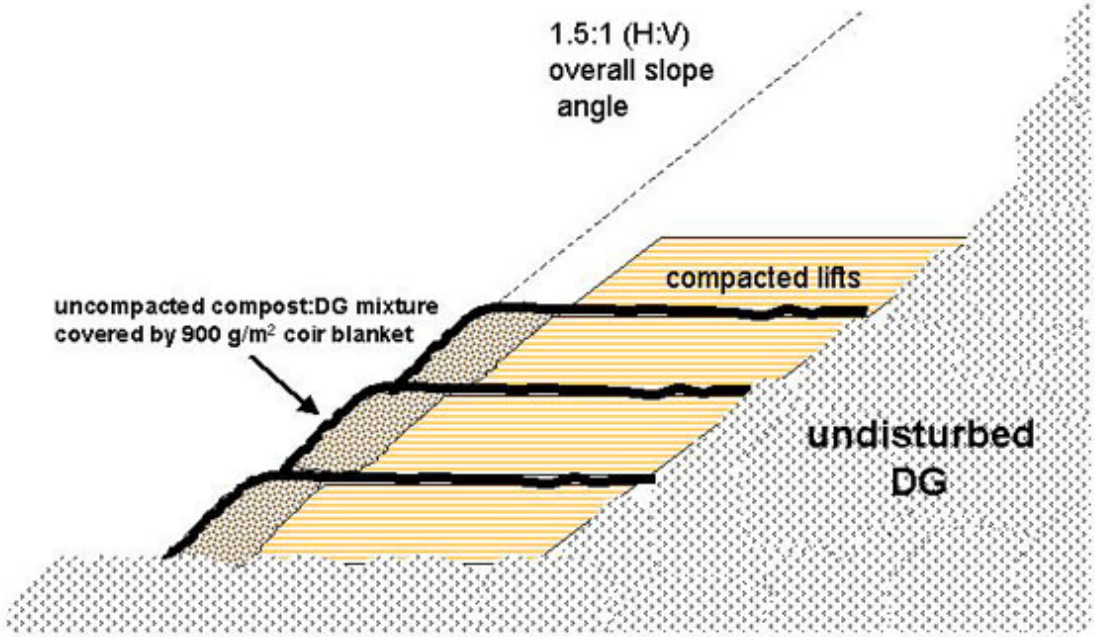
Spading **can be used to open up a moderately compacted slope using tines mounted on a bucket or forklift loader. If the spaded slots are vertical, compost could be raked into the slope. Care must be taken to not generate a uniform blanket of substrate with increased porosity that overlies an inclined slippage plane. When the substrate volume saturates, failure is likely to occur.**

Benching and backfilling, **or "fill cut" construction has been achieved on a large slope in decomposed granite. The term "fill cut" is meant to be distinct from "cut and fill" in which volumes are moved from cutslopes to engineered fill slopes. The "fill cut" operation refers to a method in which a slope is cut roughly to the final grade, and then a bench is cut across the base of the slope. Then, by sequentially cutting higher benches, while spoiling the material downward and incorporating amendment materials, the final cut slope is created by backfilling the benches starting from the bottom of the slope and moving upward.**



The amendments can be bladed across the working bench, mixing them with the substrate, and then spoiled down across the outward face of the bench. This creates a compacted fill for structural stability, but provides an unconsolidated rootable volume across the face for revegetation and sorptive surface hydrology .

In the case of the Buckhorn summit project at SHA 299 0.06, the remaining rock matrix was so weathered and incompetent that continued slumping was a concern. At this site, the benches were cut deeper into the slope and a compacted fill was created in 1.2 m (4 foot) lifts that were set back 30 cm (1 foot) from the final slope grade. Compost and DG were mixed (24 % vol compost / vol DG) and bladed across the slope face to fill the set-back volume. A coir blanket (900 g/m2) was laid across the level bench and draped down and across the loose compost/DG fill. It was anchored with bats across the bottom of the blanket.



Augered holes **can be used to develop a rooting volume in a compacted material, but typically, the holes are far too small to sustain a mature plant. The rotating bit polishes the walls of the hole, causing roots to circle around the inside of the hole and not to branch out into the surrounding soil. Many of these projects have failed. Exceptions may occur in which the auger penetrates a thin compacted layer and roots can be led to deeper rootable horizons. Other soils may crack and allow roots to escape the original hole. Predominantly, the plant is stuck in the hole and it becomes stunted and dies. This method is not recommended.**

Explosives **may be used to fracture the subgrade material without destabilizing the slope. This is a conceptual idea only and has not been tested on this project. A positive aspect would be the ability to treat large slopes without heavy equipment. A liability is that the cracking may not increase rootable volume enough, since only cracks are produced, not fine soil materials. Trained personnel would be required.**

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SRE step 3). Soil Water Relations (infiltration and water holding capacity

OBJECTIVES:
The site must have 1) a high enough [infiltration rate] to avoid overland flow and surface erosion and 2) it must provide enough [plant available water] (PAW) in the rooting profile to support adequate plant growth.

3.1.0 Evaluate soil infiltration rate.

<u>Infiltration - crusts</u> ***Soil crust*** **: A layer of increased bulk density a few to tens of millimeters in thickness caused by raindrop impact, clay dispersion and clay translocation that blocks pores and decreases infiltration. Becomes brittle when dry.** ***Seals*** **are layers that form when substrates are wet and they reduce infiltration but are not hard when dry.**

[bhdgseal]

This decomposed granite cut slope was exposed by excavation about 20 minutes earlier after millions of years below ground. Note the coarse grains deeper in the shallow pit dug into the weathered granite. During the next 15 minutes, a light drizzle dispersed the minerals at the surface. This created a thin slurry or seal across the surface, visible as a more uniform gray layer. Whereas the infiltration rate of weathered decomposed granites are measured to be 100 mm/hr or more, the infiltration rate of similar slurry seals are 10 to 15 mm/hr. Rainfall is prevented from infiltrating, and it begins to run overland, creating small debris flows and rills.

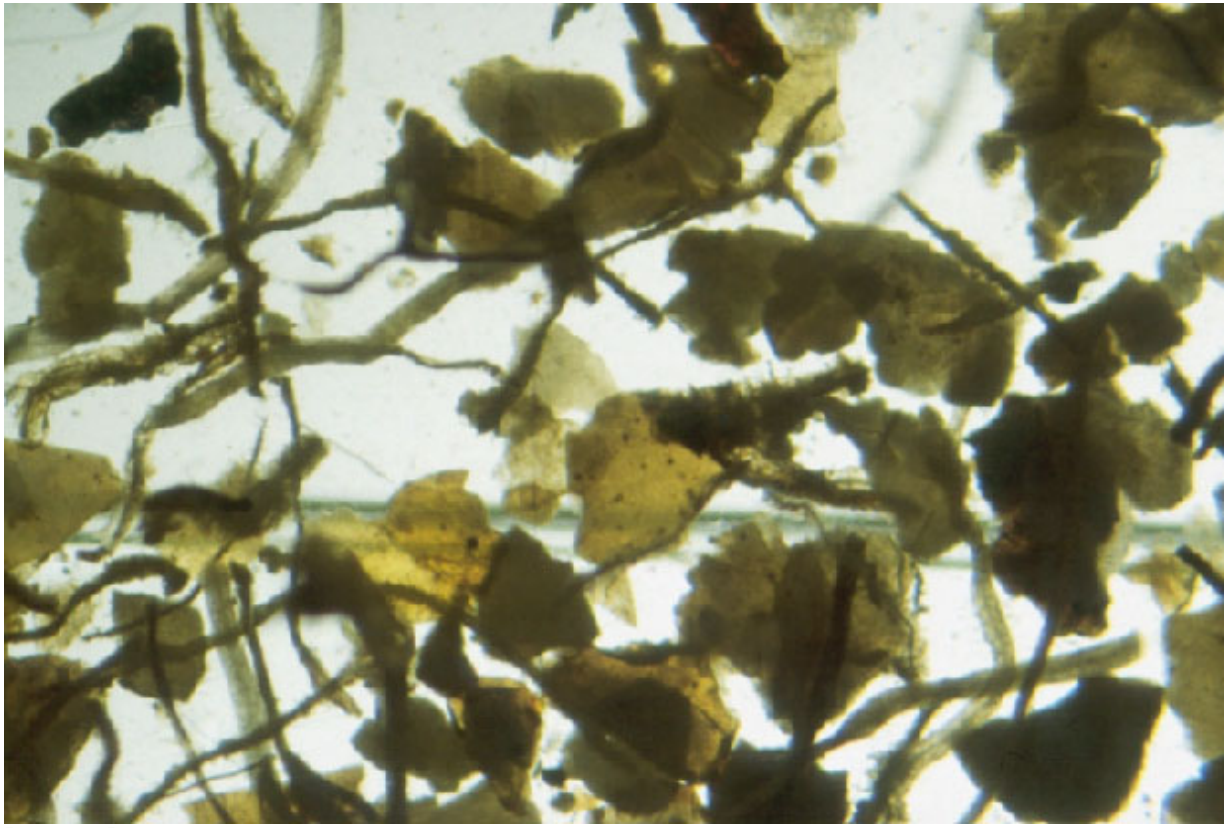
[scbhseal1]
A small debris flow starting after only a few minutes of drizzle on a freshly cut DG slope.

[scbhseal2]

As the debris flows gather volume, they begin to scour rills and transport sediment, all in a few minutes on a freshly exposed slope.

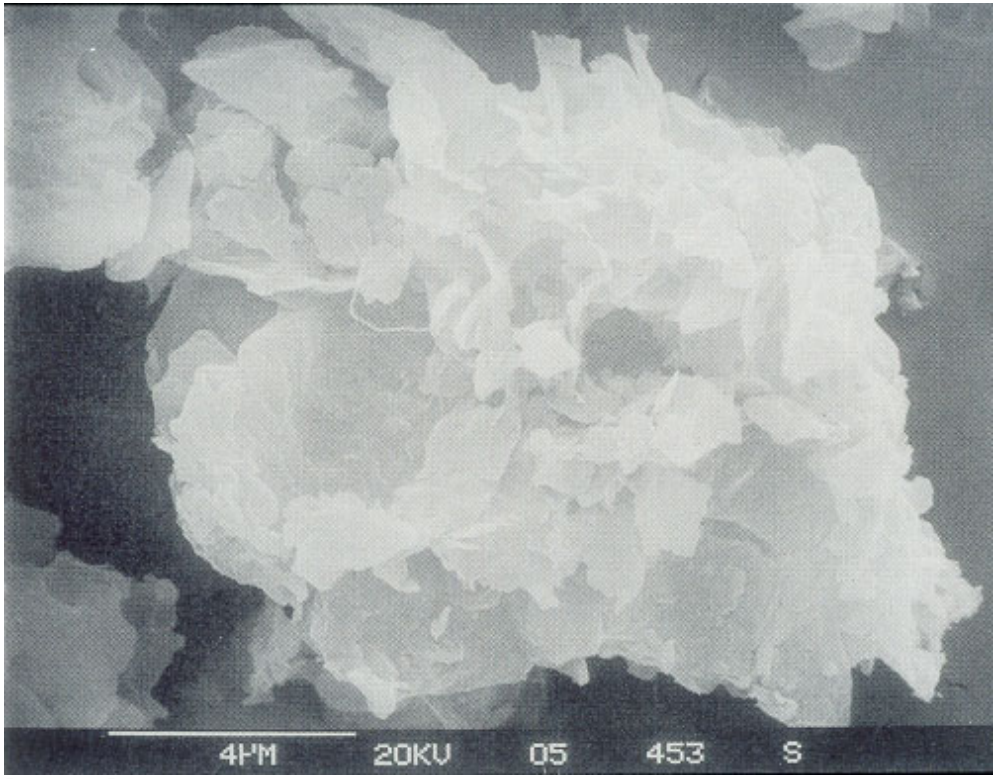
[scbhseal3]

The dispersed slurry running over the surface of a cut forms a layer of low permeability under the canopy drip of a shrub.



[scmica1]

A reason for the rapid formation of the seal layer is the plate-like structure of decomposed granite minerals, particularly of the biotite mica. In this photo, the larger strands are roots and the finer strands are fungal hyphae. The mica flakes are several millimeters across. The flat, platelike structure allows these mineral to stack together like leaves plugging a gutter.



[scmica2]

Smaller particles can also have a planar structure. This photo shows an overall particle that is only 1 % of a millimeter across, with smaller particles that are clay sized. These particles easily wash down into DG soils and plug pores because they have low charge and are easily carried by pore water.

[scmica3]

A consequence of these platelike biotite particles is that small volumes of water can move DG sediment easily. This small rill (40 or 50 mm across) has made its own levee system with lobes accumulating along various former flow paths.

[scmica4]
On this cutslope on fine granite sands and silts (MER 99; Livingston), the hydroseed slurry created these lobes with a minimum amount of water. With this low infiltration rate, rainwater ponded on flat areas the then rapidly cut meter deep gullies into the slope as the accumulated water found an outlet.

Infiltration - pores and aggregation

Infiltration is determined by macro-pores. These are large pores created by worms or insects, spaces between soil aggregates, cracks in the soil matrix, and old root channels. When soils are moved, compacted, or traveled on, the large pores are crushed. When infiltration rates are less than rainfall rate, overland flow will commence, initiating surface erosion. Damp or moist soils compact more easily than dry soils because the soil-to-soil contacts are lubricated with water. Soils intended to hold ponded water or for travelways may be intentionally compacted to reduce water content and increase strength when wet. On compacted substrates or constructed fills, pores tend to be small or non-continuous. Incorporation of unscreened yardwaste compost can recreate these larger pores. Use of wood chips increases the porosity of the soil, but the pores are not continuous, so water fills the pores but does not drain. This adds weight without drainage capacity, and probably with reduced tensile strength because of the short length of the chip particles.

[scsoil agg]

The soil in the lower half of this photo is from a Class I agricultural topsoil. The aggregates are strong enough that raindrop impacts will not break them apart. The upper half of the photo shows the same soil that was soaked in bleach for 10 minutes. The organics are oxidized away, the soil structure collapses, and the minerals disperse. This degraded soil will seal against infiltration because the individual

particles are unaggregated and will settle into nearby pores. This soil will generate overland flow and surface erosion with minor rain events. The powdered surface of dirt roads is an example of this type of dis-aggregated soil. Organics make erosive soils resistant, but they require consistent organic matter inputs from plants. Low organic matter soils crust more easily than soils with adequate organic matter.

[scinfiltr1]

The most obvious erosion problem in this photo is that the straw bale dam is too high, which directs water around the end and erodes the soft soil, mobilizing more sediment. A better treatment would be a low wattle keyed into the substrate. Ponded water should spill back into the existing drainage channel. The real problem on the site, however, is that the soil surfaces are all shiny with water, indicating infiltration is very low. Grading and traffic on the site has compressed the macropores, and the soil cannot infiltrate the light rain that is falling. Particles are easily detached by raindrop impact on saturated soils contributing to the sediment in the water. In contrast, saturated soils and surface water flow are rare on undisturbed soils because infiltration typically exceeds rainfall amounts.

Measuring infiltration capacity

Ponded water infiltrometer. The classical method to measure infiltration is to set up rings on the soil surface and to fill them with water. Measuring the drop in water level indicates the infiltration rate. The problem with this method is that many sites will have slopes that are steep

enough that water will spill from the low side of the ring before the other side is ponded. This problem is solved by decreasing the size of the ring and fitting it with a valve that controls flow rate (photo below). Now, the infiltration rate is determined by water loss per time (tracked with the vertical graduated cylinder). This method has the advantage that infiltration at various depths down an augered hold can be measured. This device is called a constant head permeameter because the height of water (head) is kept constant at 15 cm above the soil surface to be measured. This mimics the depth of irrigation water a furrow in an agricultural field.

[buckperm]

The disadvantage of either the ponded water ring infiltrometer or the constant head permeameter is that when water finds old root channels, burrows, cracks in a dried soils, or cracks due to geotechnical movement, the pressure from the constant head of water creates much more water flow than would be the case with rainfall. Rainfall uniformly soaks the surface but does not accumulate, at least initially (an accumulated volume of water would make it a drainage issue, not an infiltration issue). In order to accurately measure the ability of a soil to infiltrate rainwater, a drop forming rainfall simulator is used on steep, heterogeneous wildlands soils.

Drop forming rainfall simulators are constructed to deliver the amount of water representing a rainfall event, and can be made to give the appropriate drop size and impact velocity. Because Soil Resource Evaluation emphasizes the characteristic of soil infiltration rather than the mechanics of sediment production, all slopes in these studies are covered with straw or mulch following standard erosion control practices. The problems of raindrop splash detachment are disregarded. This allows use of a rainfall simulator that is shorter and easier to transport onto steep slopes.

[scbhrfsim] A drop forming rainfall simulator rains on a square (0.8 x 0.8 m) plot at a high intensity. Water in excess of the infiltration rate is collected and analyzed for volume of runoff and sediment content. Amendment of the bare DG substrates with coarse, unscreened yard waste compost increased infiltration to that of the stable, vegetated reference site.

Increasing infiltration by incorporation of unscreened yardwaste compost

Data from various experiments is compiled in the following table on example infiltration values. Different amounts of compost were amended on various substrate materials (listed in the third line of each heading). Infiltration rates are listed in rates of mm/hr when steady state infiltration occurs.

Example infiltration values attained by different amounts of coarse, unscreened yardwaste compost incorporation (v/v) at various locations in Northern California. An asterisk indicates treatments that were not tested at these locations. Rates are listed in mm/hr at steady state infiltration.

compost incorp% (v/v)	Buckhorn SHA 299 granite	Colusa COL 20 serpentine	Willits MEN101 clay	Willets MEN101 sandstone	Tahoe PLA 89 moraine
non-tilled	*	42	26	42	44
0	34	50	38	52	*

6	34	*	*	*	*
12	46	*	*	*	*
24	60	53	39	51	50

Checking if infiltration rate is adequate for design storm events
Use the infiltration rate (mm/hr) from the example infiltration values table (above) and compare it to a table of return frequency storm intensities (below). Does the soil treatment infiltrate the desired design storm event?

Table of return frequency storm intensities by site location (mm/hr for 15 min interval). Weather data taken from nearby weather stations and from on project sites are used to estimate the volume of precipitation that occurs with different return frequency storms.

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Return Frequency Interval (yrs)	**Buckhorn SHA 299 DG**	**Colusa COL 20 serp**	**Willits MEN 101 clay**	**Willits MEN 101 sand**	**BlueCyn PLA 89 vol lahar**
station location	**Whiskytown data**	**Clear lake data**	**Willits data**	**Willits data**	**Blue Canyon data**
2	38	19	28	28	23
5	51	25	38	38	32
10	60	29	44	44	37
25	70	34	52	52	43
50	78	38	57	57	
100	85	41	62	62	52

Predicting potential for runoff in different return frequency storms by season.

Using the meteorological data in the Table of return frequency storm intensities, the probability that a site will produce runoff can be predicted depending on the dryness of the soil before the storm (the antecedent water content) and the intensities of the storms during various seasons of the year. The table below is for the Buckhorn Summit site at SHA 200 0.06. Even when the treated slope (24 % v/v) starts to produce runoff, the sediment loss (measured by field rainfall simulator) is much lower than from control (no amendment) plots.

Table III. Percent of time during the month that runoff will occur during a 15-minute storm with the corresponding return frequency and rainfall intensity, on the a) control and b) compost treatments. Sediment loss (kg/ha) during a 15-miute storm throughout the year (2003) at Buckhorn Summit on the c) control and d) compost treatments.

	Return Frequency (yrs)	RFI (mm/hr) *	Jan.	Feb	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
a)	2	40	100	100	78	100	50	0	0	0	0	0	24	100
	5	47	100	100	100	100	74	0	0	0	0	0	69	100
	10	55	100	100	100	100	100	63	0	15	0	0	72	100
	25	64	100	100	100	100	100	100	100	100	100	100	100	100
	50	70	100	100	100	100	100	100	100	100	100	100	100	100
b)	2	40	0	0	0	0	0	0	0	0	0	0	0	0
	5	47	99	54	59	67	35	0	0	0	0	0	0	6
	10	55	100	100	100	100	100	0	0	0	0	0	66	100
	25	64	100	100	100	100	100	100	100	100	100	100	100	100
	50	70	100	100	100	100	100	100	100	100	100	100	100	100
c)	2	40	5.6	1.1	0.8	2.6	0	0	0	0	0	0	0	1.3
	5	47	20.6	11.2	10.2	14.9	4.6	0	0	0	0	0	0	11
	10	55	42.7	29.8	28.3	34.9	19	0	0	0	0	0	7	30.8
	25	64	68.3	54.5	52.6	60.7	41.5	5	2	3	1	0	25	55.5
	50	70	85.1	72.3	70.3	78.2	58.2	13	9	10	7	4	39	73.4
d)	2	40	0	0	0	0	0	0	0	0	0	0	0	0
	5	47	0.2	<0.1	<0.1	0.3	<0.1	0	0	0	0	0	0	0
	10	55	9.0	6.9	6.7	9.2	4.0	0	0	0	0	0	0	4.4
	25	64	23.6	21	20.7	23.8	16.1	2.2	0.8	1.6	0.5	0.2	4.6	16.9
	50	70	33.4	31	30.7	33.5	26.4	7.4	4.7	6.3	4.0	2.9	11.3	27.2

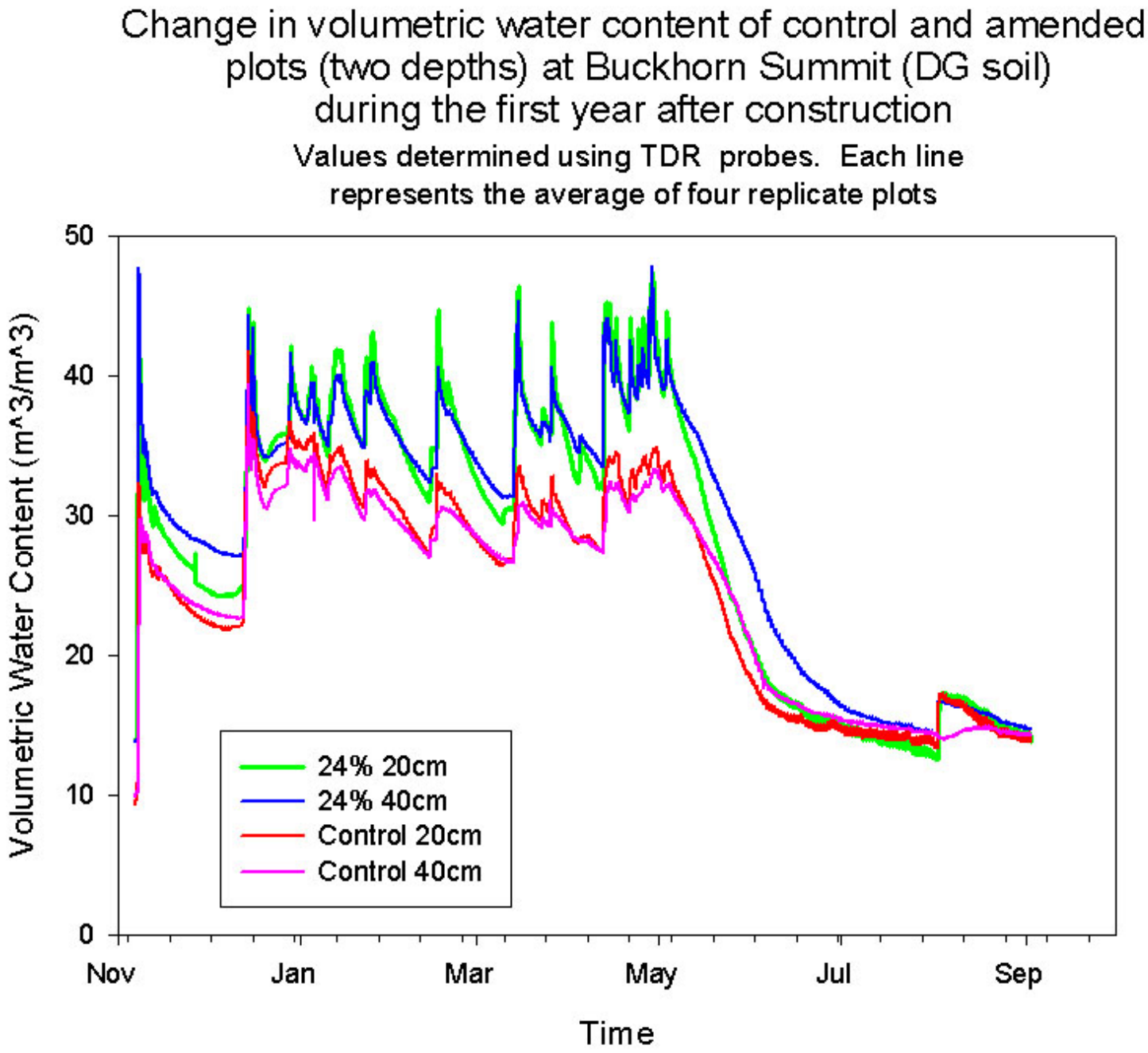
* RFI-Rainfall intensity
Rainfall duration and intensity data taken from the Coffee Creek rain gauge.

Infiltration, water content and drainage changes resulting from compost amendment on DG substrates.

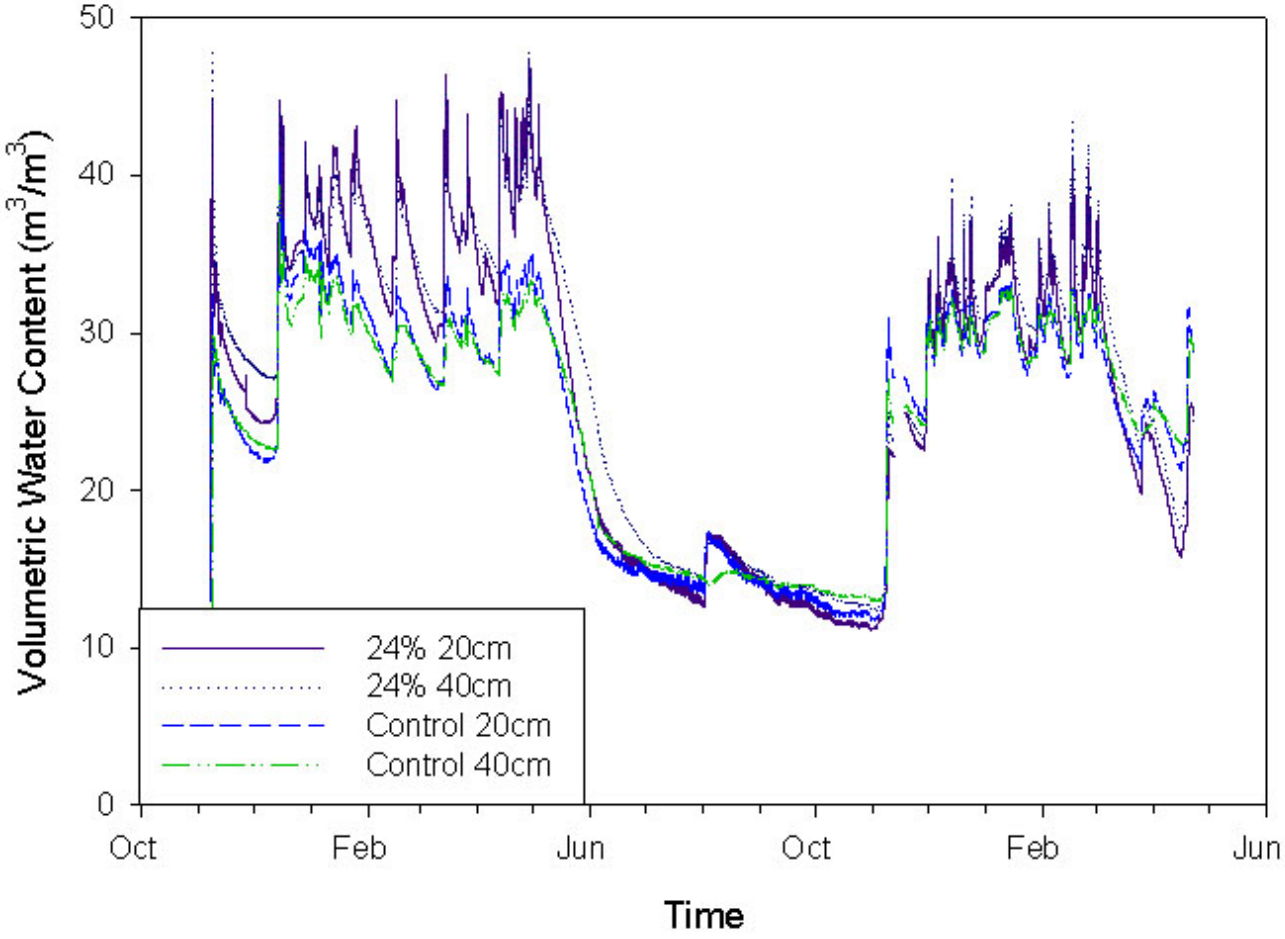
The decomposed granite slopes at SHA 299 0.06 were instrumented for water content during the 2002-2003 winter season. The green trace shows the water content at 20 cm depth and the blue line shows water content at 40 cm depth in the compost treated substrate. Note that the soil is dry in November, and then wets up with the first rain of the fall. Water content of these surface horizons then declines because the water rapidly drains internally away from the surface. In December, the soil profile has now been moistened throughout and periodic rains continue to re-saturate it. The compost treated substrates consistently retain more rainfall during each rainfall event (sharp peaks) but the amended substrates drain the surface water away faster (indicated by the slope of the declining line to the right of each peak) compared to the unamended plots (red and magenta lines). Internal percolation of water from the shallow horizon to the deeper horizon (blue line at 40 cm) can be seen after each storm because the blue line (40 cm) shows a higher water content than the green line (20 cm). In May, a series of heavy storms occurred in rapid succession. The amended soil rapidly imbibes the rainfall and then rapidly percolates it away from the surface, acting to regenerate the infiltration capacity of the surface horizon.

Note the difference in soil water content between the compost amended substrates (green and blue lines) and the control (non-compost amended) substrates. This water volume is consistently about 10 % of the volumetric water content of the soil (measured at peak contents between the amended and unamended substrates). This surplus water that was infiltrated into the compost amended plots was shed as surface water flow off of the control plots, resulting in erosion and sediment transport. After May, the rains stopped and the soil gradually dried to summer levels. The spike in August was a single summer thunderstorm with intensity greater than 1000 year return frequency.

Notice that the compost did not increase the soil water content as much in dry conditions as it did at saturation. Water in dry soils is held by clay sized particles, not in coarse organic particles like composts. But, since root growth was so much more extensive in the compost treated plots, second year plant growth was nearly 5 times greater on the 24 % plots than the control plots, even when fertilizers were added to compensate for nutrient differences.



[scbhinfiltr1]



[scbhinfiltr2]
The traces on the left half of this graph are the same as in the previous figure, but a second year of data (2003-2004) was added in the right half of the plot. The compost plots still infiltrated rainfall quite well, but the overall water content was lower. This suggests that the compost treatments were becoming less effective for internal drainage or water holding capacity due to settling or to decomposition. The concern is that the effective "service life" of a compost amendment would be quite short. But, by the third year, the plots growing Elymus multisetus (Squirreltail) plants had increased their infiltration rate above even that of a newly tilled plot. As long as plant growth is maintained, the soil appears to be trending to better hydrological properties. This finding suggests that the beneficial effect of compost treatments on soil properties is not permanent, and must be replaced by plant growth in order to maintain adequate infiltration rates.

A soil characteristic that acts to maintain high infiltration rates is the accumulation of stabilized (humified) soil organic matter. This sticky material keeps fine particles from settling in pores, and maintains infiltration at the surface and percolation at depth. The organic matter content of vegetated soils increases and stabilizes over several decades to several centuries. Humic materials, and the constant renewal of biological activity and soil aggregates from plant inputs, must continue to after the compost amendment decomposes, or the site will revert to a barren state. A good example of this process is described by Perry and Amaranthus (1990) involving a Site I (highest class) timber producing site covered with white fir. This site in southern Oregon on decomposed granites was logged by clearcutting in 1968. During replanting, herbicides were sprayed to reduce brush competition. Plant growth continued to decline as several successive replantings were attempted and the soil began to resemble beach sand. Twenty years after supporting a productive forest, all what could survive on the clearcut site was a 30 % cover of cheat grass, scattered patches of

fern and an occasional manzanita bush. Desertification of this site was attributed to loss of soil aggregate structure. The objective of regeneration of drastically disturbed substrates essentially to run this scenario in reverse.

Ksat measurement (steady state saturated hydraulic conductivity)

Percolation is the internal drainage rate of a substrate (in mm/hr) in the same way that infiltration indicates the capacity to infiltrate water into the surface of the substrate. The Ksat value is obtained during rainfall simulations by running the simulation for an extended period of time. Initial infiltration values are very high. This occurs when the dry soil rapidly soaks up moisture. Gradually, the pores fill and a lower, constant rate of infiltration occurs. This is variously governed by lateral flow on steeper slopes, or by the deep percolation rate of internal drainage, indicating Ksat has been attained. It is critical that amended slopes have percolation rates that allow excess water to drain freely from the soil on a slope so that positive pore pressure does not cause liquefaction and failure of the porous amended section. Root channels and animal burrows accomplish this on functioning soils, and long shreds of coarse, unscreened yard waste compost accomplish this on freshly constructed, amended plots. Wood chips are often used on field sites because of their ready availability, but their short fiber length is suspected to not create the continuous pores needed for infiltration or percolation.

3.2.0 Plant available water

Water Holding Capacity

Water Holding Capacity (WHC): The amount of water a soil holds at a given matric potential.

Saturated capacity: Soils with all the air space filled with water after flooding. Saturated soils are significant on slopes because they can start to lubricate between soil masses and facilitate geotechnical failures. Saturated paste solutions are made by flooding soils with water and then analyzing the solution that is drained from the soil sample.

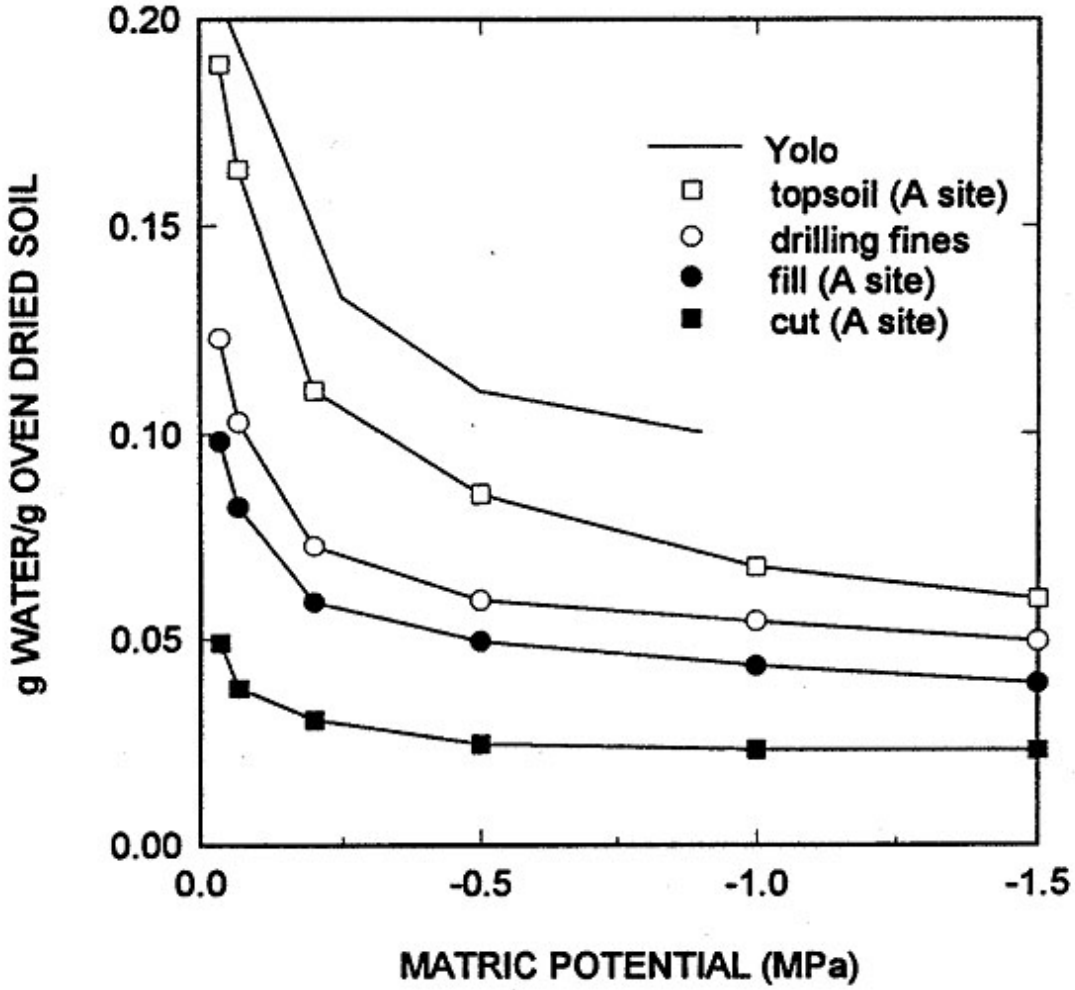
Field capacity: (FC) The water content in the soil after no more water drains away due to gravity. The water content at field capacity is assumed to be about -0.001 MPa (-1/10 bar) in coarse, sandy soils and -0.03 MPa (-1/3 bar) in loamy soil. Water holding capacity at field capacity is determined by macro pore content.

Permanent wilting point (PWP): The water content of a soil when crop plants wilt and can no longer take up water. This is generally set to be -1.5 MPa (- 15 bar). Water holding capacity at permanent wilting point is determined by clay content.

Plant available water (PAW): For wildlands soils, the difference between field capacity and the maximum extractable water. For wildlands plants, this is usually more than the 1.5 MPa used for crop plants. Wildlands plants can extract water to 3.0 5.0 or even 7.0 MPa (-30, -50, or - 70 bars) rather than the -1.5 MPa (-15 bars) that are set as a limit for crop plants. Water holding capacity at very dry water contents is determined by clay content and possibly waters of hydration on mineral surfaces and interlayers.

Matric potential: Generally: The force needed to pull water out of soil by the plant, or to drain soil pores by gravity. Technically: The amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water, identical in composition to the soil water, from a pool at the elevation and the external gas pressure of the point under consideration, to the soil water. (Sidle et al., 1985)

Soil water retention curve: A graph of the water content as plants dry out the soil volume. Typically, saturated soils are placed at the left, where water content is high. Droughty soils are placed at the right, where water content is low and remaining water may be unavailable for plant uptake. Aggregated soils, high clay soils, and high organic matter content soils hold more water than sands.



[screlcurve]
SHA 299 0.6. Old Faithful, Buckhorn Summit. Soil moisture release curves for DG soils. A Yolo loam agricultural soil is included for reference. The two lowest lines tabulate the water holding capacity for each material calculated from the difference between -0.033 MPa and -1.50 MPa gravimetric water contents. Although the lower three lines have the same mineralogy as the topsoil (open squares), the organic matter in the topsoil retains moisture, and aggregates the minerals such that the water availability for plant growth approaches that of the agricultural soil.

Plant water use target.

The table lists generalized target summer season water use from literature review information and from northern California field data and other arid environments.

plant life form	Water Use Needs
annual	30 - 40 mm[1]

perennial	100 - 200 mm^2
shrub	200 - 300 mm^3
tree	400 mm4

Source notes:
[1]Annual grass summer season water use estimated from Caltrans field site data and observation on harsh roadway sites.
[2]Perennial grass summer season water use data from constructed Caltrans plots.
[3]Shrub water use data estimated from literature values.
4Tree water use data estimated from literature values.

Plant available water (PAW) resulting from different treatment depths.

Select a target plant type from the table above. Check the plant available water values from the table below for treatment depths. All treatments use 24 % v/v unscreened yardwaste compost amendments. Note that these treatment depths probably will not provide enough soil moisture for larger shrubs and trees. The underlying substrate must be rootable for a large shrubs or trees to survive on these sites.

tillage depth mm	**Buckhorn SHA 299** 1.5 MPa 14.5 % PAW	**Colusa COL 20** 1.5 MPa 9.3 % PAW	**Colusa COL 20** 5.0 MPa 11.3 % PAW
150	22	14	17
300	44	28	34
600	87	56	68
1000	145	93	113

Limits to the ability to improve soil water relations with compost amendment.

In soils with greater than 9 % PAW, water availability will not be greatly increased by compost amendment. The clays and organics in the soil are merely displaced by volumes of material (compost) with approximately the same the same PAW characteristics. Removal of coarse rock fragments by screening is a more direct approach to increasing PAW on sites that are not sandy but have high rock content.

Compost incorporation on moderately or poorly structured (aggregated) soils may decrease infiltration because of the tillage needed to incorporate composts.

Compost amendments appear to settle or decompose by about 30 % in the year or two after addition. Regeneration of plant growth (roots, organic matter inputs) is critical for maintaining the increase infiltration that was gained with initial tillage. Generation of soil aggregates requires large amounts of stabilized carbon, but the processes are probably dependent on the soil mineralogy of different sites. Dynamics of soil organic matter carbon are discussed in SRE Step 4. Soil Organic Matter and C and N Pools.

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SRE step 4). Soil Organic Matter and C and N pools

OBJECTIVES:

The site must provide adequate soil organic matter (SOM) for three main functions: 1) coarse organic fragments generate macropores to increase [infiltration], as outlined in Step 3; 2) decomposable carbon supports microbial activity and humified (stabilized) residues, which promote [soil aggregation]; and 3) available [nitrogen] (N) released (mineralized) by decomposition of organic matter supports plant growth and community development.(xxxcopy to ES)

Introduction to soil organic matter and soil aggregation Soil aggregation Application of coarse organic fragments can immediately generate pore structure to increase infiltration and soil organic matter for microbial and plant activity. But, because the compost is more decomposable than natural soil organic matter, it will not provide the same long-term effects. Long-term organic matter inputs and soil aggregation must be provided by plants growing on the site for subsequent years. In this section, the function of soil organic matter in newly constructed substrates is described first, and following that, the role of compost and plants in carrying on these functions will be addressed.

Massive soils are those substrates that will dry to a large, uniform, hard mass. This happens in soils that are compacted, that have any amount of fine soil materials (clays or silts) and that have low organic matter content. Chunks of this massive structure can be broken off and are called "clods". The fracture lines when breaking clods are not anong faces, and break through the clod, not along natural planes. Clods and massive soils can be seen on almost any construction site because excavation equipment moves soil around and compacts it, especially when wet. Massive soils do not infiltrate water well, so they create overland flow, and they do not permit easy rooting from young seedlings, making revegetation difficult. The process of creating water-stable soil aggregates involves developing a smaller breaking pattern in these large clods or massive soil volumes, breaking them into smaller aggregates measuring several millimeters in diameter. Simple grinding and fracturing by force will not create aggregates because the next rain will melt the mass together again.

Aggregated soils are those soils with small regions of strength (millimeters to centimeters across; 1/8 to 1 inch or so) that are bounded by planes of weakness. The strength is provided by several kinds of processes (described below), while the planes of weakness are films and layers of organic matter and clay. When crumbling these aggregates in your hand, they consistently break into smaller and smaller pieces along these natural fracture lines. These fracture lines can be observed by the occurrence of roots pushing along the face and of polished, wax-like dark surfaces. The natural unit of aggregation is called a "ped." Peds can be shaped like a small piece of popcorn or bread crumb (granular structure), or they can be larger and squarish (blocky structure) the size of a matchbox or medicine box. Soil structures formed under vertical compression (snow load or traffic) are flattened and are called "platy." The term "water stable aggregate" is significant because the crumb structures at the surface of a soil must be strong enough so that a large raindrop falling at xx km/hr will not break up the aggregate and disperse the fine particles into pores. While the process of aggregation has been studied on agricultural soils, little is known about the process on wildlands soils, especially as they become less like agricultural soils. This means coarser in texture, less well weathered, with fewer organic coatings and with less organic matter content. Still, some generalities can be made about the process as it occurs in more typical, agricultural soils.

[scsoilagg]

Hierarchy of soil aggregation processes. The source of strength inside an aggregate is derived in agricultural soils from several stages of "construction" or formation, ranging from small scale to large scale (still less than a few millimeters in diameter). At the smallest scale, clay and

silt particles are cemented together by oxides (rusts) forming on the mineral surfaces. Adjacent mineral particles are then bridged together by humified soil organic matter. Once formed, these small aggregates are persistent, meaning that this smaller type of (micro-aggregate, < 250 um) structure can last through the soil harvesting, stockpiling and reapplication process. These microaggregates can only get so big before they are not strong enough to adhere together. They break apart in the constant churning within the soil cause by root growth, wet/dry cycles, water flow, and hot and cold temperature cycles. Larger aggregates (macroaggregates, > 250 um) are formed when microbial colonies grow on old roots, dead insects, or bits of compost. These colonies create gels of mucilage that glue the microaggregates together into macroaggregates. They do not last much longer than the microbial activity occurs (several months), and they decrease rapidly with tillage or lack of organic inputs. Macroaggregates are easily disrupted and lost. Fungi, especially mycorrhizal hyphae, are especially good at wiring together these macroaggregates into fairly large structures, thus generating the granular structure several millimeters across that can be seen with the eye in well aggregated soils. Larger aggregates also tend to be reinforced with plant roots, especially the fibrous roots of grasses. (Tisdall and Oades, Water and Oades, Jastro and Miller)

The application of this information to revegetation of harsh sites is that the regeneration of soil function on drastically disturbed substrates is that the process cannot be corrected with a single treatment. Drastically disturbed substrates have some fundamental characteristics that make aggregation difficult. They are typically coarse and have low clay content, they can be relatively unweathered chemically (especially granites and sandy soils), they are typically very low in organic matter content, and they initially have no decomposable substrate to support microbial activity. For all of these reasons, the tendency for disturbed substrates to have poor structure and low infiltration is understandable. Many of these problems can be corrected for at least a few years, however, by application of large volumes of coarse, unscreened yardwaste compost. In some substrates or locations, the use of intensive, agricultural-style plant growth may be able to regenerate the process of soil regeneration, thus reducing the expense of amendment but probably increasing maintenance costs to keep the plants thriving through these difficult first seasons.

Stabilization of soil organic matter (humification)

There are three ways that the decomposable carbon that is added as compost or plant materials becomes stabilized in the soil so that it can persist for long periods of time (many decades to centuries) (Christensen, 1996). Microbial decomposition converts organized, energy rich compounds like plant material (cellulose) into a slowly-degradable mixture of left-over compounds like microbial residues. These various compounds may have chemical resistance to decomposition, or perhaps they are simply too disorganized to allow effective enzymatic decomposition by microbes. This is called *chemical recalcitrance*. Secondly,*chemical stabilization* occurs when cations in the soil, mainly positively charged calcium, iron and aluminum ions, bind to the negative charges on partially decomposed organic matter, and bind it into a resistant structure, such as a coating on a mineral surface or as a dense mass of organic matter that cannot be dissolved. Thirdly, the clay particles create a*physical protection* that occurs when layers of clay coat the organic matter and keep it from being degraded by microbes, even if it is decomposable. Also, some soil pores are too small to allow microbes to get into and degrade organics that have diffused into these pockets. As mentioned previously, drastically disturbed soils commonly have low biological activity (so low microbial residues and little organic residue to stabilize), they have relatively unweathered mineral surfaces (low oxide content to bind organics through chemical stabilization) and they have low clay levels to shield organics by physical protection. For these reasons, organic matter stabilization and accumulation on drastically disturbed sites is problematic.

Lastly, a component that may occur commonly in natural soils that may be missing from most newly exposed substrates is char from previous burning of plant materials. These char particles are essentially activated carbon, and like the cartridges in water filters, they adsorb large quantities of organics, keeping them from decomposition so they can sorb water and nutrients, and hold them for eventual plant uptake.

4.1.0 Evaluate soil organic carbon (C) pools.

Coarse organic fragments Natural soils have extensive root channels, animal burrows and macropores between soil aggregates that allow water to infiltrate into the surface until a restrictive layer is reached. The moisture then flows laterally downslope within the soil. If flow increases or pore volume decreases, the soil will saturate, and moisture will seep to the surface. If pressures become positive, the soil may liquefy. The stability of the slope is a function of continuous pore space for water flow and of the soil's tensile strength and ability to hold the moist soil against gravitational pull.

Disturbed substrates, especially constructed fill slopes, tend to be uniform masses of substrate with low pore space. The result is a low infiltration rate and a diversion of rainfall to overland flow. Incorporation of coarse, unscreened yardwaste compost has been shown to regenerating these drainage pores (Curtis et al., 2004). A compost amendment approaching 24 % on a volumetric basis (8 % by dry weight) was required to regenerate the infiltration of a vegetated reference site. Other studies also suggest a volume of incorporation of approximately 25 % (v/v) to positively impact soil structure (Brandt and Hendrickson, 1991).

The particle size of the compost is important. Although the studies addressed composts applied as surface amendments, not soil incorporations, evaluations at the Texas Transportation Institute found that although compost and shredded brush were effective as erosion control, fine compost applications (< 7 mm; 1/4 in minus) had greater sediment loss (Landphair and McFalls, 2000). For this reason, application of normal commercial compost (< 19 mm; < ¾ inch) would be expected to provide much lower benefit for infiltration and percolation.

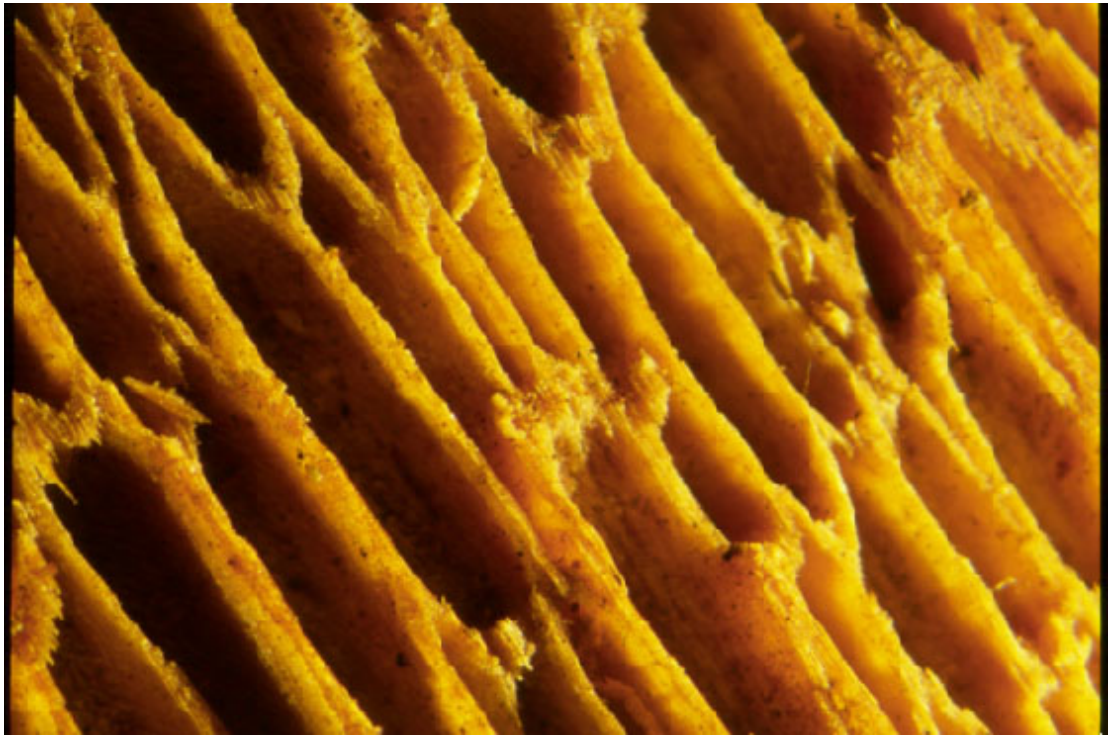
[sccomp1]

The unscreened yard waste composts used in this study were produced by the City of Redding municipal composting facility. The initial yardwaste material was shredded by a tub grinder with no additional screening other than an initial pass through a 75 x 125 mm (3 x 5 inch) grate. Although the two materials were not tested against each other directly, the longer fiber length (individual shreds to 150 mm, 6 inches) of unscreened, shredded tub ground material is expected to be more beneficial than the chipped wood materials that are commonly available. The longer shreds add more continuous pore space and greater tensile strength to the amended substrate volume than the chips. An option in soils that are compacted but do not need additional nitrogen would be to use the coarse materials that are screened during production of "fine" compost for gardening use. Coarse wood fragments may persist in the soil for an estimated 3 to 5 years (Tietjen and Hart, 1969) before decomposition reduces their effectiveness.

Fine (decomposable) carbon

Much of the compost volume is made up of medium to fine shreds with visible cell wall structure. The finest of these particles resemble small shreds or fibers. The cell wall materials are mainly cellulose, which are steadily degraded into sugars by microbes. The application of compost to soils increases root growth and plant biomass production in ways that are not duplicated by fertilizer and water addition. Although the exact reason for this is not known, some aspect of microbial activity is suspected.

Approximately xx % of the soil organic carbon in a natural soil is thought to be decomposable (Stevenson, 19xx). In a rough calculation, this would be comparable to xx kg/ha compost per year, but the decomposition rate of the finer and coarser fragments would have to be accounted for. The 24 % volumetric addition of coarse yard waste compost to the top 300 mm provides about 4 % total organic C. This is high relative to natural soils, but much of this C will decompose away within a few years. More field work needs to be done on the practical aspects of compost decomposition in different situations.



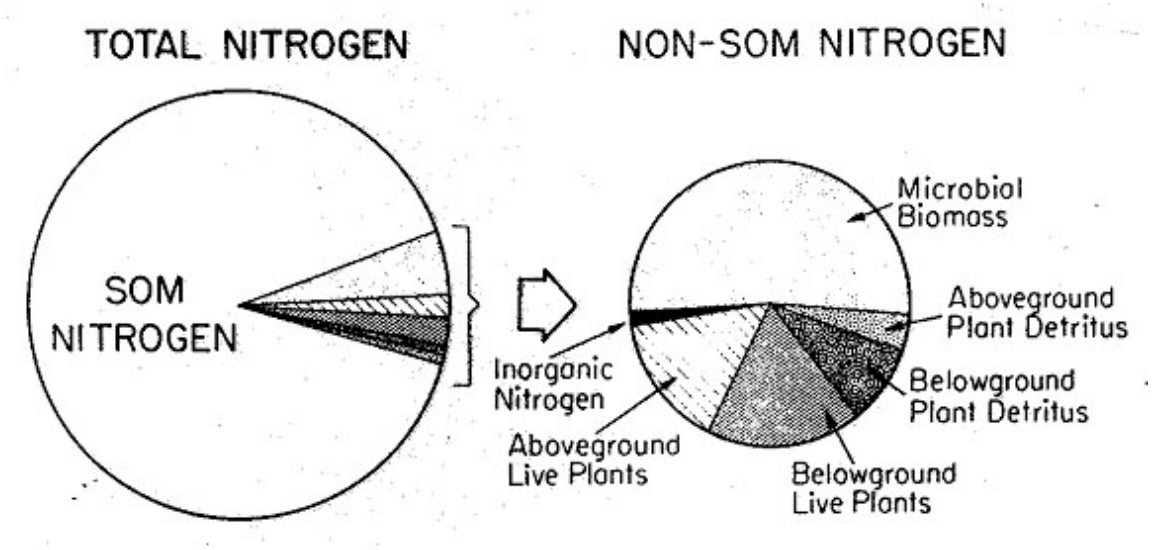
[scNC]
Empty cells from a fragment of coarse woody material from a conifer in the Sierra Nevada. The cell walls are primarily constructed of cellulose.

Numerous examples of excellent plant growth response following large amendment with unscreened yard waste compost are provided in the Case Studies section. Plant growth is regenerated even on substrates that had been barren for decades. So, in spite of the lack of complete information on organic matter performance on disturbed sites, this application method is effective in many situations. While the efficiencies of compost utilization can undoubtedly be improved, especially in the first season or two of use, compost application is works to regenerate plant growth and soil function.

4.2.0 Evaluate soil organic nitrogen (N) pools.

Nitrogen pools
Soil nitrogen (N) can be categorized into three conceptual pools. The largest is the stable organic matter pool that contains N in humified organic forms. These materials decompose only very slowly, with half lives of hundreds to thousands of years. These stabilized N pools amount to

between one and several thousand kg total N/ha. A smaller pool, but one that is much more active and dynamic is the mineralizable pool. This material consists of decomposable organics, mainly of microbial and plant origin. This pool may only be a tenth of the size of the stable organic matter N pool, perhaps several hundred kg N/ha. A similar amount of N is contained in plant shoots, roots and decomposing litter. The plant pools are not actually in the soil, but are necessary to continuously feed the soil. The smallest soil N pool is the extractable N pool (ammonium and nitrate) of 10 kg N/ha or less. Soil N pools in a foothill woodland environment were studied in northern California by Jackson et al., (1988). The pie charts show the amounts of the soil N pools for a California wildlands soil.



[scN5.jpg]
The left diagram shows the large, stabilized pool of soil organic matter N. The small wedges in the left circle are expanded in the right figure. Here, the size of the mineralizable, mainly microbial, pool can be seen, along with the various amounts of N in liiving and dead shoots and roots and plant litter. The smallest wedge is the amount of extractable N (ammonium or nitrate). This is the amount typically reported in soil analyses. It is important in agricultural soils because it is much larger and is the direct way that crop plants take up N. In wild lands soils, it is much smaller, and is extremely variable due to weather, soil temperature, plant growth stage, etc. The extractable N pool has low correlation to the amount of plant cover growing on a site (Claassen and Hogan, 2002).

Nitrogen availability Nitrogen availability coming out of the mineralizable pool in a soil depends on the biological cycles of decomposition of organic matter (and, in some locations, on the atmospheric deposition of nitrogen from the atmosphere) and on the rate of removal of nitrogen from the soil by plant uptake, microbial uptake, leaching or gaseous losses.

If the organic matter being decomposed has an excess N content (dried leaves, manures), typical microbial activity will use the C for energy and the excess N will be released to the soil (mineralized). If the organic matter has less N, or a great deal of C (such as wood or straw), any available N will be taken up into microbial biomass (immobilized) to increase the microbial population. Typically, ratios of C:N of greater than 25 suggest that microbial immobilization of any available N will occur and that little will be available for plant growth. C:N ratios of less than approximately 18 indicate that more N will be mineralized than will be used by microbes, and the excess will be available for plants uptake.

Microbial decomposition of plant inputs, whether from composts or plants growing on site, depends on the ratio of available carbon to available nitrogen in the organic amendment. Clean wood chips have a great deal of carbon but very little nitrogen, making microbial decomposition slow. This is good for persistence of the coarse wood fragments needed for macropores for infiltration, but it does not provide the microbial residues that are the source of the humified organic matter. MIcrobial growth depends on both decomposable organic material and available nutrients. Fresh

leaves have enough excess nutrients that they are actually given off (mineralized) by the microbed during decomposition. In general, if soils have a ratio of total C to total N (C:N ratio) that is greater than 25, mineral N (ammonium or nitrate) will not be produced in net excess, while if the ratio is less than 15 to 120, excess mineral N will be produced. But, these are based on total elemental analysis of the substrate, not all of which the microbes will perceive as "available." Development of improved "available" C:N ratios will be much more useful for analyzing the N uptake or release from organic amendments than the current total C:N analysis methods.

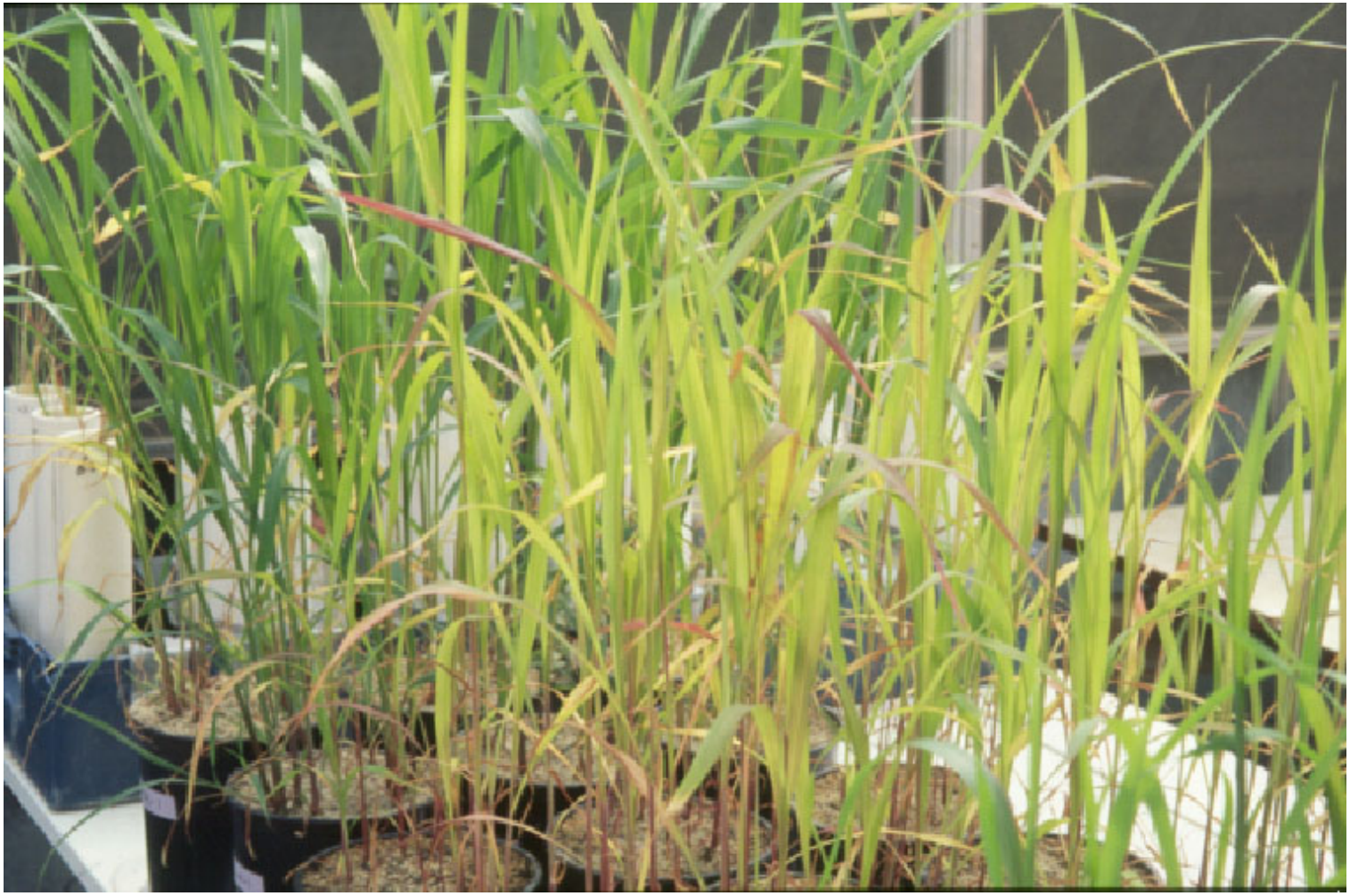
Some common materials and their C:N ratios are: Alfalfa hay 13:1 Seaweed 19:1 Rotted manure 20:1; Leaves 40-80:1; Oat straw 24:1; Wheat straw 80:1 ; Paper 170:1; Sawdust 400:1

In undisturbed soils, the average proportions of stabilized soil organic matter and fresh plant litter and microbial residues makes a general rule of N mineralization possible. Worldwide, approximately 1 to 3 % of the total N that a soil contains will become "available" for plant growth each year. This makes it possible to do an easy total C and N budget for a soil (including all depths, not just the surface) and to estimate the N release. When the site is impacted by toxic chemicals, anaerobic conditions, fresh organic amendments, atmospheric deposition, or topsoil removal, this general rule is less likely to apply.

Nitrogen fertilization Recommendations for nitrogen (N) fertilization vary from "never" to "usually". If ambient soils exist, even if they are mixed (excavation and refilling of a pipeline, for example) the mechanical process of soil handling will probably result in an increase in the available N, and no further N should be added to reduce the risk of weedy growth. On the other hand, deep excavations into native rock material probably means that little or no N will be available for plant growth. In these cases, additional N is required. Further more, areas near road ways may get annual doses of N from the atmosphere (from car exhaust) of over 30 kg / ha / yr. Depending on the residual soils, the proximity to traffic, and the growth rate of the plants, dosages from zero added N, to 20 to 70 kgN/ha are justified. The higher rates would only apply if there were near agricultural conditions, with good weed control and adequate water. Typically, rates of 20 to 40 kgN/ha would be used.

A close observation of the plant growth will tell a great deal about the plant's perception of N fertility. When all, or perhaps all but the newest leaves become yellowish, the plant is stripping N from older tissues to build new ones. With age, all older leaves may yellow, but with young growth, yellowish coloration is often an indication of N deficiency, or perhaps sulfur (S) deficiency.

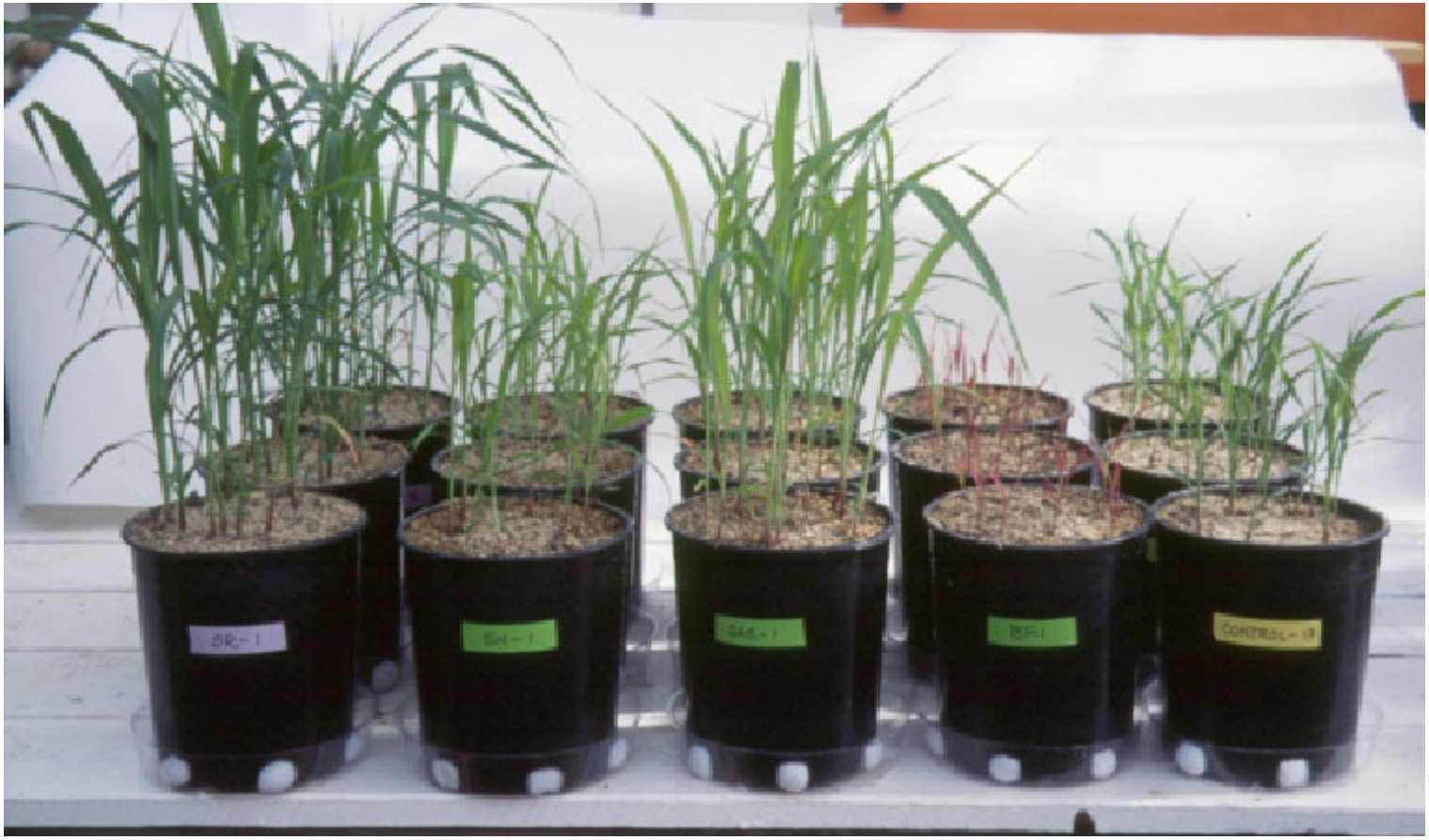
Plant indicators of nitrogen deficiency



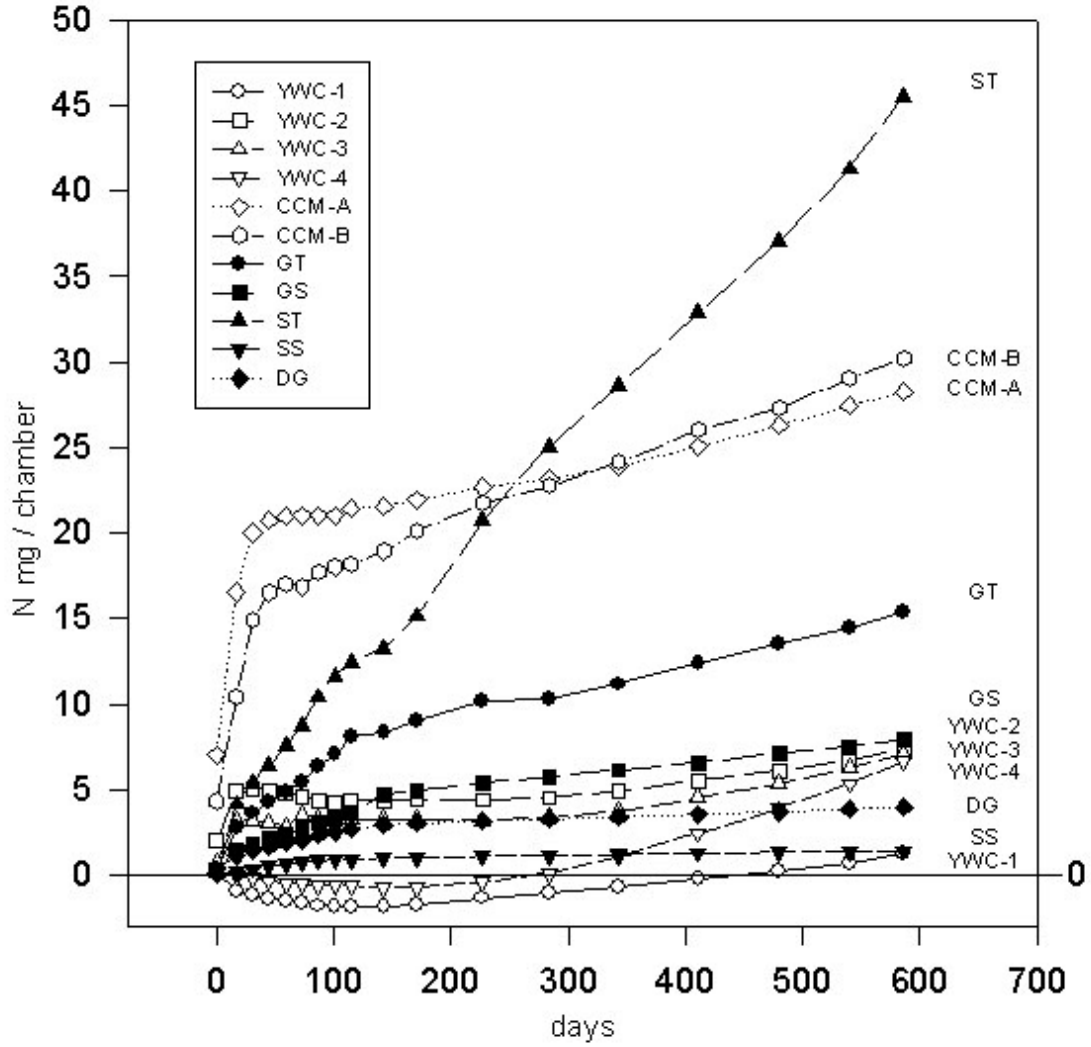
[scN4]
These Sudan grass plants show a range of N content, from sufficiency (plants in rear) to N deficiency and growth reduction (center front). In a few cases, root growth is low enough that the plant can't get phosphorus (P), creating the reddish coloration on some leaf tips.

[scNconif]
These Douglas fir plants from Washington state show a range of N content symptoms. The tree at left grew next to a nitrogen fixing alder tree and has sufficient N. The tree at right grew about 10 m (30 feet) away on poorer soil and is N deficient. (Zasoski, pers. comm)

[scN1]
Recent hydroseed treatment along Hwy 101. The bands are interpreted to indicate that the center area got sprayed three times because it is at the edge of three staging locations of application, the lower right section that stops at the rocks, the left field application, and the top band. Repeated application gave the junction adequate N, while the broader areas tend to be underfertilized.



[scN6]
All pots in this experiment received the same total amount of N. The pot at left is a biosolids compost. The three center pots are all yard waste composts. The right set of pots is unamended decomposed granite. In the second treatment from the right, the compost actually withdrew available N from the decomposed granite, reducing plant growth compared to the unamended treatment. Eventually, all this N will again become available for mineralization, but the first season's growth may be poor. These differences in N availability cannot be predicted at this time but are expected to be related to different types and amounts of organic materials in the compost as well as feedstock and curing time.



[scn7]
These data are from a Caltrans state wide survey on compost materials available for erosion control. The top two plots of dark symbols are topsoils from sedimentary (COL 20 8.0) or granitic locations (ELD 89 1.8). Top two plots with open symbols are biosolids yardwaste co-composts bottom four open circles are yard waste composts. All were loaded at the same rates of total N (equivalent to 500 kg total N/ha), so the differences in N availability with time represents the mineralization rate of each compost type. If the application rate were doubled to 1000 kg total N/ha, the curves at the right hand side of the graph (YWC 2,3,4) would be similar to the granite topsoil. The left hand side of these same curves, however would not match the N release that is typical of the topsoil from this location. Amendment of the compost may correct the initial release pattern. Co-composts with biosolids release much greater amounts of N.

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SRE step 5). Soil Fertility (non-N nutrients)

OBJECTIVES:
The site must provide adequate soil chemcial conditions and nutrient availability to support revegetation on the site.

5.1.0 Evaluate soil chemical conditions.

Soil pH
Soil pH is a measure of the intensity of the acidity or alkalinity of the soil. It is not the measure of the amount of acidity, which would be measured by buffering capacity. The intensity of pH determines whether plants can grow on the site, and it increases or decreases the availability of different nutrients. The amount of acidity determines the number of tons of lime needed to correct acidity. The amount of alkalinity determines the amount of acidifying amendments like elemental sulfur that are needed. Gypsum does not change soil pH. Alkaline and acid soils reduce the availability of phosphorus.

Cations
Positively charged ions in the soil. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) have two positive charges; potassium (K^{+}) and sodium (Na^{+}) have one postive charge.

Anions
Negatively charged ions in the soil. Phosphorus exists as an ion compound with between one and three negative charges (PO_4^{3-}, HPO_4^{2-}; $H_2PO_4^{-}$). Sulfur exists as a sulfate ion with two negative charges (SO_4^{2-}).

Cation Exchange Capacity (CEC)
Cation exchange capacity is the amount of negative charge scattered across the soil surface that ionically (magnetically) holds the positive charge of various nutrient cations (calcium, magnesium, potassium, ammonium, some micronutrients). It is measured in cmol charge/kg soil and should be 10 or more. Because sandier soils with low CEC may not hold many nutrient cations, the cation content of the soil is expressed as a percent of the nutrient compared to the whole CEC. For balanced nutrient uptake, look at the % of CEC for a particular cation nutrient.

Salinity (EC)
The electrical conductivity of a site (EC) indicates the salt content. This is expressed in deciSiemens per meter (dS/m) but the main thing is to look for values less than 2 or for salt tolerant plants if it is higher. Saline soils start at 4 dS/m. Composts can be fairly salty, mainly because of nutrient ions like K and SO_4^{2-}. This is not as bad as having salt caused by sodium chloride (NaCl) that disperses soil and plugs pores.

Treating Saline Sites
If a soil is naturally saline, then in theory the plants native to it are already adapted to saline conditions. It is possible, however, to build up salts in the soil. This can be a product of irrigation with saline water, excessive use of fertilizers, or even hunters or herdsmen placing out salt blocks. Deer have been observed grazing at the road edge, which may be because of saltier soils or only because of fresh herbage in the drainage ditch. If a salty white crust is observed, then your site may be saline, but winter rains can wash the crust deeper into the soil and seedlings will still suffer.

Two issues arise with saline soils. The initial challenge is to discourage stock or wildlife from pawing and eating salty soil in order to reestablish native vegetation. In addition, if the salinity level is very high, the soil may actually be toxic to native plants. The best way to determine this is to analyze the soil for a "saturated paste" electrical conductivity. If 1:2 or 1:5 soil:solution ratios are used for salinity analysis, the indicated values will be lower than those experienced by the plant root.

Salinity can be reduced by flushing soils with copious quantities of water, or by treating soils with gypsum prior to flushing. The calcium with its double charge is effective at displacing the sodium with its single charge. Wildlife or stock disturbance can be reduced by the above methods, or by physically blocking access to the salty area such as building an enclosure, placing lots of barriers (like logs) on the ground, and so on. If human activities have resulted in poor soil drainage, then improving drainage should also be considered.

5.2.0 Evaluate soil non-N nutrient availability.

Soil Macronutrients and Micronutrients

There are three macronutrients, nitrogen (N), phosphorus (P), and potassium (K), which are found in significant quantities in most soils. The macronutrients are most likely to be missing if the topsoil layer has been removed.

Nitrogen (treated in the previous section) is supplied from the atmosphere, or from decayed plant and animal matter. Phosphorus and potassium are supplied by the decomposition of parent rock material or from decayed plant and animal matter. Fertilization generally replaces some combination of the three macronutrients.

Micronutrients, while still important to the growth of plants, are in the soil in trace amounts and deficiencies are less common. Calcium (Ca), magnesium (Mg), and sulfur (S) sometimes require supplementation.

The respective amounts of the macronutrients in fertilizers are expressed as percentages of elemental content of nitrogen (N), phosphorus pentoxide (P_2O_5), and potassium oxide (K_2O). So, for example, a "20-10-5" formulation is 20% nitrogen, 10% P_2O_5, and 5% K_2O. The percentage of elemental phosphorus in P_2O_5 is calculated as the % P_2O_5 X 0.43. The percentage of elemental potassium is calculated as % K_2O x 0.83. The fertilizer formulation is often expressed more simply as N-P-K. For instance, someone may say "The N-P-K is 16-48-0."

Phosphorus (P)
A lack of phosphorus is the second most common soil deficiency, especially on arid lands. Phosphorus is lost off the site through erosion because it sorbs to fine mineral particles or in the organic matter fraction. In contrast to nitrogen, phosphorus is very immobile and insoluble in the soil. The over-application of phosphorus does not have toxic affects to plants, but guard against transport of sediment-bound P to local watersheds, especially on newly constructed sites. Due to its immobility phosphorus is not prone to leaching and must be incorporated into the root zone of the plant.

Phosphorus stimulates root growth, which is very important for seedlings. It also promotes maturity including seed production. As such, phosphorus counterbalances the reverse effect of nitrogen, which stimulates shoot growth. Phosphorus also strengthens stems, aids in the absorption of other nutrients, and increases disease resistance. Plants deficient in phosphorus exhibit a general stunted appearance and the seedlings may have purplish foliage (Redente 1993, Hingston 1982).

Synthetic phosphorus is present in many compound fertilizers including ammonium nitrate-phosphate (23-23-0) and ammonium phosphate (11-48-0). If only phosphorus is needed, triple superphosphate (0-46-0) is the common choice; this formulation also contains sulfur and calcium (Redente 1993, Hingston 1982).

Organic amendments containing phosphorus include rock phosphate, basic slag, bone meal, bloodmeal, cottonseed meal, and activated sludge. These are all applied at three to four times the rate of triple superphosphate (Rodale 1961). Steamed bone meal and pelletized rock phosphate (with a ligno-sulphate binder) are reputed to be the best source of organic phosphorus (Integrated Fertility Management 1995). Preparing a site by tilling in legumes as a green manure will also add phosphorus (Rodale 1961).

In clayey soils, the soluble phosphorus in fertilizer will eventually bind with clay particles, thus becoming temporarily unavailable to plants. Legumes have a high phosphorus demand, which, if in ample supply, will stimulate nitrogen fixation.

Measurement of P availability in soils is done by extracting the loosely held nutrient by an extracting solution. For P, acid soils are extracted by an acid extractant, such as "weak Bray" or "double acid" extracts. For neutral and alkaline soils, the "bicarbonate" (Olsen) extract is used. Soil test

reports must specify which extract was used. Available P levels should be over 10 for Bray acid extracts and over 5 ppm for bicarbonate extracts.

Potassium (K)
Potassium, also called "potash", is less likely to be deficient compared to nitrogen or phosphorus, but can be limited on coarse, sandier soils. It is more mobile than phosphorus, but leaching is generally not a concern unless soils are sandy or prone to flooding. Potassium is most effective if incorporated into the root zone. Yard waste composts supply abundant potassium.

Potassium promotes photosynthesis, root development, vigor, growth, and maturation of flowers, fruits, and seeds. Potassium counterbalances excess nitrogen. Potassium also increases winter hardiness in legumes (Hingston 1982, Redente 1993). Signs of potassium deficiencies in plants can include dull bluish green leaves with yellowing between veins, which then progresses to either browning leaf tips, spots or patches of discoloration, or on older leaves, the appearance of scorched looking rolled edges.

Synthetic potassium is commonly available as potassium chloride, also called muriate of potash (0-0-60). Potassium is also available in compound fertilizers.

Organic amendments used to increase potassium in the soil include kelp, manure, compost, granite dust, greensand, basalt rock, wood ash, and hay. Kelp is especially high in potassium, and is also rich with trace elements. Leaves, canola meal, and bonemeal have lesser amounts of potassium (Rodale 1961, Integrated Fertility Management 1995).

Measurement of all nutrient cations occurs by displacement by some salt solution (often neutral ammonium acetate) and measurement of the proportions of K, Ca, Mg, and Na. These amounts are expressed both as parts per million (in units of ppm, ug/g, or mg/kg) or as percent of the total number of cations exchanged or CEC.

Potassium should account for more than 1 % of the CEC or greater than 100 ppm.

Calcium (Ca)
Calcium is a component of lime, and may be lacking from soils that have become acidified such as certain foothill or sedimentary soils or mining spoils. Serpentine soils are naturally low in calcium, but deep, developed serpentine soils contain adequate amounts, although they are low in proportion to magnesium.

Calcium aids in cell wall formation and shoot growth. Calcium in the form of bonemeal has long been used as a supplement with bulb plants to replace nutrient reserves. It decreases the uptake of iron, aluminum, and manganese which can be present in toxic levels on acid soils.

Calcium deficiencies show as several symptoms. Terminal buds or root tips may fail to develop, and leaves may be distorted by either appearing rolled forward along the margins or appearing rolled backwards towards the under surface. The edges of the leaves may show yellow bands or the appearance of brown scorching. Root necrosis (death) caused by lack of calcium is a mechanisms by which non-serpentine adapted ecotypes do not survive on these substrates.

Calcium is applied most commonly as various forms of processed lime. Processed limestone fertilizers include burned lime, quicklime (very caustic), lime oxide, or lime hydroxide.

Ground calcium carbonate, also called limestone flour, is a good choice if magnesium is not lacking as it is safer and releases more slowly. Ground dolomite lime (contains both calcium and magnesium carbonates) should only be used if magnesium needs to be supplemented as well. If it would be undesirable to alter pH, gypsum makes an excellent calcium amendment as it contains 23% available calcium. Gypsum also contains 18% sulfur. Gypsum is a common amendment on clayey soils where it loosens the cohesion of the clay particles, making the soil more workable.

Calcium in extracts should account for more than 20 % of the Mg level, and at least 200 ppm. Usually this is never a problem except on serpentine substrates. In this case, a trained botanist or plant expert will help identify serpentine tolerant materials.

Magnesium
Magnesium occurs naturally in limestone formations and is a predominant cation in serpentine soils and substrates.

Magnesium functions in the formation of chlorophyll, aids in the assimilation of phosphorus, and regulates respiration. Magnesium deficiencies appear as interveinal discoloration on older leaves or yellow leaves with brilliant tints which then drop. With grasses a deficiency is evidenced by dwarfed growth and yellow stripes between veins.

Magnesium in extractions should be at least 10 % of the CEC and at least 100 ppm.

Sulfur
In nature sulfur is mineralized from organic matter. Along roadways, vehicle exhaust is a significant source.

Sulfur stimulates root growth, chlorophyll production, seed production, and the formation of root nodules on legumes. Legumes have a higher sulfur demand than grasses. Sulfur is converted into proteins and amino acids by the plant.

Sulfur deficiencies observed in plants include leaves turning light green then yellow, plants are small and spindly, and seed maturation is delayed. In legumes, nodule formation is reduced. Sulfur deficiency looks like nitrogen deficiency, but with nitrogen deficiency, the most recent leaves are often somewhat greener, while in sulfur deficiency, the newest leaves are the most chlorotic (yellow).

Synthetic sulfur is found in compounded fertilizers, or as elemental sulfur, which is a byproduct of the petroleum industry. Very basic soils are treated with the addition of elemental sulfur, which then slowly oxidizes to form sulfuric acid.

Organic soil amendments include pelletized sulfur which is used if the objective is to acidify soils. If increasing the acidity is not desired, gypsum or K-mag can be used instead. K-mag is a mineral containing 27% sulfur, 22% potassium, and 11% magnesium.

Sulfur availability is determined in water extracts, but these are difficult to establish target values for. Sample on the reference site as well as the impacted site and compare values.

Sodium is not a nutrient but may be an issue on salty sites.

Application of Fertilizer or Soil Amendments
With most restoration projects, fertilizer is added at the same time as seeding- generally in the fall. This timing, however, is for convenience and cost-savings. The risk is that the fertilizer will "burn" the germinating plants, since chemical fertilizers tend to be soluble. The better approach is to fertilize the seedlings once true leaves have appeared on the plants. The added benefit to this approach is that the nitrogen will be available right when it is needed rather than leaching quickly through the soil during the wet winter when plants are growing slowly.

Fertilizer can be broadcast with a spreader. Fertilizer should not be placed directly into planting holes unless it is slow release.

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SRE step 6). Soil Biology

OBJECTIVES:
The site must support adequate biological activity for nutrient decomposition and cycling, nutrient uptake and to generate soil aggregation.

Decomposer (saprophytic) microbes.

Addition of inoculants, stimulators, activators, or enhancers for decomposer microorganisms are unnecessary. If microbes are not active, suitable substrates are evidently missing and should be provided for them to grow on. Microbes constantly are blown around on dust in the wind and carried by animals. Keeping microbes out of a field site is impossible, so inoculants are unnecessary. Feeding them is necessary.

Mycorrhizal Fungi

Ectomycorrhizae- This group of mycorrhizal fungi is associated with many tree and shrub species. The prefix "ecto" refers to the fungal hyphae wrapping a web-like structure around plant roots and colonizing the spaces between the cells without penetrating the interior of the cells. Nutrients are then absorbed through the plant's root cell walls. Some plant roots can even be linked together by ectomycorrhizal hyphae, acting like a plumbing system allowing nutrients to move from plant to plant. Young seedling plants may be supported by this hyphal network until they are large enough to have a larger carbon flow through photosynthesis.

Douglas fir (Pseudotsuga menziesii) associates with up to 2,000 different species of mycorrhizal fungi throughout its distribution in North America (Trappe 1977). Ectomycorrhizal fungi tend to be generalists, meaning that one species of fungi will interact with many different species of plants.

The spores of ectomycorrhizae can be airborne and can travel readily through the soil. Due to this trait, ectomycorrhizal host plant are unlikely to require inoculation.

Arbuscular Mycorrhizae (AM) - This group is found associated with grasses and forbs as well as some shrub and tree species. The prefix "arbo" refers to the vesicles branching in a treelike pattern. The hyphae of arbuscular mycorrhizae penetrate cell wall of the cortex (an outer layer of root tissue) where they interface directly with the cell membrane of the plant. Vesicular arbuscular mycorrhizae have large soil-borne spores that only migrate short distances through the soil. They are more likely to need inoculation on areas that have not had plant growth previously.

In arid and semi-arid lands, ninety percent or more of the vascular plant species depend on VAM species. The VAM fungi are a less diverse group than the ectomycorrhizae, but are still generalists. Sagebrush (Artemesia), for example, has only four species of fungus that interact with it, but these same fungi will interact with other species as well (Moldenke and others 1994). Western Red Cedar (Thujaplicata), Ceanothus species, and Rubus species (blackberries and salmonberry) are also known VAM plants.

Ericoid Mycorrhizae- This group is specific to the heath family (Ericaceae) which includes many diverse North American plants such as heather, huckleberry, azalea, rhododendron, Labrador tea, and salal. If you are working with a heath family plant species, it will be important to collect inoculum from the same species.

Arbutoid Mycorrhizae- This group is specific mostly to mediterranean species, but also interacts with Arbutus (madrone) and Arctostaphylos (manzanita and kinnikinnick) which may include one of your restoration species.

Orchidaceous Mycorrhizae- As the name suggests, this type of mycorrhizal fungi is specific to the orchid family. The hyphae form a spiraling structure in root cells called coils. This group is mentioned here because of the possibility that a mitigation project may involve orchid species.

How to Inoculate Plants with Mycorrhizal Fungi

Mycorrhizal propagules are the composite of spores, hyphae, and plant root fragments containing mycorrhizal fungi. The technique for collecting

mycorrhizal inoculant is quite simple; dig into the root zone of the type of plant species (or group) that you will be using for restoration. Remove some soil, including small pieces of roots. This soil is your inoculant. If local topsoil or organic matter is being used, the appropriate fungal spores are also likely to be present.

There are two junctures at which you might inoculate, either off-site in the greenhouse or on-site when planting. Using both methods will enhance success. Inoculation is most successful during the seedling stage; an attempt to inoculate a more mature nursery grown plant during outplanting is less likely to succeed.

Nursery inoculated plant stock will thrive better once outplanted than plants that are not inoculated. While it is beneficial to inoculate in the nursery, the nursery growing conditions will alter the soil flora due to the growing conditions and chemical use (such as fertilizer) being different than the native plant community. Some nurseries may not want to use this technique because of the risk of introducing soil pathogens to the nursery. Other nurseries are capable of isolating different plant populations in their facility.

The second method is to inoculate plants on site. Ideally, if you are topsoiling, you will already be introducing mycorrhizal fungi (and soil bacteria). If topsoiling is not feasible, you can spread a thin layer (about 1-2 teaspoon's worth) into the root zone of each planting hole. If direct seeding, it is best to inoculate as soon as the seedling plants have emerged. The other option is to inoculate just before seeding, but, as noted above, the delay between seeding and seedling emergence may result in a die off of fungal species. With this option the soil is prepared, a thin layer of inoculant is spread over the soil surface, seed is sprinkled on top of the inoculant so that roots push through the inoculant upon emergence, then a thin layer of soil is spread on top of the seeds (depending on the species). Adding woody materials on the planted site will benefit fungi by making a reserve of moisture available, as will mulching on top of the soil.

Reintroducing Soil Mycorrhizal Fungi and Bacteria

Even though 80% of the earth's vascular plants depend on mycorrhizal symbionts, many plant species do not. These include the genera Saxifraga (saxifrage), Juncus (rushes), Carex (sedges), and plants in the Brassicaceae (mustard) family and Caryophyllaceae (pink) family. These plants are often the first colonizers of naturally disturbed areas.

Most of our weedy introduced species also live mycorrhizae-free lifestyles. This is a key reason why they are able to rapidly invade disturbed areas when the local native plants can not.

Soil Nitrogen-fixing Bacteria
Nitrogen-fixing plants have different types of bacteria depending on the type of plant. The legume or pea family (Fabaceae) is the most well-known group of nitrogen-fixing plants and is colonized by a bacteria called Rhizobium. Various plants form symbioses with different genera of bacteria. An easy way to get the appropriate symbiont is to take soil from under growing plants of the same species and transfer small volumes (a few tablespoons full) to the planting holes of new plantings.

If a plant is a known nitrogen-fixer, and nodules can be identified on the root, inoculation can be done from these nodules. A slurry can be made by blending the roots with water to break open the nodules and release the bacteria. This slurry can be used to irrigate and inoculuate the new plants.

Soil Biotic Crusts
Some soils, especially soils lacking a litter or duff layer, form visible microbiotic crusts. These crusts are comprised of bacteria, fungi, lichen, and mosses. The crusts are easy to spot as the soil is often textured into tiny pinnacles and buttes several centimeters high. Crusts are easily pulverized underfoot. These soils are commonly spotted in arid lands as well as subalpine or alpine areas. If intact, these organisms both serve to hold the soil in place.

The restoration of soil crusts is an emerging science. It is best not to disturb these crusts in the first place as full recovery can take hundreds of years. However, if the damage has already been done (or is otherwise unavoidable) it may help to stockpile and reinoculate the restoration site.

Once the site has been stabilized, backfilled, and planted, the final step is to broadcast the pulverized crust back over the restoration work. The ideal is to replace the crust at a 1:1 ratio, however it is rare to have this much crust material available. A 1:10 or 1:20 ratio is more commonly used. The maximum depth of a respread pulverized crust is one inch.

If salvaged soil must be stored prior to reuse, the top inch of crust should be removed and stored separate from the remaining 3-8 inches of topsoil. Salvaged crusts can be stored in an active or dormant state. To remain active, the crust must be able to photosynthesize and receive moisture; this is accomplished by spreading soil to only an inch or two thick. Dormant storage is accomplished by storing dry soils more thickly away from moisture and sunlight; this can be accomplished by using buckets with lids. For dormant storage, soils must be dry when stored (Belnap and Furman 1997).

Biological or microbiotic crusts are also referred to as cryptogamic, cryptobiotic, and microphytic depending on the type of organisms present. Biological crusts are recognized by the distinct presence of living organisms or their byproducts, creating a surface crust of soil particles bound together by organic materials. In otherwise disturbed areas, look for biological soil crusts in fenced areas, low use areas under shrubs, or between closely spaced rocks.

Biological crusts vary tremendously in thickness, texture, percent cover, color, and species present. For example, cyanobacteria, dominant in arid soils, forms pinnacles up to 15 centimeters high. Other soils may have evident moss or lichen growing on the soil surface (NRCS 2001b, NRCS 1997). A common pattern is for a moss or lichen crust to form a mini-terrace, creating benches 5 to 10 cm wide that are flatter than the slope angle. Because they are stable when wet, they trap sediment and persist during rains.

Jayne Belnap (USGS) provides photos of pinnacles and soil aggregates bound by sheaths at www.soilcrust.org.

If a biological soil crust is broken, compressed, or removed due to factors such as grazing pressure or compaction, the soil is left susceptible to wind and water erosion, as well as formation of a physical crust. In addition, the nitrogen fixing capability of the crust is reduced. If crusts are buried, they will die. Fire can also kill crust organisms.

[scbiocrust] This desert soil has a well developed biotic crust that keeps the fine particles aggregated so that moisture can infiltrate. The crust is easily degraded, however, as shown by the crushed soil in the tire track in the lower quarter of the photo.

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SRE step 7). Site Surface Stability and Erosion Control

OBJECTIVES:
The site must be adequately stable against surface erosion and desiccation that plants can germinate, grow and cover the site before erosion resumes.

Overall site drainage
The site should be protected from run-on from slopes above the site. Diversion ditches and armored drains shield the new slope from the volumes of water that move downslope in the soil above the site. These volumes of water are harmless in existing soils with well aggregated structure and good root strength, but they are distructive when they hit the unconsolidated and unaggregated disturbed substrates.

Drainage within the slope can be improved by breaking the slope into shorter segments with wattles or diversion ditches. This, however, avoids solving the problem that a slope needs infiltration and percolation capacity. At the Buckhorn project (SHA 299 0.06) the coir fabric layers formed multiple seepage zones that wicked the water to the surface and allowed it to flow downward across the face of the slope without erosion. These horizontal layers of coir blanket, along with willow poles layed horizontally on each lift, provided a safety valve for water within the unconsolidated, compost amended surface of the slope.

Surface (rain drop impact) protection.
Conventional erosion control methods are effective for this component. Straw is cheap and effective. In some areas, pine needles are available, and form erosion and wind-resistant layers as they interlock. Long needle lengths are important, and care should be taken to not break up long (ponderosa pine type) needles. High technology, bonded fiber matrixes and expensive blankets are often used, but straw remains a standard for effectiveness.

Mulch effects
Protection against rain drop impact takes only a thin layer of straw or hydromulch. Thicker layers of mulch protect against frost heave in cold, high elevation areas and against heat and dessication in hot, dry areas. The thresholds of mulch thickness have not been tested in California.

Thick mulches also have some negative aspects. Small rains may wet the mulch but not the soil. Also, the mulch that keeps the soil from freezing in mid winter, may also keep the soil too cool to germinate seeds in the spring. Despite these potential drawbacks, the protection of a soil against a hard freeze to significant depths (30 cm, in Lake Tahoe on unmulched fill) allows roots of perennials to grow and prepare for the short growing season when the spring arrives.

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SRE step 8). Site Appropriate Plant Materials

OBJECTIVES:
The plants selected for the site must be able to grow, stabilize and reproduce on the site in the initial amended conditions as well as the longer term site conditions. These conditions include having tolerance for the amended substrate (rooting into fresh materials, poor nutrient cycling, lack of soil development), for a range of climatic conditions (droughty or wet, cool or hot) and for biological pressures (weed invasion, lack of microbial activity).

This additional section is included to provide information on soil and plant interactions. It is not a plant materials list.

The more atypical the soil or environmental condition, the more likely it will be that a local ecotype of a plant species will be needed to revegetate a disturbed site.

Grasses tend to be more indifferent to ecotypic specificity to serpentine substrates. Shrubs and forbs tend to be more highly ecotypically selected for serpentine substrates and are more likely to require local or site-specific seed collection.

Consult the Calflora website or the Caltrans Native Grass Data Base for information on plant materials.

Bibliography

(Curtis et al., 2004) 24 % incorp at Buckhorn

Landphair, H.C. and J.A. McFalls, 2000. Performance of Yard Waste Compost for Erosion Control and Vegetation Establishment. Texas Transportation Institute Report Research Study Number 473400

Society for Ecological Restoration International Science & Policy Working Group. 2004. *The SER International Primer on Ecological Restoration*. www.ser.org & Tucson: Society for Ecological Restoration International. Stevenson, F.J., xxx Soil organic matter

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Case Study 1 Data Table

1. common name	Buckhorn summit
2. location code	SHA 299 0.06
3. lat long	40.6390 N lat, 122.6670 W long
4. Caltrans route	299
5. highway type	state
6. mile marker	0.06
7. county	Shasta
8. Caltrans district	2
9. geology	decomposed granite, quartz diorite
10. geographic region	north coast range
11. elevation	1009 m (3300 feet)
12. biome	mixed conifer forest
13. construction date	Fall, 2002
14. construction method	bench fill, fill cut, geotextile reinforced benches
15.	
16.	
17. case study #	1

Photos

Figure 1. SHA 299 0.06. Site before construction, October, 2002. Note old finish grade faces visible at the right hand 10% of the slope indicating volume and extent of loss.

Figure 2. SHA 299 0.06. Site after third winter season, March, 2005. Areas at left and top received less compost.

Figure 3. SHA 299 0.06. Construction of gabion wall at foot of existing slope for construction of first year 2:1 compost test plots.

Figure 4. SHA 299 0.06. Site before reconstruction of overall slope, but with a row of field trial plots at the toe of the slope behind a gabion wall. December, 2002. Note sediment fans from untreated slope overtopping plots and gabion wall.

Figure 5. SHA 299 0.06. Response of *Elymus elymoides* to 0, 6, 12, and 24% compost additions after two years.

Figure 6. SHA 299 0.06. Cutting and compacting (track walking) a bench in the eroding DG slope. November, 2003.

Figure 7. SHA 299 0.06. Mixing 3 parts DG to 1 part unscreened yard waste compost.
November, 2003

Figure 8. SHA 299 0.06. Spreading compost/DG mixture on the narrow, unfilled face of a compacted lift (sliver fill), while blading the compacted bench clean of amended DG. November, 2003.

Figure 9. SHA 299 0.06. Laying coir fabric blanket (900g/m^2) across bench and down uncompacted fill of amended DB. November 2003.

Figure 10. SHA 299 0.06. Filling and compacting another lift over the coir blanket on a previous bench. Note unfileed volume of about 30 cm wide to be filled with uncompacted compost/DG mixture. Willow stakes are palced on the blanket before filling. November 2003.

Figure 11. SHA 299 0.06. Cross sectional diagram of fill/cut or bench fill construction in concept.

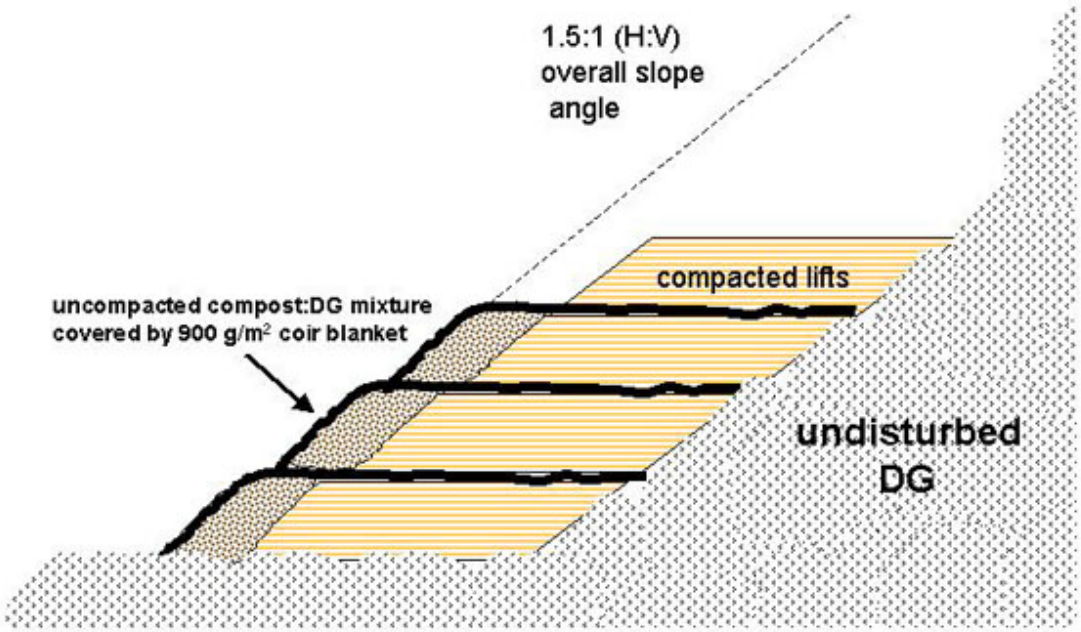


Figure 12. SHA 299 0.06. Cross sectional diagram of fill/cut or bench fill construction as build at the Buckhorn summit site.

Figure 13. SHA 299 0.06. Site after construction and after the first winter season. March, 2003. Note weep lines (lighter streaks of sand and gravels) that start at the layer of each geotextile blanket.

Figure 14. SHA 299 0.06. View of finished slope from top of Buckhorn Summit. April, 2005.

Figure 15. SHA 299 0.06. View of finished slope from road. April, 2005.

Narrative

History

Buckhorn summit site is located on highly weathered "decomposed granite" (DG) with quartz diorite mineralogy. The site was originally cut to about a 1:1 slope in about 19xx, and a remnant of the old slope face is visible on the right hand 10 % of the "before" picture (Figure 1). Soon after construction, the cutslope face was destabilized by groundwater flow originating from an old logging landing located 10 to 50 m behind the top of the slope. Ground water flow caused slumping in the mid-slope region of the original slope, and surface flow eroded the crest of the cut. The slope retreated about 5 to 15 m away from the road, with sediment moving off site. An estimated xx cu yd per yr were removed from the shoulder of the site before treatment.

Treatment

As part of a revegetation research project (RTA # xxx), a 1.2 m high gabion wall was constructed and backfilled so as to construct a 2:1 fill slope (6 m slope length) using DG from the SHA 299 1.0 slope repair. The plot fill material was slightly finer than the existing slope face material at 0.06 because of repeated handling, mixing with compost, or because of the different source location. The constructed 2:1 slope included treatments with 0, 6, 12, and 24 %(vol/vol) (0, 2, 4, and 8 % by dry weight) of unscreened, yard waste compost that was mixed with DG by backhoe bucket. The compost source was the City of Redding's municipal recycling facility (90 days of US EPA 503 thermophilic process followed by 90 days aerobic curing; unscreened, with up to 15 cm shredded wood fragment length). The treatment depths were 60 cm depth over unconsolidated DG. Data from rainfall simulation indicated that the 24 % compost mixture had comparable infiltration to a

disturbed, but revegetated reference site located 1.6 km (1 mi) west on 299. This finding was used to model the probability that an amended slope would produce negligible erosion over the various rainfall intensities experienced in that region. Findings were used to plan a follow-up series of test plots, as well as to design a treatment for the entire slope.

The second year study plots were constructed at a slope angle of 2:1, and with varying incorporation depths, to evaluate optimizing construction costs and efficiencies. At the same time, a design was developed to stabilize the remaining unstable slope into a series of benches that had a compacted portion nearest the remaining slope, and an uncompacted, compost incorporated portion filled onto the exposed edge of the bench. The overall slope angle after filling the benches was to be 1.5:1 (H:V). The thickness of the compost amended horizon was 300 mm when measured perpendicular to the slope face. A heavy (900 g/m2) coir fabric covered the compacted bench portion and was anchored into the slope by the overlying lift. The outer edge of the fabric was draped over the compost-incorporated slope face, providing short-term surface erosion control. Native grasses, shrubs and trees were planted in the uncompacted, compost-amended layer.

Additional design and construction information for this and several other slopes information is contained in the Final Construction Report (McCujllah, 2003).

Response

Field Plots

Roots of native perennial grasses (Elymus elyjmoides) reached 2 m depth at the end of the first growing season and set viable seed. The first year there were no differences in plant shoot biomass cover between compost treatment plots. The second year, however, the till/no compost plots grew 3.17 g biomass per plant while plants on the till/24 % compost plots grew 14.17 g per plant. On plots with no tillage (plants installed directly into the very porous but untilled DG matrix), plant growth was 0.44 g/plant while plants on the tilled/24 % compost treatments grew 4.0 g/plant. This comparison is analogous to conifers planted into small planting holes at the Kelsey site located south across the canyon. Evidently, the undisturbed DG is very porous to water flow (infiltration rates of 100.8 mm/hr) but they are not penetrable to root growth.

Table 1. Technical Tables for Case Study #1

Buckhorn Summit

SRE Step	Ref site	Constructed fill slope	Compost treated	Comments
1. Site Locations				
Buckhorn Summit	TRN 299 xx	SHA 299 0.06	SHA 299 0.06	ref site is regraded logging landing reveg'd in 1987
aspect	south	south	south	
slope	2:1	2:1	2:1	
parent material	DG	DG	DG	
2. Slope stability				
geotechnical	stable fill	active gullying	stable, no slumps	seepage from upslope slumps, gullies
erosion	none, 15 yr veg	barren, active erosion	surface rill from first yr	installed diversion ditch the first year, no erosion after

3. Soil water relations				
infiltration rate (mm/hr)	50.6	29.0	60.0	measured 3 yrs after construction
internal drainage (Ksat) (mm/hr)	16.8	51.1	38.6	ref site had compaction layer from construction
plant avail water %	14.0	9.3	14.5	to approx. -5.0 MPa
4. Organics, C, N pools				
carbon pools		near zero	loaded to 135 MgC /ha	measure end of season 05
nitrogen pools		near zero	loaded to 4.3 Mg N/ha	unscreened yardwaste compost
5. non-N nutrients				
chemical cond	sufficient	sufficient	sufficient	
macronutrients	sufficient	sufficient	sufficient	measure end of season 05
micronutrients	sufficient	sufficient	sufficient	
6. Soil biology				
	AMF colonized	none	AMF colonized	
7. Surface erosion stability (mulch, waterflow)				
mulch	stable	large sed losses	stable	
g sed per 15 min storm per m^2	5.01	41.55	0.62	60 mm/hr storm, 15 min interval
nitrogen loss				
8. Plant response				
shoot biomass g/pl		3.17	14.17	no growth difference first yr; these data for 3rdyr
root depth m		>2.0	>1.3	measured after first year
root density cm/ml		0.88	1.75	measured after 2yr growth

Critique

The construction process was intensive, partly because the slope area was constrained and the oversteepened slope required movement of a large volume of material from head of the cut, storing it on the bench above the slope, and bringing it back down during reconstruction. The small working environment meant that backhoe and bulldozer equipment size was also constrained. The intensive process was successful through the first three seasons, and resulted in the "only slope to stay up through the first rainy season in the last 30 years" according to Milt Apple, Caltrans District 2 Maintenance Supervisor.

A main result of the improved infiltration is the increase in the rainfall intensity that the slope can experience before overland flow starts. The significance of overland flow is, of course, the start of sediment transport and erosion, but it is also an indicator of whether a slope will regenerate soil fertility or whether it will chronically lose the nutrient rich surface duff and fine weathered particles that are critical for soil regeneration. The following table indicates the results from infiltration capacity modelling, coupled with long term rainfall data from representative weather stations.

Table III. Percent of time during the month that runoff will occur during a 15-minute storm with the corresponding return frequency and rainfall intensity, on the a) control and b) compost treatments. Sediment loss (kg/ha) during a 15-miute storm throughout the year (2003) at Buckhorn Summit on the c) control and d) compost treatments.

	Return Frequency (yrs)	RFI (mm/hr) *	Jan.	Feb	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
a)	2	40	100	100	78	100	50	0	0	0	0	0	24	100
	5	47	100	100	100	100	74	0	0	0	0	0	69	100
	10	55	100	100	100	100	100	63	0	15	0	0	72	100
	25	64	100	100	100	100	100	100	100	100	100	100	100	100
	50	70	100	100	100	100	100	100	100	100	100	100	100	100
b)	2	40	0	0	0	0	0	0	0	0	0	0	0	0
	5	47	99	54	59	67	35	0	0	0	0	0	0	6
	10	55	100	100	100	100	100	0	0	0	0	0	66	100
	25	64	100	100	100	100	100	100	100	100	100	100	100	100
	50	70	100	100	100	100	100	100	100	100	100	100	100	100
c)	2	40	5.6	1.1	0.8	2.6	0	0	0	0	0	0	0	1.3
	5	47	20.6	11.2	10.2	14.9	4.6	0	0	0	0	0	0	11
	10	55	42.7	29.8	28.3	34.9	19	0	0	0	0	0	7	30.8
	25	64	68.3	54.5	52.6	60.7	41.5	5	2	3	1	0	25	55.5
	50	70	85.1	72.3	70.3	78.2	58.2	13	9	10	7	4	39	73.4
d)	2	40	0	0	0	0	0	0	0	0	0	0	0	0
	5	47	0.2	<0.1	<0.1	0.3	<0.1	0	0	0	0	0	0	0
	10	55	9.0	6.9	6.7	9.2	4.0	0	0	0	0	0	0	4.4
	25	64	23.6	21	20.7	23.8	16.1	2.2	0.8	1.6	0.5	0.2	4.6	16.9
	50	70	33.4	31	30.7	33.5	26.4	7.4	4.7	6.3	4.0	2.9	11.3	27.2

* RFI-Rainfall intensity

Rainfall duration and intensity data taken from the Coffee Creek rain gauge.

A secondary result of related work on the same Soil Resource Evaluation project is the finding that deep cuts into DG materials have a potential for fixation of ammonium fertilizers or organic matter decomposition products, so that the ammonium is unavailable for plant uptake. Detailed measurements on the neighboring slope at SHA 299 0.6 (Old Faithful) indicate that over 55 % of the ammonium released from fertilizers or from organic matter decomposition is fixed (bound) in the mineral interlayers. This requires a compensating increase in the amount of fertilizer applied or the compost release rate so that plants acqure adequate nutrients during the first year of establishment. This effect occurs in other DG substrates as well Figure 16.

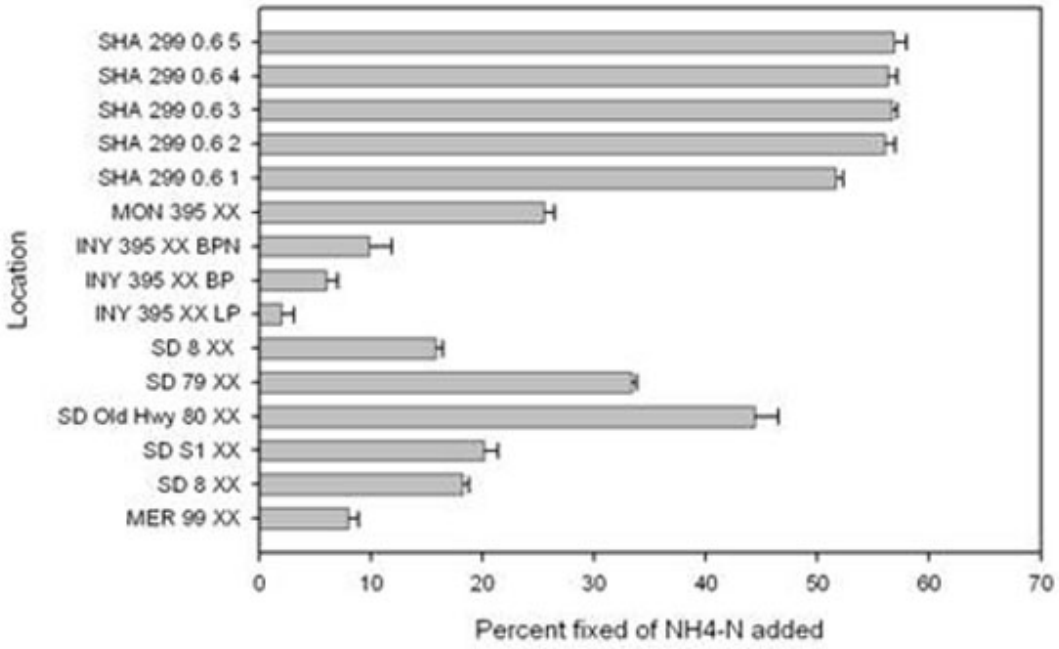


Figure 16. Fixation of ammonium in interlayer minerals in vermiculites (weathered micas) in decomposed granite rocks. Location key: INY, Inyo; MER, Merced; MON, Mono; SD, San Diego,

Remaining questions regarding this type of installation are the ability of the slope substrate to make the transition between compost-enhanced infiltration and natural soil structure that is generated by plant growth on site. Third-year infiltration data documented an increase in infiltration on vegetated plots, which is a positive sign. Continued fertility will be required in order to support adequate plant growth and maintain infiltration rates. The long-term behaviors of compost materials, however, has not been documented. Additionally, a large amount of organic matter is stabilized in soils as soils develop good aggregation. The soil aggregation process (accumulation of humic materials and microbial biomass residues generates a nutrient requirement in addition to that required for vigorous plant growth. Failure of the slope from nutrient deficiency will not be sudden, but will be observable over several years by an increase in plant spacing, less litter cover on the soil surface, and possibly by an increase in N-fixing species or by plant leaf indications of nutrient deficiency. A surface amendment of approximately 30 to 50 kg N/ha of slow release nitrogen would regenerate plant growth on the slope for another period of several years. If the ammonium fixation capacity is not saturated, these fertilization rates should be increased by 50 to 100 %. Eventually, the slope can be expected to become permanently self-sustaining, if infiltration remains high enough to prevent overland flow. and if nutrients (especially N) remain at adequate levels required for vigorous plant growth.

Plant list

Elymus *multisetus*(Bigsquirreltail) were plug-planted on a grid pattern (20 cm spacing) for experimental purposes. Plants seeded on the slope included Elymus *multisetus* (Bigsquirreltail) and Bromus carinatus (California brome), Achillea millefolium (yarrow) and Eriophy*llu*m lanatum (woolly sunflower) (locally collected). The second year, seedlings of Pinus ponderosa (Ponderosa pine), Pinus lambertiana (sugar pine), and Quercus kelloggii (Black oak) were planted randomly on the slope to provide a woody component.

Other suitable plant species include *Poa secunda* (Bluegrass),*Ceanothus lemmonii* (Lemmon's Ceanothus), *Ceanothus prostratus* var. *laxus* (Mahala Mat), *Acer macrophyllum* (Big Leaf Maple), *Aster oregonensis* (Oregon Aster), *Lotus crassifolius* (Big Deervetch), *Calocedrus decurrens* (Incense Cedar), *Pseudostuga*

menziesii (Douglas Fir).

Technical data

Permitting: Chris Cummings, Project Engineer, Shasta Trinity Counties, Redding, CA. Grant administrator: Jack Broadbent, HQ Landscape Architecture, Sacramento, CA. Erosion control and slope design: Salix Applied Earth Care, Redding, CA. Contractor: Cross Country Construction, Douglas, CA. Soils: Soils and Revegetation Lab, University of California, Davis. Matt Curtis, lead hydrologist; Ryan O'Dell, lead botanist; Eric Rider, lead soil chemist.

McCullah, J. 2003. Final Construction Report CTSW-RT-03-058.33.12, June, 2003.

Case Study 2 Data Table

1. common name	Colusa 1.5
2. location code	COL 20 1.5
3. lat long	39.0143 N lat, 122.3889 W long
4. Caltrans route	20
5. highway type	state
6. mile marker	1.5
7. county	Colusa
8. Caltrans district	3
9. geology	serpentine
10. geographic region	north coast range
11. elevation	400 m (1200 feet)
12. biome	serpentine chaparral
13. construction date	2002
14. construction method	surface tillage
15.	
16.	
17. case study #	2

Photos

Figure 1. COL20 1.5. Overall view of the COL20 1.5 serpentine site from directly west.

Figure 2. COL20 1.5. Overall view of the COL20 1.5 serpentine site from the northwest.

Figure 3. COL20 1.5. View of the wide bench at the top of the second slope (fill section) with concrete diversion ditch.

Figure 4. COL20 1.5. View of the first year soil moisture plots just upslope from the diversion ditch. These plants *Elymus elymoides* (Squirreltail) were measured for water use to determine the reason for lack of plant growth on the site. Utility boxes housed instruments for measuring soil moisture.

Figure 5. COL20 1.5. View of the first slope next to the road. Plots will go in the foreground area to the left of the gully and to the right of the paddle sign.

Figure 6. COL20 1.5. Tillage of compost into the top 30 cm of the plots by backhoe.

Figure 7. COL20 1.5. Plots in mid-winter the second season, with no irrigation either season. Plots in the top section are the same plant materials as the bottom, except without compost amendment. Three green plots are native, serpentine adapted plants from seed. Three of the non-green plots are zero controls to test for seed in the compost or that blows in from the surrounding area. The remaining non-green plots are plant seeding trials. The grid of plots to the far left are field tests for mycorrhizal response.

Figure 8. COL20 1.5. Close-up of mid-winter plant growth, second year from seed without irrigation. The center section was clipped for biomass study.

Figure 9. Close up of mid-winter plant diversity, showing Streptanthus, Gilia, Yarrow, and native grasses.

Figure 10. COL20 1.5. Plots in spring growth, April 2005.

Figure 11. COL20 1.5. Close-up of spring growth. Some weeds (burr clover, red brome and prickly lettuce) have colonized the plot. The white flower blooming is the native *Plagiobothrys sp.*

Figure 12. COL20 1.5. Close-up (overhead view) of spring growth.

Narrative

History

The COL 20 1.5 site is located on serpentinized ultramafic minerals. Serpentinization is a process of hydrothermal alteration of ultramafic rock types, which can vary from only alteration to complete modification of the minerals in the rock. As a result, there are a wide variety "serpentine" substrates with different growth conditions. All, however, have the characteristics common to serpentines, of high heavy metal contents, high magnesium contents, low calcium contents and low plant availability of other nutrients and water. Because of the extensive fracturing and hydrothermal alternation of these materials, they can also be geotechnically unstable and prone to failure and erosion, especially when oversteepened by road cuts or other nearby slumps.

The COL 20 1.5 site had developed repeated slumps and slips within the last several decades, closing Hwy 20 several times. In 1991, a large failure developed, and a project was developed to permanently stabilize the slope. In 1992, the lower portion of the slope was excavated deeply and lined with a rock drain layer covered with geotextile fabric. The excavated material was replaced and compacted, forming two lower slope segments with concrete diversion ditches at the top of each segment. Angles of the lower two slopes were 2:1 (H:V). Four upper slopes were cut into the original undisturbed rock material at a steeper angle of 1.5:1 (H:V), with a concrete lined diversion ditch at the top of each slope segment.

In 1992, gypsum, fertilizer and a mix of native and exotic plants were seeded onto the slope. A limited area at the top left (north) of the site received a thin (1 - 2 cm) overlay of topsoil that was salvaged from the site before excavation. After 10 years, this area was the only part of the site to regenerate even a thin revegetation

cover, predominantly of native, serpentine tolerant shrubs with a thin covering of annual grasses between the cobbles. The rest of the slope completely failed to revegetate except for small patches along the very foot slope by the road, and for small areas along the concrete drain ditches. The fertilizer and gypsum in the amendments may have altered the serpentine chemistry characteristics (low nutrients, low calcium) on the site for a few years initially, but as it eroded away or was depleted, the selected plant materials did not survive on the cut face materials. Long-term plant cover on the lower two slopes was thin (a single 50 mm tall plant scattered every 5 to 10 m), consisting predominantly of the serpentine tolerant species *Streptanthus drepanoides* (Sicklefruit Jewelflower) and *Erigonum nudum* and small, widely scattered individuals of the weedy invasive *Bromus madritensis* (red brome).

Treatment

Treatment The combination of high magnesium and low calcium levels makes plant growth on serpentines difficult and necessitates the use of serpentine tolerant plant species or ecotypes. Vegetative cover on natural, undisturbed serpentines is often sparse, but can be robust and diverse at sites where soils are deep. This is the case at the COL 20 1.5 site, which is located on "detrital" or "clastic" xx serpentine material. The material at this site is extensively fractured, providing deeper rooting volumes compared to other sites on unfractured serpentinized rock. The adjacent, undisturbed serpentinitic soils were well vegetated by a diverse plant community. Because of the level of excavation on the site, an appropriate disturbed-but-revegetated reference site was not available for comparison study, but native soils were measured for water use and nutrient content to use as general target values.

In 2002, unscreened yardwaste compost from the City of Redding municipal composting facility (themophilic process followed by 90 day aerobic curing) was applied at 30 % by volume. NPK fertilizer was also added to compensate for unknown release rates of nutrients from the compost and for low ambient macronutrient levels in the substrate.

Preliminary trials were established at the bottom of the second slope section to test water use patterns at the site using site-collected Elymus elymoides (Squirreltail). Plants were installed as plugs on 20 cm centers in grid patterns of 4 x 4 plants. Plots (except the non-tilled treatment) were excavated 1 m by 1 m wide and 600 mm deep. Compost was mixed to provide 0, 12 and 24 % ratios of compost volume to serpentine substrate. One year after construction, the 24 % compost amended plots had greater infiltration than the tilled plots ($p = 0.06$)(Table 1), but infiltration was still much less than the native, untilled sites. No disturbed-but-revegetated sites were available for reference sites, since all disturbed areas were nearly completely barren. A storm intensity with an estimated return frequency of 100 years storm for this location is 41 mm/hr for a 15 minute duration, which is approximately the same as the ambient infiltration capacity 42.5 mm/hr (Table 2), partly explaining why the slope is relatively uneroded after 20 years without cover. None-the-less, 5 to 8 cm of soil material is estimated to have been lost since construction, based on exposure of protruding rocks and stakes scattered across the surface of the slopes and from mass loss near the concrete drain structures. If true, this is equivalent to approximately xxx kg/ha/yr. Improved long-term weather data and modelling of near-surface hydrology will improve the accuracy of these estimates.

Other effects of compost incorporation were that the sediment yield per volume of runoff per meter declined by half from the ambient untilled treatment. This measurement is scaled to give a "concentration" of sediment in whatever runoff occurs. The other way to look at runoff is to give a very heavy storm 60 mm/hr) and compare sediment losses in this extreme event (> 100 year return frequency). In this case, the 24 % compost treatment produces only about 4 % of the sediment of the untilled treatment in this simulated rainfall measurement. Compost amendment improves water quality, and is beneficial to the site even though the infiltration capacity of this substrate is not inherently limiting.

Table 1. Infiltration on compost-amended plots at COL20 1.5 one year after construction. Values in the same column followed by the same letter do not significantly differ (p=0.05).

Treatment	Infiltration	Sediment Yield	15 min Sed. Yield
	mm/hr	g/mm runoff/m^2	g
Not tilled	42.5 a	2.82	15.7
Tilled	49.5 bc	1.74	0.5
12% compost	49.1 b	1.55	0.8

24% compost	53.2 bc	1.11	0.6
Native	111.4 d	0.92	0.3

Table 2. Table of return frequency storm intensities by site location (mm/hr for 15 min interval).

Return Frequency Interval (yrs)	Buckhorn SHA 299 DG	Colusa COL 20 serp	Willits MEN101 clay	Willits MEN101 sand	BlueCyn PLA 89 vol lahar
station location	**Whiskytown data**	**Clear Lake data**	**Willits data**	**Willits data**	**Blue Canyon data**
2	38	19	28	28	23
5	51	25	38	38	32
10	60	29	44	44	37
25	70	34	52	52	43
50	78	38	57	57	48
100	85	41	62	62	52

Plant growth increased greatly on the 24 % compost amendment (Table 3), nearly doubling between 12 and 24 % compost additions. Ground cover was nearly 100 % in this treatment. Greater top growth corresponded with slightly greater rooting depth, nearly three times greater root mass, and much greater evapotranspiration (ET). Increased water loss by evapotranspiration depletes soil moisture between rain events, increasing the infiltration capacity of a subsequent rain event.

Table 3. Biomass production on compost-amended plots at COL 20 1.5 one year after construction. Values in the same column followed by the same letter do not significantly differ (p = 0.05). nm = not measured; ET = evapotranspiration

Treatment	Per plant biomass (g)	Average rooting depth (m)	Root mass (g root/kg soil)*	Estimated ET (mm)
Not tilled	1.8 a	0.48	0.05 a	24.6
Tilled	1.2 a	0.61	0.08 a	26.7
12 % compost	3.9 a	0.74	0.20 a	35.5
24 % compost	8.7 b	0.80	0.58 b	84.2
Native	nm	nm	nm	56.2**

* measured 200 to 500 mm. **rooting depth of 800 mm assumed by comparison to soil profile, although grass plugs were out-competed by native vegetation.

The greater water use by plants, which facilitated greater biomass production and ground cover, is made possible by two factors. One, roots are more dense on compost treated soils, perhaps because of the calcium addition to these serpentine materials, but also because of a poorly understood enhancement effect resulting

from organic matter incorporation. Second, the compost increases the water availability to plant roots. The amended serpentine, however, does not hold more moisture at field capacity (FC) when drained after a saturating rain. The added available water in the soil at permanent wilting point (PWP) (the dryness that most crop plants wilt (-1.5 MPa, -15 bars tension)) is much lower in 12 and 24 % compost than unamended or untilled. When crop plants dry soil more thoroughly (to -5.0 MPa, -50 bars tension), the compost treated soils release and additional 27 % available water, compared to only 15 % extra on tilled but unamended treatments. The net result is the compost amendment can provide over 2.5 times more water to a growing wildlands plant than the unamended soil.

Table 4. Soil water relations of the serpentine COL 20 1.5 site. Field capacity (FC) is maximum soil water content after draining following a rain. Permanent wilting point (PWP) is conventional maximum of water use by crop plants. Evapotranspiration (ET) is plant water use to conventional dryness or to maximum dryness (right two columns).

Treatment	Field Capacity (-0.03 MPa)	Permanent wilting point (-1.5 MPa)	Plant avail water (%vol/vol)	Estimated ET dryer than PWP	Total ET (max dryness)
Not tilled	24.0 a	20.0 a	4.0 a	0.8 a	4.8 a
Tilled	22.2 a	18.2 a	4.1 a	0.6 a	4.7 a
12 % compost	16.2 a	12.2 b	4.0 a	1.5 a	5.5 a
24 % compost	21.1 a	11.8 b	9.3 b	2.5 a	11.8 b
Native	31.2 b	25.8 c	5.4 a	2.6 a	8.0 ab

The clay content of the cut face soils is quite low (Table 5). The available water content at the dry part of the release curve is attributed to some aspect of the magnesium mineralogy, although this was not evaluated as part of this project. The high infiltration rate of an unamended soil, however, is easily explained by soil physical characteristics, namely that the ability of the soil to shrink and swell (COLE; coefficient of linear expansability) is high. This function, combined with a high rock content (25 %) on the face material, makes the soil shrink away from the rock surface, making many small infiltration channels for infiltration to occur.

Table 5.

Treatment	% sand	% silt	% clay	BD	% rocks	min dens	COLE	total C %	total N %	pH	Ca:Mg ratio
Native soil											
0-8 cm	50.4	40.1	9.5	1.10	22.4	2.09	0.07	4.8	0.2	7.3	0.25
8-38 cm	28.6	50.8	20.6	1.10	22.4	2.09	0.09	1.0	0.1	7.3	0.17
Slope material											
0-30 cm	49.2	47.2	3.6	1.04	25.4	2.29	0.07	0.3	0.01	8.5	0.40
Compost	---	---	---	0.45	---	---	---	27.1	2.0	8.6	1.90

The ability of the soil to grow plants is attributed to plant available water, discussed previously, to soil nutrients (N, P, K), which were amended to sufficiency, and to the ratio of calcium to magnesium cations. Serpentine substrates are derived from ultramafic materials that have low calcium levels and high magnesium, iron and other heavy metals. The process of serpentinization (hydrothermal alteration) further reduced calcium. Adding compost the face material increases the molar ratio of calcium to magnesium from 0.40 (face material) to about 1.2 (with 24 % amendment). Compost by itself is 1.9. Amendment with compost increased grass growth by over 4.8 times for Elymus elymoides (Squirreltail) but shrub growth was much slower. Shrub survival was high, but growth may be constrained by internal stress adaptation of these plants. Planting on an amended site should mix fast growing, serpentine tolerant species like squirreltail with slower growing shrubs that will provide longer term cover and deeper root growth.

Critique

Better measurements of ambient P and N release from the compost need additional work.

Plant list

Native species were collected from around the Colusa 1.5 site and from serpentinitic areas near Indian Valley Reservoir. Other suitable plant species include *Achillea millefolium* (Yarrow), *Eriophyllum lanatum* (Wooly Sunflower), *Streptanthus drepanoides* (Sicklefruit Jewelflower), *Lotus humistratus* (Hill Lotus), *Quercus durata* ssp. *durata* (Leather Oak), *Sisyrinchium bellum* (Blue-eyed Grass), *Pinus sabiniana* (Foothill Pine), *Bromus laevipes* (Chinook Brome), *Elymus elymoides* (Squrreltail), *Melica californica* (California Melic), *Melica torreyana* (Torrey Melic), *Poa secunda* (Bluegrass), *Ceanothus jepsonii* ssp. *albiflorus* (Muskbrush), *Styrax officinalis* var. *redivivus* (Storax).

Technical pages

Table 6. Technical Tables for Case Study #2

Colusa serpentine

SRE Step	Ref site	Constructed fill slope	Compost treated	Comments
1. Site Locations				
Colusa serpentine	none (constructed site)	COL 20 1.5	COL 20 1.5	whole site was regraded, no disturbed, veg site for ref
aspect	west	west	west	
slope	2:1	2:1	2:1	
parent material	serpentine	serpentine	serpentine	
2. Slope stability				
geotechnical	stable fill	stable fill	stable fill	
erosion	none	bare, gullies, lag gravels	stable, veg'd at 2 years	installed diversion ditch the first year, no erosion after
3. Water relations				
infiltration rate (mm/hr)	42.5	42.5	53.2	
internal drainage (Ksat) (mm/hr)				
plant avail water %	8.0	4.8	11.8	to approx. -5.0 MPa
4. Organics, C, N pools				

carbon pools	near zero	near zero	loaded to 135 Mg C/ha	measure end of season 05
nitrogen pools	near zero	near zero	loaded to 7 Mg N/ha	unscreened, yardwaste compost
5. non-N nutrients				
chemical cond				measure end of season 05
macronutrients		higher Ca than native		
micronutrients	none toxic	none toxic	none toxic	
6. Soil biology				
	non-colonized	non-colonized	mycor col on grasses	no nodulation on Ceanothus, no mycor on manzanita
7. Erosion stability				
g sed per 15 min storm per m^2	15.7	0.5	0.6	60 mm/hr strom, 15 min interval
nitrogen loss				
8. Plant response				
shoot biomass g/pl	1.8	1.2	8.7	
root depth m	0.48	0.61	0.80	
root density cm/ml	0.05	0.08	0.58	

Critique

Nitrogen release rate of the coarse yard waste compost is not well known, but no N was available from this material for the first 60 days after planting. Additional work is needed to evaluate compost materials for field use so that their N release is not excessive or deficient. Additional work is also needed to identify other native species that can grow on minimally amended substrates, so that natives can be favored and weeds excluded from the site.

Recommendations:

The basic requirements for plant growth on subgrade serpentines have been identified and demonstrated. Careful attention for varying soil conditions, seasons and plant responses is still needed, but the process of revegetation on barren serpentine substrates can now be viewed as possible rather than improbable. A remaining concern is that amending the barren substrates for improved plant growth also encourages weedy invasion of the site by red brome, goatgrass, burr clover xx..xx.

Two approaches have been identified for revegetation with a strong component of weed control. First, limit soil amendments to the minimum that native plant species can tolerate and maintain adequate growth. Second, use plant combinations that allow weed control, such as planting broadleaved plants and using a grass herbicide on the site. Native species that can grow into the unamended substrate include yarrow and elymus elymoides. Field plots have demonstrated rapid spread of gilia and lotus and yarrow from seed. The response of shrubs is not known in field situations, but growth in field plots was slow and roots were not naturally inoculated. Propagation of the serpentine tolerant *Ceanothus jepsonii, Styrax officianalis,* and *Quercus durata* from seed was excellent but *Arctostaphylos viscida* did not germinate with treatment. Our recommendation for a next step in revegetating the mostly barren face at this site is to broadcast 1 - 2 cm of unscreened yard

waste compost without incorporation, and seeding of broadleaves. Control of annual grass weeds would be done by herbicide application.

Grant administrator: Jack Broadbent, HQ Landscape Architecture, Sacramento, CA, Monica Finn, District 3 Biologist, Marysville, CA. Erosion control and slope design: Salix Applied Earth Care, Redding, CA. Contractor: Soils: Soils and Revegetation Lab, University of California, Davis. Ryan O'Dell, lead botanist, Matt Curtis, lead hydrologist.

Case Study 3 Data Table

1. common name	Willits sandstone/clay
2. location code	Mend 101 38.4
3. lat long	39.4116 N long, 123.3439 W lat
4. Caltrans route	101
5. highway type	federal
6. mile marker	39
7. county	Mendocino
8. Caltrans district	3
9. geology	sandstone/clay
10. geographic region	north coast range
11. elevation	422 m (1373 feet)
12. biome	oak conifer woodland
13. construction date	2002
14. construction method	surface tillage
15.	
16.	
17. case study #	3

Photos

Figure 1. A common hydrological problem in the Coast range occurs when porous sandstones occur next to clay layers. Rainfall rapidly infiltrates and percolates in the sandstone section above the clay layer. Hydrostatic pressure increases and lubricates the lower section, which moves in a rotational failure.

Figure 2. A smaller version of a slide occurs when porous sandstones are positioned above non-permeable clays. Water saturates the pores and a translational (slide) failure occurs.

3. The same slide as in Figure 2, viewed from bottom. Note a similar failure several years old below the current, active failure.

Figure 4. Although the sandstones were extensively fractured, rooting volume was very small. To increase the rooting volume, a breaker tool was used to open the rock structure to 60 cm depth. Construction of amended soil volumes on sloped base as is shown IS NOT RECOMMENDED because of the likelihood of translational (slide) failures. This was done at this site only because a uniform rooting depth was needed for research reasons. All other times, the base of the amended soil must be flat or out-sloped at a small (2 º) angle.

Figure 5.The excavated amendment volumes showing replicated locations of compost amended (COMP), tilled but not amended (TILL) and non-tilled (NON) treatments. All treatments were replicated four times for research purposes.

Figure 6. The first year's plant growth using *Nassella pulchra* on a sandstone substrate. Refer to Figure 5 for treatment locations. No irrigation was applied at this site.

Figure 7. An overhead (raindrop) view of the ground cover generated on a compost amended treatment.

Figure 8. The first year's plant growth using Nassella pulchra on a clay substrate. Refer to Figure 5 for treatment locations.

Figure 9. Plant biomass in summer when plants are semi-dormant. Note slight green at base of leaves. Plants will green up and become active before the fall rains, functioning to reduce erosion and nutrient loss.

Figure 10. Oblique view of compost amendment plots on clay substrate, compared to the overall slope that has not be amended.

Narrative

History

This site was constructed in 1985 xxwith widening of Hwy 101 at the foot of the slope. Xx and xx were seeded on the slope following construction. Since then, only scattered annual grasses have persisted on the site. The slope is steep (2:1) and has alternating areas of dense clay and hard but fractured sandstone. These plots were located on the sandstone portion of the slope.

Treatment

In 2002, compost from the City of Redding municipal composting facility (thermophilic process followed by 90 day aerobic curing) was applied at 30 % by volume. NPK was also added in excess to compensate for unknown release rates of the compost and low ambient macronutrient levels. Native seeds were obtained from commercial sources since there were nearly no native grasses in the local area. Plugs were grown and installed onto the site in November, 2003. The plot treatments included 1) no tillage or compost (ambient conditions), 2) tillage alone to 50 cm, 3) 24 % compost tilled in to the top 50 cm.

Response

Test plots showed growth response to compost and tillage on the sandstone, but only compost application increased growth on the clay substrate, when compared to non-tilled, non-composted plots. Infiltration increased with tillage on both substrates, but the clay is expected to re-seal within a few seasons unless compost was also amended.

A sustainable vegetative cover has two components that determine adequate soil water relations, which are infiltration and plant available water. The infiltration of the compost amended clay (39.3 mm/hr) and the compost amended sandstone (51.2 mm/hr) are adequate for storms with estimated return frequencies of 5 to 10 years for the amended clay substrate, and nearly a 25 year storm for the amended sandstone (Table 2). Continued addition of organics and generation of greater soil aggregation would increase these infiltration levels higher. The infiltration determines the ability of the site to resist overland flow and surface erosion.

The second component is whether adequate moisture is stored within the soil profile to support plant growth through the late spring and summer season. If annual grasses require 30 to 40 mm of water per summer season, then adequate plant available water will be available with 224 mm (9 inches) of amended soil depth in the clay, and 746 mm (30 inches) of amended soil depth in the sandstone. Treatments were constructed to 500 mm (20 inches), plus there is at least some rooting available deeper through fractures.

If perennial grasses require at least 100 mm of water per summer season, then adequate plant available water for sustained plant growth will be available with 320 mm (12 inches) in the clay substrate and 1068 mm (42 inches) in the sandstone. Although the plots had to be jackhammered out for mixing with compost, there would be limited additional rooting through fractures in the rock. A perennial grass stand would probably become somewhat thinner on the sandstone patches than the clay, but plants would survive.

Table 2. Table of return frequency storm intensities by site location (mm/hr for 15 min interval).

Return Frequency Interval (yrs)	**Buckhorn SHA 299 DG**	**Colusa COL 20 serp**	**Willits MEN101 clay**	**Willits MEN101 sand**	**BlueCyn PLA 89 vol lahar**
station location	**Whiskytown data**	**Clear Lake data**	**Willits data**	**Willits data**	**Blue Canyon data**
2	38	19	28	28	23
5	51	25	38	38	32
10	60	29	44	44	37
25	70	34	52	52	43
50	78	38	57	57	48
100	85	41	62	62	52

Critique

Better measurements of ambient P and N release from the compost are needed. Long-term accumulation of organics in these two very different substrates (clay versus shattered sandstone) is needed to predict long-term soil development patterns.

Plant list

Native perennial grass species suitable for this site include *Elymus glaucus* (Blue wildrye), *Nassella lepida* (Foothill Needlegrass), *Nassella pulchra* (Purple Needlegrass), and *Poa secunda* (Bluegrass). Native forbs include *Achillea millefolium* (Yarrow), *Lupinus microcarpus* (Chick Lupine), *Sisyrinchium bellum* (Blue-eyed Grass), *Eschscholzia californica* (California Poppy). Woody species include *Quercus douglasii* (Blue Oak), *Quercus lobata* (Valley Oak), and perhaps Manzanita or Coyotebush.

Technical pages

Table 3. Technical Tables for Case Study #3

Willits sandstone

SRE Step	Impacted	Tilled	Treated	Comments
1. Site Locations				
Willets sandstone	MEN 101 38.4	MEN 101 38.4	MEN 38.4	sandstone substrate
aspect	west	west	west	
slope	2:1	2:1	2:1	
parent material	clay	clay	clay	
2. Slope stability				
geotechnical	2 x 5 x 0.1 m slides	stable	stable	whole site is moving as a slump onto 101

erosion	local slides and rills	none	none	tillage/amendment fixed surface erosion, slope still globally unstable
3. Soil water relations				
infiltration rate (mm/hr)	44.9	51.8	51.2	
internal drainage (Ksat) (mm/hr)				
rootable depth, m	0.0	0.5	0.5	subgrade unrootable except scattered fractures
plant avail water %	0.0	8.7	10.4	to approx. -5.0 MPa
4. Organics, C, N pools				
carbon pools	near zero	near zero	loaded to 135 Mg total C/ha	3.5 % total C using compost
nitrogen pools			loaded t0 7 Mb total M\N/ha	unscreened yardwaste compost
5. non-N nutrients				
chemical cond				
macronutrients				
micronutrients				
6. Soil biology				
7. Surface erosion stability (mulch, waterflow)				
mulch				
g sed per 15 min storm per m^2	3.15	0.18	0.15	60 mm/hr storm, 15 min interval
nitrogen loss				
8. Plant response				
shoot biomass g/pl	0.67	2.01	3.47	45% of plants flower in impacted, 97% in treated
root depth m	0.10	0.5	0.5	deeper roots very thin
root density g/kg	0.01	0.02	0.06	

Table 4. Technical Tables for Case Study #3

Willets clay

SRE Step	Impacted	Tilled	Treated	Comments
1. Site Locations				
Willets clay	MEN 101 38.4	MEN 101 38.4	MEN 38.4	clay substrate
aspect	west	west	west	
slope	2:1	2:1	2:1	
parent material	clay	clay	clay	

2. Slope stability				
geotechnical		stable	stable	
erosion	bare clay substrate with shallow sides	stable	stable	complete ground cover after first year
3. Water relations				
infiltration rate (mm/hr)	25.9	38.5	39.3	
internal drainage (Ksat) (mm/hr)				
plant avail water %	21.9	18.5	14.9	to approx. -5.0 MPa
4. Organics, C, N pools				
carbon pools			loaded to 135 Mg total C/ha	measure end of season 05
nitrogen pools			loaded to 7 Mg N/ha	unscreened yardwaste compost
5. non-N nutrients				
chemical cond				
macronutrients				
micronutrients				
6. Soil biology				
7. Erosion stability				
mulch	none	straw	straw	
g sed per 15 min storm per m^2	10.9	1.41	0.63	60 mm/hr storm, 15 min interval
nitrogen loss				
8. Plant response				
shoot biomass g/pl	2.26	3.03	12.77	80% of plants flowered in impacted 100% in treated
root depth m	0.5	0.5	0.5	deeper roots very thin
root density cm/ml	0.04	0.05	0.22	

Case Study 4 Data Table

1. common name	Blue Canyon lahar
2. location code	PLA 80 51.5
3. lat long	39.2760 N long, 120.7080 W lat
4. Caltrans route	80
5. highway type	interstate
6. mile marker	51
7. county	Placer
8. Caltrans district	3
9. geology	lahar
10. geographic region	Sierra Nevada
11. elevation	1817 m (5000 feet)
12. biome	oak conifer woodland
13. construction date	2003
14. construction method	surface tillage
15.	
16.	
17. case study #	4

Photos

Figure 1. Blue Canyon. PLA 80 51.5. A lahar is a mudflow that was formed when an ancient volcano created a debris flow of hot ash, melted ice and volcanic debris. The lahar at this site is weathered into a loose, sandy substrate that is about 150 mm deep over a non-penetratable (welded) lahar. At that depth, all plant roots are forced to grow out horizontally. Drought stress is extreme because roots cannot go deep. Woody shrubs survive because of their large root systems, but as a result, they are widely scattered across the slope. Ground covering grasses and forbs cannot get enough soil moisture to survive and are virtually absent from the site.

Figure 2. Blue Canyon. PLA 80 51.5. Deeper rooting depths were provided by breaking the lahar to 500 mm depth. Treatments included non-tilled planting areas, tilled to depth, and compost amended 24 % to 500 mm depth.

Figure 3. Blue Canyon. PLA 80 51.5. The growing season at this site is short, but some thundershowers provide supplemental moisture during the summer. Most erosion proabably occurs at snowmelt.

Figure 4. Blue Canyon. PLA 80 51.5. Because the site is bare, heat loss is great on cool winter nights. Without snow cover, ice crystals form and extend upward, pushing soil particles and plants out of the soil. This particular ice formation has 9 or 10 darker bands of soil, showing multiple nights of ice formation, bounded by layers of soil slurry where the ice partially melted during the day.

Figure 5. Blue Canyon. PLA 80 51.5. Plant growth on plots that are tilled to 500 mm to increase rooting depth, but did not receive compost amendment.

Figure 6. Blue Canyon. PLA 80 51.5. Plant growth on plots that were tilled to 500 mm and amended with 24 % (volume/volume) unscreened yardwaste compost.

Narrative

History

This site was constructed in xxx during construction or widening of Interstate 80. Xx and xx were seeded on the slope following construction. Since then, only scattered shrubs and conifers have persisted on the site. Grasses and forbs are almost non-existant due to the shallow rooting volume. The slope is relatively flat (3:1) but the underlying lahar geology is impermeable to roots and to digging by backhoe. The site has frequent rills resulting from overland flow. Infiltration is adequate, but the depth to impermeable layers are so shallow (150 mm) that the soil volume is easily saturated during rains or snowmelt. Because the surfaces are non-cohesive sands, the rills that form during runoff easily blow shut and are undetectable a few days after they form. i

Treatment

In 2002, compost from the City of Redding municipal composting facility (thermophilic process followed by 90 day aerobic curing) was applied at 30 % by volume. NPK was also added in excess to compensate for unknown release rates of the compost and low ambient macronutrient levels. Native seeds were obtained from nearby plant communities (Yuba Gap). Plugs were grown and installed onto the site in November, 2003. The plot treatments included 1) no tillage or compost (ambient conditions), 2) tillage alone to 50 cm, 3) 24 % compost tilled in to the top 50 cm.

Response

Plant growth increased by over ten times greater than the untilled control even when fertilizers were added to the control plants. Water is the main limiting factor at this site, and that is controlled by the shallow rooting depth. Mechanical tillage is recommended to increase rooting volume.

Table 2. Table of return frequency storm intensities by site location (mm/hr for 15 min interval).

Return Frequency Interval (yrs)	Buckhorn SHA 299 DG	Colusa COL 20 serp	Willits MEN101 clay	Willits MEN101 sand	BlueCyn PLA 89 vol lahar
station location	**Whiskytown data**	**Clear Lake data**	**Willits data**	**Willits data**	**Blue Canyon data**
2	38	19	28	28	23
5	51	25	38	38	32
10	60	29	44	44	37
25	70	34	52	52	43
50	78	38	27	57	48
100	85	41	62	62	52

Critique

Better measurements of ambient P and N release from the compost are needed. Long-term accumulation of organics on this ground up lahar is unknown. The weathering rate of shattered lahar is unknown, but will be critical for soil development, especially water relations and nutrient availability.

Plant list

Native perennial grass species suitable for this site include *Elymus multisetus* (Big Squirreltail), *Bromus carinatus* (California Brome). Native forbs include *Achillea millefolium* (Yarrow), *Eriophyllum lanatum* (Common Woolly Sunflower). Woody species include *Chrysolepsis sempervirens* (Bush Chinquapin), *Abies concolor* (White Fir), *Pinus jeffreyi* (Jeffrey Pine), *Ceanothus cordulatus* (Mountain Whitethorn), *Rhamnus rubra* (Sierra Coffeeberry), *Prunus emarginata* (Bitter Cherry).

Technical pages

Table 3. Technical Tables for Case Study #4

Blue Canyon lahar

SRE Step	Impacted	Tilled	Treated	Comments
1. Site Locations				
Blue Canyon	PLA 80 51.5	PLA 80 51.5	PLA 80 51.5	lahar
aspect	west	west	west	
slope				
parent material	lahar	lahar	lahar	lahar is a welded mudflow
2. Slope stability				
geotechnical	solid, imperm lahar	tilled to 500 mm	24 % compost to 500 mm	

erosion	common rills to 100 mm depth	none	none	overland flow from upslope; shallow imperm layer on slope
3. Soil water relations				
infiltration rate (mm/hr)				
internal drainage (Ksat) (mm/hr)				
rootable depth	100 mm	500 mm	500 mm	imperm at 150 mm unless tilled
plant avail water %	17.3	26.9	22.1	to approx. -5.0 MPa
4. Organics, C, N pools				
carbon pools	near zero	near zero	loaded to 135 Mg total C/ha	unscreened yardwaste compost
nitrogen pools	near zero	near zero	loaded to 7 Mg total N/ha	unscreened yardwaste compost
5. non-N nutrients				
chemical cond		sufficient	sufficient	
macronutrients		sufficient	sufficient	measure summer 05
micronutrients				measure summer 05
6. Soil biology				
7. Surface erosion stability (mulch, waterflow)				
mulch	coarse soil	straw	straw	
g sed per 15 min storm per m^2				
nitrogen loss				
8. Plant response				
shoot biomass g/pl	0.34	0.49	3.68	
root depth (m)	0.15	500 mm	500 mm	
root density (g/kg)	0.00	0.02	0.16	average of top 500 mm

Application Examples

1. Earthwork

If you are looking for a quick example of a generic specification for a disturbed site, the following is provided, but with no assurance that it is appropriate for your specific site. The three keys start after this example specification.

Tentative soil treatment/amendment specification (not reviewed by Caltrans):

Example performance specification:
Substrate or soil on the site shall be treated to be porous enough to infiltrate a 20 year return frequency storm and shall not develop translational or rotational failures when saturated. Total N content in the soil shall be amended until the top 300 mm has 2000 XXXkg total N/ha distributed evenly throughout the top 300 mm using using coarse, unscreened yard waste compost with a maximum nitrogen content of 1.5 %. Extractable nitrogen shall be less than 40 kg N/ha the first year. Slopes with impermeable underlying geology shall be treated to provide 1 m rooting depth. Soils shall receive appropriate fertilizers if P is less than 5 ppm, K is less than 1 % of cation exchange capacity, S is less than 5 ppm (water extract), and pH is more acid than 5 or more alkaline than 8. Slope surfaces shall be ripped on contour if shallower than 3:1 (H:V) or track-walked when dry if steeper. The completed slope shall be made resistant to rain drop impact and surface water flow by using standard erosion control methods.

Example of typical harsh site treatment:
A typical harsh site treatment would include spreading 5 cm thick layer of coarse, unscreened yard-waste compost on the surface and ripping on contour to 30 cm. This provides adequate total N and non-N nutrients, as well as carbon for soil aggregation, if plant cover is also regenerated. Composts that are not well cured may need supplemental N amendment from small fertilizer amounts. Impermeable underlying geology will need fracturing or bench-fill ("fill-cut") treatment to achieve adequate rooting depth. Mycorrhizal inocula are useful in limited circumstances on substrates having no previous plant growth.

top of page

2. Erosion control fabrics

top of page

3. Geotextiles

top of page

4. Inoculation

top of page

5. Mulches

top of page

6. Site Analysis Forms

top of page

7. Soil Amendments

top of page

8. Soil Sampling and Testing

top of page

Soil Resource Evaluation and Treatment
Name_____

Evaluation quiz

1. Drastic disturbance is:
    a. tillage of the surface
    b. toxic salt accumulation
    c. removal of topsoil and all biological activity
    d. compaction of the surface

2. What is the function of the disturbed-but-revegetated reference site?
    a. provide example of ecological succession
    b. provide plant source for seed collection
    c. document success of revegetation activities
    d. provide model of soil conditions that support revegetation

3. Name the two main soil components that most strongly determine plant growth on most drastically disturbed sites.
    a. mycorrhizae and micronutrients
    b. water availability and slow release nitrogen
    c. P, K, Ca, Mg, S fertility
    d. temporary erosion control

4. Too much water percolating into the slope causes what problem?
    a. slope liquification and failure
    b. chronic erosion, low plant cover
    c. low nutrient levels
    d. compaction

5. Too much water shedding off the slope causes what problem?
    a. slope liquification and failure
    b. chronic erosion, low plant cover
    c. low nutrient levels
    d. compaction

5. Soil water relations are characterized by what two soil processes?
    a. nitrogen mineralization and leaching
    b. evapotranspiration and leaching
    c. infiltration and water holding capacity
    d. soil compaction and salt accumulation

6. Infiltration is water flow into the surface, while percolation is water flow:
    a. between mulch particles under the plant
    b. into a caffeinated organic solution
    c. deeper in the soil profile
    d. out of seeps at the foot of the slope

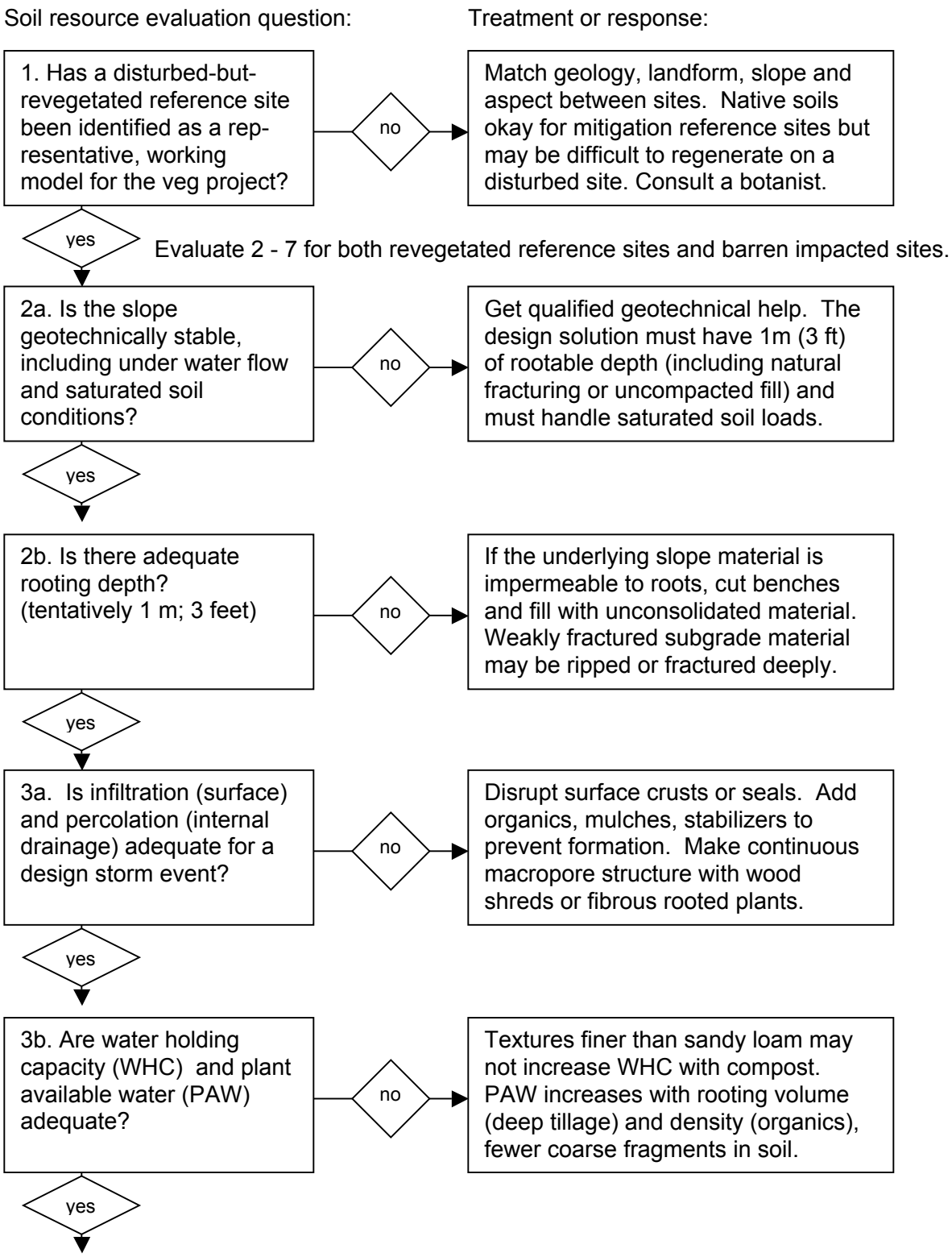
7. How is a soil's "plant available water" measured?
    a. yearly precipitation
    b. all the water from saturation to wilting point

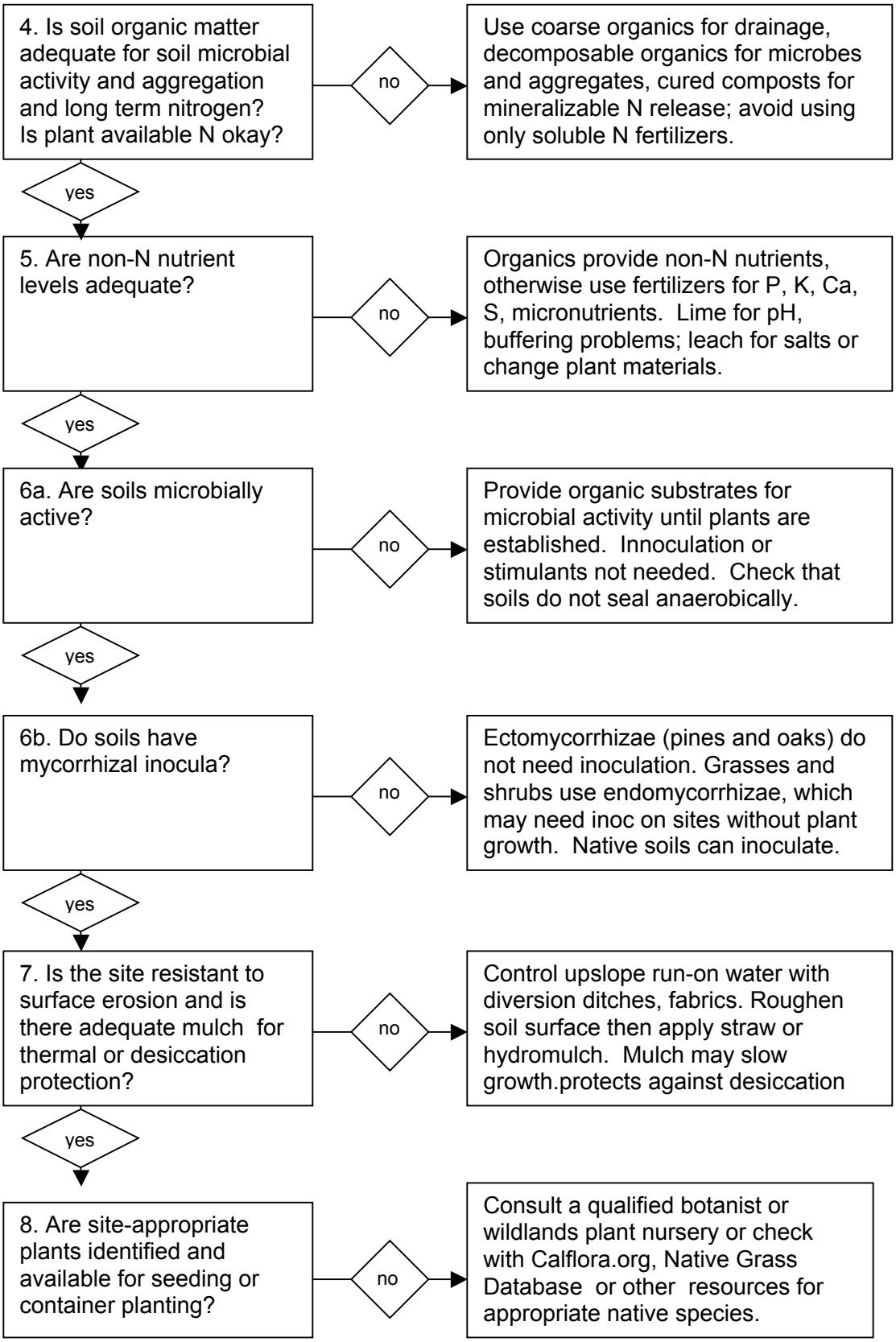
c. all the water from field capacity to wilting point
d. the water left at wilting point

8. Name three conceptual pools of nitrogen in soils.
a. total, mineralizable, extractable
b. fertilizer, nutrient and mineral
c. carbonate, nitrate, filtrate
d. extractable, atmospheric, organic

9. What test measures the amount of cation nutrients that could be held in a soil?
a. anion exchange capacity
b. cation exchange capacity
c. field capacity
d. organic matter index

10. Mulch cover can reduce erosion, but it can also:
a. increase sediment loss
b. slow plant growth in cool spring weather
c. slow plant growth by retaining summer heat
d. slow plant growth by nutrient toxicity


Soil resource evaluation question:
Treatment or response:
1. Has a disturbed-but-revegetated reference site been identified as a representative, working model for the veg project?
no
Match geology, landform, slope and aspect between sites. Native soils okay for mitigation reference sites but may be difficult to regenerate on a disturbed site. Consult a botanist.
yes
Evaluate 2 - 7 for both revegetated reference sites and barren impacted sites.
2a. Is the slope geotechnically stable, including under water flow and saturated soil conditions?
no
Get qualified geotechnical help. The design solution must have 1m (3 ft) of rootable depth (including natural fracturing or uncompacted fill) and must handle saturated soil loads.
yes
2b. Is there adequate rooting depth? (tentatively 1 m; 3 feet)
no
If the underlying slope material is impermeable to roots, cut benches and fill with unconsolidated material. Weakly fractured subgrade material may be ripped or fractured deeply.
yes
3a. Is infiltration (surface) and percolation (internal drainage) adequate for a design storm event?
no
Disrupt surface crusts or seals. Add organics, mulches, stabilizers to prevent formation. Make continuous macropore structure with wood shreds or fibrous rooted plants.
yes
3b. Are water holding capacity (WHC) and plant available water (PAW) adequate?
no
Textures finer than sandy loam may not increase WHC with compost. PAW increases with rooting volume (deep tillage) and density (organics), fewer coarse fragments in soil.
yes


4. Is soil organic matter adequate for soil microbial activity and aggregation and long term nitrogen? Is plant available N okay?
no
Use coarse organics for drainage, decomposable organics for microbes and aggregates, cured composts for mineralizable N release; avoid using only soluble N fertilizers.
yes
5. Are non-N nutrient levels adequate?
no
Organics provide non-N nutrients, otherwise use fertilizers for P, K, Ca, S, micronutrients. Lime for pH, buffering problems; leach for salts or change plant materials.
yes
6a. Are soils microbially active?
no
Provide organic substrates for microbial activity until plants are established. Innoculation or stimulants not needed. Check that soils do not seal anaerobically.
yes
6b. Do soils have mycorrhizal inocula?
no
Ectomycorrhizae (pines and oaks) do not need inoculation. Grasses and shrubs use endomycorrhizae, which may need inoc on sites without plant growth. Native soils can inoculate.
yes
7. Is the site resistant to surface erosion and is there adequate mulch for thermal or desiccation protection?
no
Control upslope run-on water with diversion ditches, fabrics. Roughen soil surface then apply straw or hydromulch. Mulch may slow growth.protects against desiccation
yes
8. Are site-appropriate plants identified and available for seeding or container planting?
no
Consult a qualified botanist or wildlands plant nursery or check with Calflora.org, Native Grass Database or other resources for appropriate native species.

Soil Resource Evaluation and Treatment: Tabular Key Data Sheet

SREdata sheetc.doc

Name:_____

Site:_____

SRE Step 1. Reference site selection. Has a disturbed-but-revegetated reference site been identified as a representative, working model for the reveg project?
OBJECTIVES:
The reference site should 1) provide an example of a local site with an acceptable vegetation community and 2) give a working example of the soil conditions needed to support this type of vegetation.

1. Geology: (circle)
- a. intrusive (granitic) / extrusive (volcanic ash, lahar)
- b. sedimentary / serpentine / sands / moraine / clay

2. Landscape position (circle)
- a. erosional: hilltop / ridgeline / planar slope / concave slope / convex slope
- b. depositional: footslope, floodplain, sediment basin, stream scour zone
- c. slope angle:_____ aspect:_____

3. Acceptable plant cover, plant types or species: (circle)
- a. trees / shrubs / perennial grass / perennial forb / annual grass / annual forb
- b. dominant species_____
- c. % cover by species_____

SRE step 2. Evaluate slope stability Is the slope geotechnically stable, including under water flow and saturated soil conditions?

OBJECTIVES:
The slope must 1) be geotechnically stable to prevent mass failures and safety hazards at the site and 2) the geotechnical design of the site must provide adequate rooting depth for growth of vegetative cover, which protects against chronic surface erosion.

1. Geotechnical stability
- a. rotational failures or translational slides? yes / no depth_____
- b. geological layers inclined toward road or escarpment Yes / No
- c. textural discontinuities (fines over sand or gravel lens) Yes / No

2. Erosional stability
- a. on-slope drainage / interceptor ditches ?_____
- b. foot-slope demarcation to avoid undercutting_____

3. Rooting depth
- a. rooting depth observed (pit, roadcut, excavation)_____
- b. fractured underlying parent material Yes / No
- c. uncompacted fill over impermeable geological layers Yes / No

SRE step 3. Evaluate soil infiltration capacity and plant available water.

OBJECTIVES:

The site must have 1) a high enough [infiltration rate] to avoid overland flow and surface erosion and 2) it must provide enough [plant available water] (PAW) in the rooting profile to support adequate plant growth.

1. Soil infiltration rate limitations (observation)

- **a.** signs of overland flow on surface Yes / No
- b. duff layer Yes / No depth, fiber type, rafting _____
- c. % area of bare soil_____
- d. soil dispersion crust (brittle) describe_____
- e. slurry seal (powdery when dry)? describe_____
- f. subsurface compacted layer depth, thickness_____
- g. describe root growth patterns, compaction layer appearance
- h. soil aggregation? size_____

2. Soil infiltration rate limitations (measured) (mm/hr)

- a. design storm event target infiltration rate_____
- b. site infiltration rates_____
- c. percolation limit? _____
- d. depth to compacted layer? _____

3. Plant available water (observation)

- a. plants widely spaced, with shallow root systems?_____
- b. shallow rooting depth?_____
- c. coarse soil texture (coarser than loamy sand)_____

4. Plant available water (measured)(mm)

- a. plant water use target _____
- b. plant available water (PAW)_____
- c. suitable plant type

SRE step 4. Evaluate soil organic matter (SOM) and carbon and nitrogen pools.

OBJECTIVES:

The site must provide adequate soil organic matter (SOM) for three main functions:
1) [infiltration] is provided by pores along coarse organic fragments, as outlined in Step 3;
2) microbial activity and [soil aggregation] is provided by decomposable carbon; and
3) [nitrogen] (N) for plant growth and community development is provided by organic matter decomposition.

1. Soil organic carbon (C) pools (observation)

- a. coarse organic matter coverage % of soil surface_____
- b. evidence for overland flow (bare soil, rafted twigs/needles/wood, terraces?
- c. litter and duff layer_____
- d. does substrate have the “soil” smell?

2. Soil organic carbon (C) pools (measurement)

- a. stabilized (humified) carbon levels adequate? (± 2 %?) _____
  (from total C lab analysis)
- b. total carbon content in top 150 mm (> 10 Mg/ha D15)_____
  (= mg/kg total C x 2 x (1- fraction rock content))

3. Soil nitrogen (N) pool (observation)

a. nitrogen deficiency symptoms_____

4. Soil nitrogen (N) pools (measurement)

a. extractable nitrogen (N) levels (< 5 ppm)_____

b. mineralizable nitrogen (N) levels (± 30 to 70 kg N/ha)_____

c. stabilized (long-term, humified) nitrogen (N) levels_____

(= mg total N/kg x 2 x (1 - fraction rock content)) (>1500 kg total N/ha)

d. mineralizable N (from total N)_____

(=1 % of total N (kg/ha))

<u>SRE step 5. Evaluate non-N nutrient availability.</u>

OBJECTIVES:

The site must provide adequate 1) soil chemical conditions and 2) plant nutrient availability to support revegetation on the site.

1. Soil chemical conditions (commercial soil fertility test)

a. soil pH (5 to 8) _____

b. soil salinity (EC) < 2 dS/m (unless plants are salt tolerant) _____

c. soil cation exchange capacity (CEC) (> 10 cmol/kg soil)_____

2. Soil nutrient availability

a. Extractable phosphorus (P) _____

(> 10 ug/g (weak Bray extract in acid soils) or > 5 ug/g (bicarbonate extract in neutral or alkaline soils))

b. extractable cations (soil analysis results must be greater than the target level)

c. soil test data (ug/g): K _____; Ca _____; Mg_____; Na_____

d. extractable SO_4-S (> 3 ug/g)_____

e. extractable micronutrients (greater than those listed on Table 6)

Soil test data: Zn_____; Mn_____; Fe_____; Cu_____; B_____; Mo_____

<u>SRE step 6. Evaluate soil biology activity.</u>

OBJECTIVES:

The site must support adequate biological activity for nutrient decomposition and cycling, nutrient uptake and to generate soil aggregation.

1. Soil microbiological activity

a. evidence that microbial decomposition occurs (litter, duff)_____

b. endomycorrhizal colonization _____

(grass, forb and shrub roots or evidence of previous vegetative cover)

c. nodules on N-fixing species_____

d. other biological activity (ants, burrows, grazing, shelter)_____

SRE step 7. Evaluate site surface stabilization (erosion control).

OBJECTIVES:

The site must be adequately stable against surface erosion and desiccation that plants can germinate, grow and cover the site before erosion resumes.

1. Surface erosion control

a. standard erosion control method specification_____

b. surface erosion resistant mulch type _____

c. surface water drainage control_____

2. Thermal protection

a. mulch thickness_____

b. mulch type_____

SRE step 8. Special plant materials needs for non-typical sites.

OBJECTIVES:

Plants must be able to grow on the site after the impacted substrates are regenerated to levels of the vegetated reference site.

1. Site-specific restrictions on plant materials or source

a. endemic plants species or local ecotypes at reference site

_____

b. unique soil conditions that restrict plant, inoculum options

_____