KEEPING DIRT IN ITS PLACE:
RUNOFF, SEDIMENT LOSS, AND
COST EFFECTIVENESS OF THREE
EROSION CONTROL PRACTICES ON STEEP SLOPES.

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By

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ABSTRACT

Keeping Dirt in its Place: Runoff, sediment loss, and cost effectiveness of three erosion control practices on steep slopes.

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Erosion is a natural process that occurs when soil particles are detached from one site and transported to another by water or wind, and can occur naturally or be accelerated by humans. Sediment can cause direct mortality or reduce growth of fish and other aquatic resources, particularly larval fish and eggs. Three treatments consisting of compost and jute netting, crimped straw with native seeds, and jute netting and vegetation filter strip were used to evaluate loss of runoff water and sediment on steep slopes. Erosion plots were built on slopes of 27 percent and filled with soil. The treatments were applied in triplicate and irrigated at 14-day intervals. Each erosion plot was irrigated with approximately 79 gallons of water for 10 hours and runoff was collected in pre-weighed containers during each period. After each collection, runoff from each plot was measured and recorded by subtracting the weight of each empty container from the combined weight of water and sediment. Turbidity, pH, and electrical conductivity were measured, and the separate weights of runoff and dry sediment were determined. The combination of jute netting over a layer of commercially available compost was over 99 percent

effective at reducing runoff and sediment loss as compared to the untreated control erosion plots. Jute netting combined with a vegetative filter strip of creeping wild rye was over 94 percent and 99 percent effective at reducing runoff and sediment loss when compared to the untreated control erosion plots, respectively. Runoff and sediment loss from plots treated with crimped straw and native seeds was significantly greater than that of the other treatments, yet this treatment was over still 80 percent effective at reducing runoff and nearly 97 percent effective at reducing sediment loss. The cost-effectiveness of each treatment was evaluated based on the cost of the total treatment compared to the amount of water each treatment prevented from leaving the site, using the control plots as a baseline. The combination of jute and vegetation filter strip cost approximately \$0.47 per liter of water prevented from leaving the site and was almost as effective at reducing runoff and sediment loss as was jute combined with compost, which cost \$1.04 per liter. While each of the three treatments significantly reduced runoff and sediment loss when compared to the barren control plots, the jute and filter strip treatment was the most cost-effective of the three treatments. All treatments were effective at decreasing runoff and sediment loss when compared to the control, though no significant difference in runoff was observed between the control and any of the treatments after ten weeks. Thus, erosion control BMPs should be implemented well before the first storm causing runoff in order to be most effective.

Keywords: Sediment, erosion control, runoff, sediment yield, cost-effectiveness, filter strip.

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INTRODUCTION

Geologic erosion is a natural process that occurs when soil particles are detached from one site and transported to another by water or wind. Sedimentation occurs when those particles are no longer transported and are deposited in a specific location, such as a pool or other area of slow-moving water. Geologic erosion and sedimentation can be beneficial processes. As rocks and soil degrade into smaller particles, they are transported by streams and rivers. Larger sediment such as cobbles and gravels provide spawning habitat for commercially important fish such as salmon and steelhead, as well as substrate for benthic macroinvertebrates that contribute to decomposition of organic material as well as provide prey for larger species. Smaller sediment particles degrade until reaching oceans, where they are deposited and form the thousands of miles of beaches that line the world's continents and help protect coastlines from the never-ending assault of ocean waves.

However, in many cases erosion is neither natural nor beneficial. Accelerated erosion occurs when humans disturb the soil or the natural vegetation for purposes such as grading, timber harvest, or construction. During the past half century, human land use and associated activities have degraded some 5 billion hectares (about 43%) of earth's vegetated land (Brady and Weil, 2004). Sediment from geologic erosion tends to be coarser and contains more gravel, while accelerated erosion tends to affect more soil surface and generates finer, more potentially damaging sediment (Hallock, personal communication, 2009).

Sediment can severely and adversely impact fish and other aquatic resources. In 1964, the European Inland Fisheries Advisory Committee determined there are five ways that excessive sediment amounts can harm fisheries (DFO, 2000). These include causing direct mortality or reducing growth rates or resistance to diseases and pathogens; preventing development of eggs and larvae; modifying natural movements and migration of fish; reducing the abundance of food available to fish; and even affecting the efficiency of methods for catching fish. Sediment, particularly fine sediment which is defined as sediment particles 0.85 mm (0.03in) or less in size, can directly affect fish by covering nests and suffocating eggs and juveniles (Kondolf, 2000), preventing emergence of fry (Everest et al., 1987), preventing sight-oriented fish from feeding (Phillips, 1971; Ward, 1992), and even eroding fragile gill filaments causing death (Phillips, 1971). Mortality among salmonid egg and fry increases sharply when the percentage of silt and sand less than 3 mm (0.12 in) exceeds 20 percent in redds (AFS, 2008). Indirect effects include sediment filling interstices between gravel and suffocating benthic macroinvertebrates upon which many fish feed (AFS, 2008; Everest et al., 1987) and accumulating in pools and reducing water depth. It is even possible that subtle chronic sedimentation can tip the ecological balance in favor of one species in mixed salmonid populations or in communities composed of salmonids and non-salmonids (Everest et al., 1987).

Sediment is such a severe problem that the United States Environmental Protection Agency (USEPA) has identified sediment as the most serious non-point source of

pollution in waters of the United States, and states that sediment is one of the most widespread pollutants affecting rivers and streams (Faucette et al., 2005) and is second only to bacterial pathogens (USEPA, 2000). When eroded sediment is transported from its site of origin to nearby surface waters, it also carries with it fertilizers, pesticides, petroleum products, and other contaminants and environmentally-damaging substances (Faucette et al. 2005). Sediment can also have major and potentially catastrophic commercial effects. For example, in the early 1900s, ocean-going vessels could travel 25 miles up Oregon's Coquille River. Today, however, people can wade across the river at that same point in midsummer (AFS, 2008). On California's Carmel River, the San Clemente Dam was completed in 1921 and had a storage capacity of 1,425 acre-feet (1,757 megaliters) of water at the spillway. Today, sediment accumulation has reduced the reservoir's usable capacity to less than 66 acre-feet (81 megaliters) (Hampson, personal communication, 2009).

In the United States, erosion at construction sites is a major concern. Erosion rates from construction sites can be as much as 40,000 times greater than rates of undisturbed soil (Raskin et al., 2005). Erosion on construction sites is usually the result of raindrop impact and sheet flow (Fifield, 2007). Sediment runoff rates from construction sites are typically 10 to 20 times greater than those of agricultural lands and 1,000 to 2,000 times greater than those of forest lands (Faucette et al., 2006; USEPA, 2000). Regulatory agencies require implementation of erosion and sediment control measures on construction sites. These measures, known as Best Management Practices (BMPs), are often incorporated into storm water pollution prevention plans. While BMPs are best

implemented throughout the construction process, many contractors do not implement BMPs until the end of the construction season or sometimes during winter months.

Early season storms can destroy some BMPs and render them useless in erosion and sediment control programs. Some commonly used BMPs include covering barren soil with loose straw and holding the straw in place using tackifying agents or by crimping with heavy equipment; covering soil with mulches, compost, or hydroseeding; or retaining or planting vegetation on site.

Failure to implement or maintain BMPs can be extremely costly. For example, in late 2003, a contractor working in California's Central Coast region did not implement adequate measures to control erosion and contain sediment on site. A mid-October storm caused sediment to flow into a stream containing southern steelhead (*Oncorhynchus mykiss irideus*) and California red-legged frogs (*Rana aurora draytonii*). The California Central Coast Regional Water Quality Control Board (RWQCB) subsequently penalized the contractor with an administrative civil liability fine of \$300,000, in addition to requiring site stabilization and restoration measures and removing sediment that left the site. The USEPA can also assess penalties for illegal discharges of polluted storm water, with penalties ranging from \$50,000 per day and up to two years imprisonment for negligent violations, to \$250,000 per day and 15 years imprisonment for violations that could result in death or serious bodily injury (Fifield, 2007). The RWQCB can impose administrative civil penalties of up to \$10,000 per day plus \$10 per gallon of sediment-laden runoff water for each violation, and fines of up to \$25,000 per day can be imposed by the Superior Court (RWQCB, 1999).

In California's Central Coast Region, the "construction season" typically extends from April 15 to October 31. Construction activities often result in soils being stripped of vegetation and topsoil and surfaces being covered with impermeable concrete and asphalt. New home sites are often left with yards consisting of exposed and unprotected soils. Road construction often results in slopes being steeply inclined, highly compacted, and lacking topsoil. In forested areas, road construction can increase the frequency of slope failures from several to hundreds of times that of undisturbed areas, depending on soil type, slope steepness, and other variables (Furniss et al., 1991). These practices can expose soil and increase the risk of erosion and sediment deposition within waterways.

Statement of Problem

The purpose of this study was to emulate late application of BMPs on steep slopes and evaluate several commonly used practices to determine those practices that are most effective in terms of reducing erosion and sediment runoff; contribute the least to changes in turbidity, pH, and conductivity of runoff water; and are most cost-effective in terms of reducing erosion and sediment runoff.

METHODS

This study project was conducted near the California Department of Transportation's (CalTrans) Erosion Research Facility on California State Polytechnic University, San Luis Obispo. The site was located on a southwest-facing slope consisting of imported fill material surrounded by a gravel parking area, horse corrals, and horse training paddocks. Vegetation at the site consisted primarily of invasive plants such as fennel (*Foeniculum vulgare*), yellow star thistle (*Centaurea solstitialis*), and other ruderal species. The area receives a mean annual rainfall of 23.5 inches (59.6 cm), with December through March being the wettest period. The mean annual temperature ranges from a high of 71.4°F (21.9°C) to a low of 47.4°F (8.6°C), with July through October being the warmest months and December through March being the coolest (WRCC, 2008).

In Spring 2007, the project site was cleared of vegetation. Twelve erosion plots measuring 16 feet (4.9 m) long, 5 feet (1.5 m) wide, and 8 inches (0.2 m) deep were constructed using untreated Douglas fir boards and placed on the site (Figure 1). The erosion plots were paired and separated by a distance of two feet, with pairs spaced 5 feet (1.5 m) apart, and located on an approximate 26 percent slope and staked in place. An irrigation system was installed so each pair of erosion plots was controlled by one valve. Four rotating heads were used to irrigate each pair of erosion plots, with the heads located 24 inches (0.6 m) from the corner and 18 inches (0.5 m) above the surface of each erosion plot.

Treatment 1: Layer of compost $\frac{3}{4}$ inch deep, covered with jute netting
 Treatment 2: Crimped straw spread at 1,500 pounds per acre and seeded with native grass and forb seeds
 Treatment 3: Lower 25% vegetated filter strip, upper 75% covered with jute netting
 Control: Barren untreated soil

Figure 1. Layout of plots and treatments.

All erosion plots were filled to within 2 inches (5 cm) of the top using soil imported from a nearby construction site (State Route 46, CalTrans post mile 31, in San Luis Obispo County). The soil was characterized as a loam consisting of sand, silt, and clay at 48, 28, and 24 percent, respectively (Stubler, personal communication, 2009). Soil between and around each erosion plot was then covered with a layer of compost approximately 4 to 6 inches (10.2 to 15.2 cm) deep to reduce vegetation growth that could interfere with treatments. When necessary, vegetation around the erosion plots was controlled using string trimmers or a commercially available glyphosphate-based herbicide.

In Spring 2009, collection trays were placed at the downhill end of each erosion plot to collect runoff water that did not infiltrate into the soil. The collection trays were powder coated to reduce friction and oxidation that could interfere with collecting runoff. The trays were covered to prevent overspray irrigation from being collected. The irrigation system was tested to ensure uniform coverage within 75 percent over individual erosion plots. To determine the amount of irrigation water actually applied to each erosion plot and not lost as overspray, black plastic sheets were installed over each erosion plot.

Irrigation was applied for 3 minute periods and runoff from the plastic was collected in containers. This procedure was performed three times and the mean volume of water per minute of irrigation was calculated to determine the rate of water being applied to each erosion plot in gallons per hour (gph), which was approximately 0.155 gph (0.59 l/hr). After measuring the rate of water being applied to each erosion plot, the black plastic sheets were removed.

Treatments

Three treatments were assigned to the erosion plots using random numbers in a random block treatment so that each treatment and the control were repeated in triplicate. Several factors were considered in selecting the treatments in this study. Two BMPs per erosion plot were selected. Combinations of BMPs protect from raindrops and can prevent or reduce overland flow. Additionally, treatments such as vegetation filter strips both provide erosion and sediment control, while treatments such as jute and compost or straw and vegetation provide erosion control. At least one erosion control BMP was used as part of each treatment. The BMPs were also selected because they are readily available to the public and can be obtained from many local sources. The BMPs were relatively inexpensive to purchase and easy to install. All selected treatments were considered to be generally accepted erosion and sediment control practices by the California Regional Water Quality Control Board (RWQCB, 1999).

Best management practices that were considered but eliminated from this study include hydromulching, tackifiers, and treatments that are strictly intended to reduce sedimentation. Hydromulching and tackifiers (such as wood fiber and guar gum) are expensive and can inhibit vegetation establishment. Other BMPs that control only sedimentation such as fiber rolls and retention basins or ponds were not feasible for the project. This study primarily tested erosion control, as effective erosion control measures usually result in good sediment control, but not vice versa (Fifield, 2007). All treatments

were applied to cover the entire surface of each erosion plot. Vegetation was allowed to grow and cover the erosion plot throughout the study.

Treatment 1: Compost and Jute Netting

A layer of compost was spread over these erosion plots and leveled to create a uniform depth of approximately 0.75 inches (1.9 cm). The compost was then covered with 1-inch (2.5 cm) square jute netting, held in place with metal landscape staples. The compost was a commercially available brand made from composted forest humus, redwood, composted chicken manure, worm casings, kelp meal, bat guano, and gypsum, with oyster and dolomite lime for pH adjustment. Compost was selected because past CalTrans studies at Cal Ply showed it to be effective in controlling erosion and sediment runoff (Hallock, personal communication, 2009) and is readily available at commercial locations. The compost was not compacted and any compaction that occurred was incidental and due to the leveling process. Loose-weave jute netting was then installed over the erosion plots per Fifield (2007). Metal landscaping staples were applied to hold the jute in place. Jute netting was used due to its low cost and biodegradable nature, and because the loose weave which helps reduce entrapping and harming reptiles (Barton and Kinkead, 2006) and enhances seedling emergence.

Treatment 2: Crimped Straw and Seed

In these erosion plots, loose straw with minimum fiber length of 6 inches (15 cm) (Fifield, 2007) was spread at a rate of 1,500 pounds (680 kg) per acre. The straw was crimped into the soil using a garden spade to simulate tracked equipment moving up and down slope. Crimped straw was selected because it is an accepted best management practice by the California Regional Water Quality Control Board (RWQCB, 1999) and other entities and due to its relatively low cost and ease of application. After installation, these erosion plots were seeded with a mixture of native seeds including California brome (*Bromus carinatus*), golden yarrow (*Eriophyllum confertiflorum*), and Spanish lotus (*Lotus purshianus*). The seeds were applied at a rate of 25, 1, and 2 pounds (11.3, 0.4, and 0.9 kg) per acre for California brome, common yarrow, and Spanish lotus, respectively (Curto, personal communication, 2009). Approximately four weeks prior to conducting the study, the seeds were hand broadcasted across the soil to emulate seeds falling from plants under natural conditions.

California brome is a cool season perennial bunchgrass that establishes rapidly and has good soil stabilizing capabilities. Because its roots are fibrous, grow very quickly, and become deep and widespread, it is useful for erosion control in disturbed areas including roadsides (USDA, 2004). It establishes rapidly and can be used on slopes due to its drought tolerance, and has shown to be effective in improving water infiltration. It is also an important forage species for species such as elk, bear, waterfowl, rodents, and upland birds. Golden yarrow is a perennial shrub native to California's coast and inland

mountains. It grows to approximately 1 to 2 feet (0.3 to 0.6 m) in height and is often found on dry slopes and washes in coastal sage scrub and chaparral (USDA, 2001). Spanish lotus is an annual herb native to California and reaches a height of up to approximately 20 inches (0.5 m). California brome, golden yarrow, and Spanish lotus are commonly used in seed mixes for soil stabilization (CalTrans, 2009).

Treatment 3: Vegetation Filter Strip and Jute

A vegetation filter strip of creeping wild rye (*Leymus triticoides*) was established on the downhill 25 percent of these erosion plots. Creeping wild rye was selected for the filter strip vegetation because it is a perennial grass native to coastal California. It is common to stream banks, moist meadows, and areas subject to flooding. Creeping wild rye can grow in dense stands and to a height of 4 feet (1.2 m) (CDFG, 2002). Several features make this plant desirable for streambank protection and erosion control. It spreads by rhizomes, and its fibrous root system binds soil and assists with erosion control. When inundated during high flows, the stems lay flat along the soil surface but recover quickly when flows recede. As stems and leaves die, they form a dense layer of duff that covers and further protects soil, thereby offering excellent erosion control protection.

Creeping wild rye was harvested from an existing stand along Chorro Creek. At this location, the plants were observed to be approximately 3 to 4 inches (8 to 10 cm) apart and in dense stands. Harvested clumps of plants were separated into plugs. Approximately 200 to 225 plugs were planted at intervals of 3 to 4 inches (8 to 10 cm)

throughout the lower quarter of the erosion plot to emulate the stand at Chorro flats, with plants staggered from row to row. Immediately upon transplanting, the plants were treated with a commercial root stimulant to minimize transplant shock and encourage growth. One week later, plants were trimmed to a height of approximately 10 to 12 inches (25 to 30 cm) and trimmings were removed from the erosion plots. Jute netting was then spread over the upper 75 percent of the erosion plot, installed per Fifield (2007) and held in place using metal landscape staples.

Control Erosion Plots

No BMPs were applied to three control erosion plots throughout the study. These erosion plots were leveled to form a uniform surface approximately 1.5 inches (4 cm) from the top of the erosion plots. Any accumulated leaves, litter, or vegetation growing on these erosion plots during the study was allowed to remain on the erosion plots.

Data Collection and Sample Analysis

Lengths of PVC pipe were placed immediately below the collection trays to channel all runoff water to individual containers. Each erosion plot was then irrigated continually for ten hours and runoff was collected in the containers. At approximately 0.16 gph (0.59l/hr), approximately 79 gallons (299 liters) of water was applied to each erosion plot during the ten hour period, which is comparable to a rate of 1.55 inches (3.9 cm) of rain during that period. After each period, runoff from each erosion plot was measured and

recorded by subtracting the weight of each empty container from the combined weight of water and sediment. Electrical conductivity (EC), pH, and turbidity (NTU) were measured. Data was collected at 15-day intervals over 96 days for a total of 8 trials.

Turbidity

Turbidity was measured using a Hach 2100P turbidimeter. Each collection container was stirred vigorously for at least 30 seconds using a clean PVC pipe. A sample was obtained by dipping a glass vial into the swirling water. After capping it, the vial was rinsed in deionized water, dried, shaken, and inserted into the turbidimeter to obtain a measurement of turbidity in NTUs. If the sample was unreadable due to excessive turbidity (more than 1,000 NTUs) it was diluted to a 10 percent solution and reinserted in the turbidimeter, then the final turbidity value was determined by multiplying the resulting value by 10. This process was repeated three times to determine the mean NTU value for each collection.

Electrical Conductivity and pH

Electrical conductivity and pH were determined using an Xplorer GLX PS-2002 electronic sensor. Prior to each use, the sensor was calibrated using pH solutions of 4.0 and 7.0. The pH and conductivity probes were then suspended in each sample until the pH or conductivity values stabilized and the corresponding values were recorded.

Determination of Runoff

Runoff was collected in pre-weighed 5-gallon (18.9 l) plastic buckets. The buckets were then reweighed, and the weight of the container was subtracted to obtain the total weight of water and sediment in the samples. After determining the dry weight of sediment as described below, the dry weight of sediment was subtracted from the weight of water and sediment together to obtain the net weight of water collected in each sample.

Dry Weight of Sediment

After collecting TDS, EC, and NTU data, each container was treated with 40 ml of 45 g⁻¹ calcium chloride (CaCl₂) flocculent. The flocculent was added after water within the containers was stirred vigorously with a clean PVC pipe. After allowing a minimum of 48 hours for sediment to fall out of suspension, as much clear water was siphoned from the containers as possible without disturbing the sediment. All remaining water and sediment were transferred to a plastic Nalgene bottle. If necessary, deionized water was used to remove all sediment from the containers. Also if necessary, 20 ml of flocculent was added to the Nalgene bottles to further drop sediment out of solution and allow additional water to be siphoned from the sample. The weight of sediment was determined by drying the Nalgene bottles in an oven for 24 hours at 103 °C (217°F) to remove any remaining moisture and subtracting the tare weight of the Nalgene bottle.

Prior to each instance of collecting data, each PVC pipe and bucket was thoroughly rinsed and dried to reduce the chance of collection extraneous sediment that could bias

the data. Runoff and sediment data was collected within 7 days of the initial installation of each treatment, and again at 14-day intervals for a total of 105 days.

Cost-Effectiveness Evaluation

The cost-effectiveness of each treatment was based on the cost of the treatment compared to the number of liters of runoff water that treatment prevented from leaving the erosion plot. The amount of runoff from the control erosion plots was used as a baseline, and the amount of water leaving the treated sites was subtracted from the baseline to determine the reduction in runoff water from that treatment. The cost of applying each treatment to the erosion plots was then divided by the corresponding reduction in runoff water for that treatment to arrive at a cost for each unit of runoff water that was prevented from leaving the erosion plot.

Statistical Analysis

A repeated measures analysis was conducted to determine any relationships or differences between the amount of runoff water, sediment yield, turbidity, conductivity, and/or pH from the control and treated erosion plots. Analysis of variance (ANOVA) was conducted for this project using Minitab 15. In all cases, the probability of a Type 1 error α (rejecting the null hypothesis when the null hypothesis is true) was assumed at the 5 percent level ($P \leq 0.05$). The null hypotheses in these ANOVAs were that there was no

difference in the amount of runoff water, sediment yield, turbidity, conductivity, and/or pH between the control erosion plots and any of the treatments.

Uncontrollable Factors

Several uncontrollable factors may have influenced the results of this study. The erosion plots were located outside where wind could not be controlled. All erosion plots were irrigated simultaneously for 10 consecutive hours. However, wind speeds during the collection periods varied from nearly nil to gusts exceeding 30 mph (48 km/h). This could have influenced the rate of water striking the soil, the antecedent soil moisture content, or the rate of evaporation from the soil surface.

Rodents were a constant nuisance, particularly California ground squirrels (*Spermophilus beecheyi*) which burrowed into the erosion plots and left large holes in the soil surface. In such cases, the holes were filled with large rocks and soil packed around the rocks to prevent runoff from entering the holes and biasing data. Blacktail deer (*Odocoileus hemionus*) frequently visited the erosion plots, walked over the erosion plots, ate vegetation, disturbed the ground surface, and on two occasions dislodged part of the jute netting on erosion plots containing compost. In these cases, the netting was left as found because the compost continued to provide cover. Other wildlife observed at the site included gray fox (*Urocyon cinereoargenteus*), raccoon (*Procyon lotor*), and feral cats, all of which traveled over one or more erosion plots. No efforts were made to control or remove rodents, deer, or other wildlife at the site.

RESULTS

Analysis of variance indicated that runoff water and dry sediment were significantly ($P \leq 0.05$) affected by the various treatments when compared to the control erosion plot.

Runoff and Dry Sediment Yield

The greatest runoff occurred from the untreated control erosion plots. During the first five collection periods which covered ten weeks, runoff from the control erosion plots was greater than runoff from treated erosion plots. Runoff from Treatment 2 was generally higher than runoff from the other treatments, but this difference was not significant with one exception. In period 2, runoff from Treatment 2 was significantly greater than that of the other two treatments. Mean runoff for each treatment and period is shown in Table 1.

Table 1. Mean runoff (grams) for each treatment and control by period.

Treatment	Period							
	1	2	3	4	5	6	7	8
1	47.0	294	0	16	0	11	0	0
2	1,476	7,612	4,813	512	5,943	1,238	710	1,887
3	1,651	2,623	358	98	639	53	27	1,282
Control	31,632	20,124	14,418	19,802	28,916	4,274	3,708	1,337

Treatment 1 (compost and jute netting) yielded the least runoff during the study. Runoff from this treatment was observed only 16.7 percent of the time, and no runoff was ever

recorded from one erosion plot with this treatment. Treatments 2 and 3 resulted in runoff occurring on 50 percent and 83.3 percent of the collection dates, respectively. The control erosion plots saw runoff over 95 percent of the time. Despite these apparent differences in effectiveness, there was no significant difference in the amount of runoff water between any of the three treatments (Figure 1).

Figure 2. Mean runoff water (grams) of each treatment by period.

Dry sediment yield from the control erosion plots averaged 516.4 g (18.2 oz) on the first collection period, and this was significantly greater than the average yield from treated erosion plots, ranging from 0.2 g (0.01 oz) for Treatment 1 to 12.9 g (0.46 oz) for Treatment 2 (Figure 4). However, the differences between the control and treated erosion plots were not significant during the rest of the study. On those occasions upon which

runoff did not occur, no sediment yield occurred either. Mean dry sediment yield for each treatment and period is shown in Table 2.

Table 2. Mean dry sediment yield (grams) for each treatment and control by period.

Treatment	Period							
	1	2	3	4	5	6	7	8
1	0.2	2.1	0.0	1.1	0.0	0.0	0.0	0.0
2	12.9	3.6	1.2	0.7	2.8	0.1	0.7	1.8
3	1.9	0.8	0.6	0.0	0.1	0.1	0.7	0.6
Control	516.4	89.3	116.6	20.9	20.2	1.2	1.9	0.8

Figure 3. Mean dry sediment yield (grams) of each treatment by period.

The mean total sediment loss throughout the study for each treatment was compared with the mean total sediment loss for the control erosion plots. The mean amount of runoff

leaving each of the treated erosion control plots over the life of the study was compared to the mean amount of runoff leaving the control erosion plots during the study. The difference in runoff from each treatment was then compared to the mean amount of runoff from the control erosion plots to determine the percent effectiveness of each treatment.

Table 3. Effectiveness of treatments in reducing runoff and sediment loss from each treatment as compared to the control erosion plots.

Treatment	Mean Runoff (percent of control)	Reduction in Runoff (percent)	Mean Sediment Loss (percent of control)	Reduction in Sediment Loss (Percent)
Control	100.0	0.0	100.0	0.00
1	0.3	99.7	0.4	99.6
2	19.5	80.5	3.1	96.9
3	5.4	84.6	0.6	99.4

Treatment 1 prevented 99.7 percent of runoff and 99.6 percent of sediment from leaving the erosion plots as compared to the control erosion plots. Treatment 3 prevented 94.6 percent of runoff and 99.4 percent of sediment from leaving the treated erosion plots.

Treatment 1 was least effective in reducing runoff and sediment loss, but still prevented 80.5 percent of runoff and 96.9 percent of sediment from leaving the treated erosion plots when compared to the control erosion plots.

Turbidity, Conductivity, and pH

Values for turbidity, conductivity, and pH were obtained from sample runoff water, but no runoff was collected in 37 of the 96 samples (41.7 percent). While reliable statistical analyses for these parameters could not be obtained, some trends were observed. For example, the mean turbidity from all collection dates was greatest in runoff from the untreated control erosion plots (1,524 ntu). This was over four times greater than mean turbidity from erosion plots with Treatment 2 (378 ntu), nearly ten times that of Treatment 3 (155 ntu), and 38 times greater than turbidity from Treatment 1 (40 ntu) (Table 4).

Table 4. Mean turbidity (NTUs) for each treatment and control by period.

Treatment	Period							
	1	2	3	4	5	6	7	8
1	51	16	---	60	---	33	---	---
2	2,576	315	171	128	312	3	54	22
3	574	129	189	20	8	18	186	9
Control	5,754	2,484	871	1,018	1,113	215	200	41

The highest levels of turbidity were recorded during the first collection period for each treatment and relatively constant during each of the remaining periods. Slight differences were observed in turbidity among the treated erosion plots from the first period, and there was little difference among treatments afterward. For the control erosion plots, turbidity was high during the first period, dropped during the next two periods, remained relatively constant during the next three periods, and then dropped again for the last three periods.

While turbidity was consistently highest for the control erosion plots throughout the study, there was little difference among any treatments after the second period (Figure 4).

Figure 4. Mean turbidity (NTUs) of each treatment by period.

Conductivity was consistently lowest in the control erosion plots, followed by Treatments 2, 3, and 1 (Table 5). Conductivity was greatest in runoff from Treatment 1 although values were obtained on only three of the eight sampling dates for this treatment due to lack of runoff water from these erosion plots during much of the study.

Table 5. Mean conductivity (ms/m) for each treatment and control by period.

Treatment	Period							
	1	2	3	4	5	6	7	8
1	435	3,652	---	---	---	1,087	---	---
2	403	919	415	---	447	728	1,003	1,403
3	457	1,919	508	---	610	1,022	1,772	818
Control	428	597	407	---	449	670	731	701

Figure 5. Mean conductivity of each treatment by period.

While the pH of runoff water fluctuated throughout the sampling period, the fluctuations were consistent among treatments. The pH of runoff from the control erosion plots as well as Treatments 2 and 3 generally followed similar trends, as pH for all three treatments increased or decreased simultaneously from period to period. The pH for

Treatment 1 remained relatively static over time, but this was based on only four observations and does not necessarily reflect a valid trend (Figure 6).

Table 6. Mean pH for each treatment and control by period.

Treatment	Period							
	1	2	3	4	5	6	7	8
1	7.4	7.9	---	8.1	---	8.1	---	---
2	7.1	8.8	8.9	8.2	9.0	7.8	8.1	8.0
3	6.9	9.2	8.8	8.0	9.3	8.0	8.3	7.9
Control	7.3	8.1	8.9	7.4	9.2	8.1	8.3	8.0

Figure 6. Mean pH from each treatment by period.

DISCUSSION

Without the protection of vegetation or mulch, bare soils exhibit accelerated erosion losses due to exposure to the erosive energy of raindrops (Grace, 2002). Each of the three treatments used in this study consistently performed better than the control at preventing runoff water and sediment from leaving the erosion plots. In terms of reducing runoff and sediment loss, Treatment 1 (compost and jute netting) was most effective, followed by Treatments 3 (jute netting and vegetation filter strip) and 2 (crimped straw and seeds), respectively. Runoff water and sediment was collected in 23 of the 24 repetitions from the control erosion plots. However, in only four repetitions did runoff water leave erosion plots with Treatment 1, as a total of 141 g (5 oz) of water and less than 1 g (0.03 oz) of dry sediment left these erosion plots throughout the study.

Jute netting reduces erosion and sediment loss in two ways. First, the netting provides a physical barrier protecting barren soil from the erosive force of raindrops. When rain strikes the jute, the kinetic energy of the drop is reduced by the jute and the drop is broken into smaller, less erosive particles. Second, once the rain reaches soil, the jute traps the water in place and prevents it from passing downhill, thereby reducing the water's erosiveness and allowing it to be stored and absorbed into the soil. Compost provides similar beneficial effects. It has a high water storage capacity and slowly releases the water, allowing it to absorb into soil (CalTrans, 2008).

When used concurrently, jute netting and compost are highly effective at controlling erosion. In this study, erosion plots treated with this combination of BMPs were over 99 percent effective at reducing runoff water and sediment loss when compared to bare soil. In a similar study, runoff and sediment loss from jute netting over a 0.5 inch (1.3 cm) layer of compost was 99 percent less than that from bare soil (CalTrans, 2008).

However, compost may not be suited for some situations. Compost often contains high levels of nitrogen, phosphorus, or other nutrients. Materials high in nutrients are likely to contribute nutrients to waterways during storm events. The transport of nutrients is usually highest during the first storm event that produces overland flow. Even though nitrogen and phosphorus loading is greatly diminished after the first storm event, these nutrients may accelerate eutrophication of water bodies and contribute to growth of aquatic vegetation and algae (Faucette et al. 2006). When such organic matter decays, bacteria consume oxygen and produce carbon dioxide during the decomposition process, reducing the amount of available oxygen and resulting in mortality to fish and other aquatic organisms. Thus, other erosion control methods should be considered when working near waterways. For example, when used by itself, jute netting can reduce sediment loss by 70 to 90 percent for six months and up to 40 to 60 percent for up to two years, as well as reduce nutrient loss by 50 to 70 percent for six months and 20 to 50 percent for up to two years when compared to unprotected soil (Idaho DEQ, 2005).

The combination of jute netting and a vegetation filter strip (Treatment 3) was also effective at reducing runoff and sediment loss, as water and sediment were collected in

only 12 and 10 of the 24 repetitions, respectively. This combination was approximately 95 percent effective at controlling runoff water and over 99 percent effective at containing sediment on site when compared to the unprotected control erosion plots.

Because jute netting reduces soil detachment and transport by slowing the velocity, and thus erosiveness, of runoff water, it is primarily used to control erosion. Vegetation filter strips provide both erosion and sediment control. As flows pass through the filter strip, flow velocity decreases and large suspended particles such as sands and silts settle within a short distance, while finer particles are carried the farthest and could remain suspended if runoff velocity remains high (Fifield, 2007; Wu et al., 2003.). By themselves, vegetation filter strips have proven to be effective at removing sediment from runoff. The roots of plants in the filter strip also provide preferential flow pathways by forming spatial voids, allowing water and sediment to flow into the soil, particularly in the case of plants with extensive or prolific root systems (Wu et al., 2003).

Filter strips work well in upland areas with mild slopes, preventing formation of large rills in soil (Choi et al., 2005). Coyne et al. (1995) observed that vegetation filter strips on a 9 percent slope under simulated rainfall removed 88 percent of surface runoff and 99 percent of sediment, using a mixture of tall fescue (*Festuca arundinacea* L.) and Kentucky bluegrass (*Poa pratensis* L.) sod. Hayes et al. (1984) found vegetation filter strips to remove 94 to 98 percent of sediment. Reductions of more than 98 percent of sediment were observed in grass filters below surface mines following natural rainfall (Albrecht and Barfield, 1981). However, vegetation filter strips are not without

limitation. Filter strips are most effective at trapping sand and silt-size particles, but not as effective at capturing clays (Albrecht and Barfield, 1981). Additionally, the efficiency of sediment trapping may decrease over time (Albrecht and Barfield, 1981; Magette et al. 1989) though this is not always the case (Robinson et al. 1996). Filter strips appear to be most effective at lower flow rates and may not be suitable in areas of high flow (Abu-Zreig et al. 2003). Another concern is the interaction between vegetative species used in filter strips and potential impacts of adjacent vegetation. Tall fescue (*Lolium arundinaceum*) was found to reduce growth and survival of native tree species including sycamore (*Platanus occidentalis*) and to slow plant succession from grassland to forest, as endophytes in tall fescue can alter soil biota and suppress growth of trees (Rudgers and Orr, 2009). Other species, such as eucalyptus, emit allelopathic chemicals that can also retard or prevent growth of other species, which suggests that freshly chipped eucalyptus should not be used for mulch when vegetative growth is desired. Native plant species should be used in filter strips when feasible.

Treatment 2 (crimped straw and seeds) was least effective at reducing runoff and sediment loss, with runoff and sediment being collected on 20 and 19 of the 24 repetitions, respectively. Still, this treatment was over 80 percent effective at reducing runoff and approximately 97 percent effective at reducing sediment loss from these erosion plots.

Crimped straw is commonly used to stabilize disturbed sites and can be a permanent or temporary site stabilization practice. When used properly, loose straw is spread over the

soil surface and then pushed into the soil by means of tracked equipment such as dozers or a sheepfoot wheel. Pushing the straw into the soil holds the straw in place and prevents it from being blown away by wind, allows the straw to intercept and reduce the kinetic energy of raindrops, and interrupts the flow of water over the soil surface. Long straw mulches with fiber lengths of 4 to 8 inches (10 to 20 cm) are the most effective because they provide the best interlocking and surface coverage (Gray and Sotir, 1996; Fifield, 2007). By itself, straw that is punched or crimped in soil can reduce erosion by 10 percent (Fifield, 2007). Crimped straw can reduce runoff, increase infiltration, reduce sediment loss over time, moderate soil temperature by shading soil, protect against splash erosion, and contribute organic matter as the straw decomposes (Gray and Sotir, 1996). However, crimping the straw also disturbs the soil surface which can lead to increased soil loss (Hallock et al. 2006).

All three treatments used in this study were effective in reducing runoff water from the test erosion plots, as runoff water from the control erosion plots was greatest during the first five periods and significantly higher than runoff from the treated erosion plots. However, after the fifth period, runoff dropped and was not different from the treated erosion plots. Sediment loss from the control erosion plots was greatest following the first period, and declined substantially thereafter. Additionally, turbidity levels were greatest in runoff from the control erosion plots, followed in decreasing order by Treatments 2, 3, and 1. The steep reduction in runoff following the fifth period could be due in part to lack of significant precipitation afterward. The site received over 3 inches (7.62 cm) of rain in the week prior to the first period, followed by 1.34 inches (3.40 cm),

0.68 inches (1.73 cm), 0.18 inches (0.46 cm), and 0.25 (0.64 cm) inches during the two weeks prior to the second, third, fourth, and fifth periods, respectively (Weather Underground, 2009). However, during the last three periods of the study, the site received only 0.14 inches (0.04 cm) of rain in total, with very little runoff occurring during these periods. The higher runoff up to and including the fifth period was possibly a function of antecedent moisture in the erosion plots, and may not have been entirely due to the percent of cover or type of treatments being used.

On the surface, some treatments appeared superior at reducing runoff and sediment loss than others. However, no statistically significant difference was observed between treatments. After the third period, sediment loss from the control sites was comparable to that of the treated sites, and nearly identical during the last three periods. These results suggest the greatest loss of sediment from disturbed sites – and thus the most potentially damaging losses to fish and other aquatic resources – occurs with the first few precipitation events that produce overland flow following soil disturbance.

Soil cover such as mulch or crimped straw can reduce rainfall impact and runoff velocities and increase infiltration, while vegetation can also help retain soil particles attached to roots and trap sediment among shoots (Fifield, 2007). In this study, the greatest coverage was obtained using Treatment 1. Coverage was less using Treatment 3, while coverage for Treatments 1 and 3 were greater than coverage afforded by Treatment 2. However, during the second half of the study, coverage on the erosion plots with Treatment 2 actually decreased over time until the study ended. This corresponded with

an increase in cover on the control erosion plots due to germination of seeds that ended up on the barren soil until, at the seventh and eight periods, no statistical difference existed in coverage between the control and Treatment 2.

The difference in cover between Treatment 1 and Treatment 2 was not significant until the last half of the study. Throughout the study, Treatment 1 afforded 100 percent coverage. After the fourth period, however, coverage from Treatment 2 declined until a statistically significant difference existed between these treatments. While the reasons for this difference are unclear, it is likely that some straw became dislodged by wind and blown off the erosion plots, while some may have been consumed by wildlife. Also, the study was conducted during the late winter and early spring, and some straw might have been removed from the erosion plots and used by nesting birds or rodents. Despite the reduction in percent cover two months after the study initiated, the reduction in sediment and runoff from the control erosion plots after the fifth period suggests that the greatest benefit of BMPs to reducing erosion and sediment loss occurs during the first few precipitation events following soil disturbance.

The addition of erosion and sediment control BMPs prior to the first precipitation can significantly reduce sediment loss from disturbed sites. Appropriate BMPs reduce raindrop erosion, slow overland flow velocity, and allow water to infiltrate into the soil, thereby reducing runoff and sediment loss. If implementation of BMPs is delayed until after the first storm, much of the benefits from those practices may be lost. For example, the loss of soil and runoff from the Treatment 2 and the control erosion plots was not

different after two months of study, despite the actual reduction of cover in Treatment 2. This further supports the need for implementing BMPs prior to precipitation in order to minimize runoff and sediment loss from disturbed sites. This also suggests that if BMPs are not implemented until after the first few storms, then measures such as crimped straw might not be as beneficial as other treatments that provide greater amounts of cover on the site.

In addition to the treatments, a factor that likely contributed to reduced runoff and sediment loss on the erosion plots was vegetation that became established in erosion plots during the study. In addition to the seed species selected for the Treatment 2, other plants appeared in the erosion plots as time passed. These species occurred in all treatment erosion plots and were identified at the end of data collection, and included coast fiddleneck (*Amsinckia menziesii*), bentgrass (*Agrostis* spp), bristly oxtongue (*Picris echioides*), burclover (*Medicago polymorpha*), Bermuda grass (*Cynodon dactylon*), cheese weed (*Malva parviflora*), cudweed (*Pseudognaphalium* spp), dove weed (*Croton setigerus*), dwarf nettle (*Urtica urens*), fennel (*Foeniculum* spp), foxtail (*Hordeum jubatum*), Indian tobacco (*Nicotiana quadrivalvis*), Italian ryegrass (*Lolium perenne* L. ssp. *multif*), mustard (*Brassica* spp), pigweed (*Amaranthus* spp), rabbitfoot's grass (*Polypogon* spp), ripgut brome (*Bromus diandrus*), sweet clover (*Melilotus* spp), wild oat (*Avena fatua*), wild rye (*Leymus* spp), and yellow star-thistle (*Centaurea solstitialis*). Because no non-treatment species were deliberately added to the erosion plots, it is presumed that seeds from these species were transported to and deposited at the site by wind or animals, or were present in the soil when it was imported to the site.

Data for turbidity, conductivity and pH could not be obtained in nearly 42 percent of the repetitions due to lack of runoff leaving the test erosion plots. While statistical analyses for these parameters could not be conducted, some interesting but unsurprising trends were observed. Turbidity was lowest in those erosion plots treated with jute netting and compost. This may have been at least partly due to the lack of runoff leaving erosion plots with this treatment. Turbidity was highest in the untreated control erosion plots throughout the study. In the first period, turbidity from Treatment 2 (crimped straw and seeds) was greater than that of the other two treatments; however, from period 2 on, turbidity levels were largely similar for all treatments throughout the remainder of the study. From period 6 on, turbidity levels for the control erosion plots was nearly the same as turbidity in the treated erosion plots. These trends further suggest that BMPs should be implemented before precipitation to be most effective at reducing runoff, sediment loss, and turbidity.

Turbidity is an expression of the optical property that causes light to be scattered and absorbed by particles rather than being transmitted through water in straight lines through a water sample, and is caused by suspended material or impurities that interfere with the clarity of the water (USEPA, 1999). Turbidity has been shown to be harmful to fish and other aquatic life. This is particularly true for sight-oriented fish such as salmonids, which rely primarily on sight for obtaining food. Because suspended particles deflect light rather than allowing it to pass directly through water, light cannot penetrate as deeply in the water column of turbid water as it can in clearer water. As a result, photosynthesis is limited to the upper reaches of the water column and plant production

cannot occur in deeper areas. This can reduce the availability of food such as phytoplankton to planktivorous prey species such as threadfin shad (*Dorosoma petenense*) or commercially and recreationally important species such kokanee salmon (*O. nerka*).

Conductivity, which is a measure of salinity, was consistently lowest in the control erosion plots, followed in increasing levels by Treatment 2 (crimped straw and seeds), 3 (jute netting and vegetation filter strip), and 1 (compost and jute netting). Conductivity was greatest in erosion plots with Treatment 1, though values were obtained on only three of the eight sampling dates. It is likely that chemicals in the compost contributed to the higher conductivity, and thus greater salinity, of runoff from this treatment. This suggests that use of compost may be suitable in many areas but may not be appropriate in areas with aquatic species that may be sensitive to changes in salinity.

While runoff water pH fluctuated throughout the sampling period, insufficient data was obtained and it is not possible to determine why pH values fluctuated wildly during the study. Irrigation water used in this study came from nearby Indonesian Reservoir, which could be affected by factors such as decaying organic matter, nutrients, or upstream mining activities within the watershed. Nonetheless, it is worth noting that the pH values obtained in this study ranged from 6.8 to 9.6. Most of these values are within the pH range of 6.0 to 9.0 found in most inland waters (Cole, 1994). Of the eight pH values obtained that exceeded 9.0, half came from the untreated control erosion plots, which suggests that the BMPs used in this study may afford some buffering of pH values. In

future studies, ambient water quality measurements should be taken immediately prior to each data collection to determine if changes in such parameters are related to treatments or instead related to uncontrolled influences of the water source. Further research may be needed to determine if the treatments selected for this study may influence pH or conductivity.

Potential Impact of Sediment on Salmonids

The term “salmonids” includes all Pacific salmon, trout, and char. While spawning periods vary from species to species, salmonids construct their nests (redd) in the same general manner. After pairing, the male and female select a suitable location in the stream. This may be the center of a moderately deep “run” in the case of Chinook salmon (*O. tshawytscha*) or the shallow tail of a pool in the case of steelhead. The fish turn on one side and beat their tail vigorously for a few seconds. This creates a depression in the gravel and flushes accumulated sediment from the depression. After the eggs are laid and fertilized in the depression, a second depression is created in the gravel immediately upstream from the first. Gravel from the upstream depression forms a mound that covers the eggs.

The structure of a salmonid redd is a marvel of engineering. The upstream depression and downstream mound create a vortex effect in which water flowing downstream is guided into the depression. As water flows through the eggs, it provides life-giving oxygen while flushing out metabolic waste. The eggs and alevins are relatively safe from

predators while entrenched in gravel. Upon hatching, the alevins survive in the gravel for approximately two weeks. The alevins then force their way upward through the gravel and emerge into the water column, where they remain and grow until, in the case of anadromous fish, migrating to sea.

Sediment can adversely effect salmonid redds in many ways. Interstitial sediments finer than about 1 mm reduce the permeability of gravel and can prevent intragravel flow from providing sufficient oxygen to embryos or removing waste products (Kondolf, 2000). As a result, mortality of eggs and larvae occurs due to asphyxiation or toxicity. Successful emergence requires connected pore spaces within the gravel through which the alevins can pass. Accumulated sediments, particularly fines, can create a “pavement” that fills spaces between pores and prevents emergence. Alevins that cannot migrate upward and emerge are doomed to perish in the gravel. Thus, successful incubation and emergence is critically dependent on gravel relatively free of fine sediment.

Suspended sediment also adversely affects juvenile and adult fish. This is particularly true when fish are exposed to elevated levels of suspended sediment for long periods. In a literature review regarding the effect of suspended sediment on fisheries, Newcombe and Jensen (1996) reported that mortality of Chinook salmon smolts reached 50 percent when exposed to 488 mg/l suspended sediment for 96 hours, while non-salmonids such as striped bass (*Morone saxatilis*) larvae experienced 42 and 50 percent mortality when exposed to 500 mg/l TSS for 72 hours and 485 mg/l for 24 hours, respectively. Bluegill (*Lepomis macrochirus*) showed reduced capacity to locate prey at concentrations as low

as 15 mg/l TSS for 1 hour. Sediment can also affect fish by suffocating prey, particularly benthic macroinvertebrates found among stream cobble and gravel (Everest, et al., 1987).

The treatments used in this study proved effective at reducing runoff and sediment and would likely be effective for use adjacent to salmonid streams. This is particularly true of the Treatment 1, as it prevented 99 percent of runoff and sediment from leaving the erosion plots.

Reduction of Pollutants Using BMPs

Bioaccumulation is buildup within an organism of specific compounds, usually heavy metals or pesticides, due to biological process (Brady and Weil, 2004). Biomagnification can be described as the process by which the concentration of a pollutant or contaminant increases as that pollutant moves to higher levels of the food chain. Many heavy metals and pollutants can accumulate in soil and bioaccumulate or biomagnify in aquatic life.

Most heavy metals carry positive electrical charges. Sediments, and in particular clays, carry negative polar charges (Hallock, personal communication, 2009). As a result, heavy metals such as lead, copper, chromium, mercury, or iron are attracted to and bind with clay sediment. As soil erodes, sediment is detached and transported down slopes where it frequently enters waterways. Organophosphate pesticides such as malathion and chlorinated hydrocarbons such as dichloro-diphenal trichloroethane (DDT) can also bind with sediment and are transported by erosion or runoff into waterways, as can

polychlorinated biphenyls (PCBs) (MacDonald, 1980). By themselves, these pollutants can have direct adverse effects on both aquatic and terrestrial species. PCBs are known carcinogens, and DDT has been linked to causing weakened eggshells and reduced egg survival in many avian species. Malathion is a cholinesterase inhibitor, killing by interfering with transport of nerve impulses, and it has been shown to have a wide range of toxicities in fish, aquatic invertebrates, and aquatic stages of amphibians (NPIC, 2001). The 96-hour LC_{50} is defined as the lethal concentration of a substance at which 50 percent of test subjects have died after being exposed to the substance for 96 hours. The EC_{50} concentration is the concentration of a substance that provokes a response half way between the minimum and maximum responses. In brown trout (*Salmo trutta*) and cutthroat trout (*O. clarkii*) exposed to malathion, the 96-hour LC_{50} levels are 0.1 mg/L and 0.28 mg/L, respectively. Various aquatic invertebrates are extremely sensitive, with EC_{50} at values from 1 ug/L to 1 mg/L (NPIC, 2001).

In addition to reducing runoff and sedimentation, filter strips can also filter out heavy metals, many of which are toxic to aquatic life in low concentrations or can accumulate in tissue and move up the food chain due to predation (Andrews et al., 1988; Van Hassel et al., 1980). Most heavy metals carry positive electrical charges while most clays carry negative charges (Hallock, personal communication 2009). As a result, the metals adsorb to clays and can be transported by runoff. Heavy metals such as lead, zinc, nickel, and cadmium are common along heavily traveled roadways, from sources such as lead in gasoline, nickel from diesel fuel and lubricating oils, and zinc and cadmium from tires (Van Hassel et al., 1980), while copper is commonly used in pesticides (Wu et al., 2003).

A significant correlation was shown to exist between traffic density and lead concentration in benthic insects in streams, and between traffic density and lead, zinc, cadmium, and nickel concentrations in fish (Van Hassel et al., 1980).

In a study to determine the effectiveness of filter strips at reducing transport of copper, tall fescue and switchgrass proved 100 percent effective at reducing sediment loss and transport of copper-based pesticides at flows of 0.7 gpm (2.6 l/m), and 60 percent effective at flows of 1.6 gpm (6.1 l/m) (Wu et al., 2003). Grassed buffer strips of 6, 12, and 18 meters (20, 39, and 59 feet) in length reduced runoff volume from 43 to 99.9 percent while reducing loss of suspended solids transported in runoff by 87 to 100 percent (Laurent et al., 1997). Even relatively short vegetation filter strips have also been shown to reduce concentrations and mass transport of nutrients found in cattle manure runoff, particularly phosphorus (Lim et al., 1998). This may be due to most of the sediment being deposited at the upslope side of the filter strip (Van Dijk et al., 1995). Removal of phosphorus is significant, because it can adsorb to suspended solids, adsorb to surface soil and vegetation, be assimilated by microorganisms and plants, infiltrate down into the soil profile, or move downslope with runoff (Abu-Zreig et al., 2003).

Vegetation filter strips trapped 99 percent of soil from erosion strips but only 74 percent of fecal coliforms under the same conditions (Coyne et al., 1995). Young et al. (1980) found that filter strips on a 4 percent slope trapped 70 percent of fecal coliforms. The lower retention of coliforms by filter strips may be due to the small size (0.04 – 0.08 in or

0.1 to 0.2 cm) of fecal bacteria, allowing the bacteria to behave much like clay size particles in terms of solution transport (Coyne et al., 1995).

Even relatively small buffer strips can provide effective water quality protection.

Rupprecht et al. (2009) found that buffer strips as narrow as 10 to 15 feet (3.0 to 4.6 m) can provide significant benefit for removing nutrients and pesticides from runoff. Wider buffer strips (minimum 50 feet or 15.2 m) were found to remove heavy metals including lead and copper, hydrocarbons, bacteria, and suspended solids, and provide streambank stability as well as erosion and water temperature control.

While many BMPs are available for filtering sediment and pollutants out of runoff, it is nonetheless more effective to prevent erosion from occurring in the first place. Once erosion has occurred it is extremely difficult to remove the soil suspended in runoff (RWQCB, 1999). Therefore, emphasis should be placed on preventing erosion rather than controlling sediment, and the primary protection on a site should be erosion control with sediment controls implemented as a secondary measure (RWQCB, 1999).

Cost-Effectiveness of Treatments

As has been shown, some BMPs are more effective at reducing runoff or sediment loss than others. In this study, Treatment 1 was found to be most effective BMP at reducing runoff and sediment loss, followed by Treatments 3 and 2, respectively. However, the

cost of BMPs can substantially vary, and the effectiveness of any BMP must be weighed against the cost of implementing that BMP.

For purposes of this study, BMP effectiveness was determined by the amount of runoff water that was prevented from leaving the erosion plots subtracted from the amount that left the control erosion plots. Runoff was used instead of sediment loss because when runoff is prevented, sediment cannot be carried offsite in the runoff. The mean amount of runoff lost from the control erosion plots was 15.5 liters of water. The mean amount of runoff from Treatments 1, 3, and 2 was 0.05 liters (0.01 gal), 0.84 liters (0.22 gal), and 3.02 liters (0.80 gal) respectively. Thus, the mean amount of water prevented from leaving the erosion plots was 15.48 liters (4.1 gal), 14.68 liters (3.9 gal), and 12.50 liters (3.3 gal) for Treatments 1, 3, and 2, respectively, when compared to the amount of runoff water leaving the control plots.

Labor and installation expenses can be significant components of BMP expenses. In this study, approximately 2 hours were needed to install the jute netting and creeping wild rye filter strips in each of the three erosion plots receiving Treatment 3. This was due to the relatively close proximity of the vegetation plugs spaced at intervals of approximately 2 to 3 inches on the diagonal. This time could have been reduced to approximately 0.5 hours by using strips of native grass sod instead of individual plugs of grass.

Approximately one-half hour was needed to install the other two treatments in each erosion plot, but installation time could have been reduced had the study been designed differently. For example, the erosion plots were constructed in wood frames that would

have been destroyed had a tracked dozer been used to crimp the straw in place.

Assuming a tracked vehicle could have been used, the actual time to crimp the straw used in Treatment 3 could have been reduced to less than five minutes. In Treatment 1, the compost was leveled to form a uniform layer approximately 0.75 inches (1.9 cm) deep. Had the compost been placed on the soil without deliberately creating a uniform layer, installation time could have been reduced by approximately one-half.

Most erosion and sediment BMPs occur on areas much larger than the 80 square-foot (7.4 m²) erosion plots used in this study. Because the specific installation practices used in this study were more labor-intensive and not the standard practices typically associated with these BMPs, they should not be used to determine cost-effectiveness of the treatments. Instead, CalTrans (2009) estimated the cost of installing vegetation plugs, loose weave jute netting, crimped straw spread at a rate of 2,000 pounds (907 kg) per acre, and course wood compost applied in a layer 2 inches (5.0 cm) thick. The cost of applying jute netting (Type A, loose weave) is estimated at \$35,000 per acre. Course wood compost applied in a layer 2 inches (5.0 cm) thick was estimated to cost \$20,000 per acre, while crimped straw applied at 2,000 pounds (907 kg) per acre was estimated to cost \$12,000 per acre. Vegetative plugs were estimated to cost \$3.60 to \$5.40 per square yard. The erosion plots used in this study covered 80 square feet (0.002 acre). Using CalTrans' estimates, the cost of installing the treatments used in the erosion plots are estimated at \$23 for the Treatment 2, \$54 for Treatment 3, and \$99 for Treatment 1.

The cost-effectiveness of each treatment was based on the cost of each treatment compared to the number of liters of runoff water that specific treatment prevented from leaving the erosion plot. Treatments 1 and 3 were more effective at retaining runoff and sediment than Treatment 2. The cost per reduction in units of runoff for erosion plots was \$1.04 per liter for Treatment 1 and \$0.47 per liter for Treatment 3. The cost for Treatment 2 was \$0.25 per liter. Analysis of variance revealed no significant difference in the amount of runoff or sediment loss from Treatments 1 and 3, but these amounts were significantly less than erosion plots featuring Treatment 2; therefore, this treatment was not considered to be as effective as the other two. Based on these comparisons, the most cost-effective treatment appeared to be Treatment 2, as this treatment reduced runoff almost as much but at less than half the cost of Treatment 1.

CONCLUSION

Controlling erosion and sediment loss is an essential part of any ground-disturbing activity. Many BMPs are available and all have their strengths and weaknesses. Some are more expensive than others, some more effective than others, and some have limitations regarding their use. The decision on which practices to implement must be made on a site-specific basis after considering all pertinent factors.

All of the treatments used in this study would be beneficial in reducing runoff and sediment loss and possibly in reducing nutrients and other pollutants from disturbed soil. The greatest loss of runoff and sediment occurred from the barren control erosion plots. Even the most basic and inexpensive BMP consisting of tracked straw and native plant seeds significantly reduced runoff and sediment loss from the test erosion plots when compared to the control erosion plots, while the most expensive BMP using a combination of compost covered by jute netting yielded runoff that was 38 times less than that of the control erosion plots.

It is reasonable to conclude that by slowing flow velocity and allowing runoff water to infiltrate the soil onsite, erosion and sediment control BMPs will also reduce entrainment and transport of sediment. An added benefit is that heavy metals, pesticides, nutrients, hydrocarbons, and other pollutants can be contained on site and prevented from entering downstream waters where they can adversely affect aquatic life or have other environmental consequences. This is particularly true when BMPs included vegetation

filter strips, but any of the practices incorporated in this study will likely have the same benefit of reducing water and keeping pollutants on site and out of waterways.

A primary concern is to implement appropriate erosion and sediment control BMPs before precipitation. As was shown by the use of crimped straw and seeds, relatively little effort is needed to stabilize a site and prevent erosion and sediment runoff. This is critical in the case of disturbed areas in close proximity to water bodies, particularly during the spawning period for nearby fish, amphibians, and invertebrates.

In this study, the greatest levels of runoff and sediment loss tended to occur immediately following the first three periods. After the first three periods, sediment loss from all erosion plots including the control were not significant, suggesting that the greatest sediment losses occur following the first precipitation events that result in overland flow. Also, while all of the BMPs in this study effectively reduced runoff and sediment loss, BMPs such as crimped straw may be of limited use and become less effective over time. Additionally, the most cost-effective treatment was the use of jute netting combined with a vegetative filter strip, which prevented nearly as much runoff from leaving the erosion plots as the combination of jute netting and compost, but did so at less than half the cost of the latter treatment. The cost-effectiveness of these treatments should be considered when deciding which if any of the three treatments evaluated in this study should be implemented.

OPPORTUNITIES FOR FURTHER STUDY

Additional research should be conducted to determine if any of the treatments or erosion control products used in this study would adversely affect turbidity, conductivity, or pH of runoff water. While these parameters were considered as part of this study, insufficient data was collected to allow conducting a statistically valid analysis.

Additionally, ambient water quality measurements should be taken immediately prior to data collection to determine if changes in such parameters are related to treatments or instead related to uncontrolled influences or fluctuations of the water source. Total suspended solids (TSS) should be evaluated in addition to turbidity, as TSS levels have been correlated to adverse impacts on fish and other aquatic resources.

Overland flow and runoff can be affected by the antecedent moisture content of the soil. Antecedent moisture content was not evaluated in this study, but should be considered in the design of future studies with regard to erosion control and runoff and sediment loss. Similarly, soil compaction may affect absorption and loss of sediment and runoff water. Soil compaction at the beginning of the study as well as over the course of the study should be measured and evaluated to determine potential effects of soil compaction on sediment and runoff loss.

Percent of vegetative cover is often cited as a factor in reducing erosion and sediment loss. Many of the native seeds used in this study failed to germinate or the plants grew too slowly to provide significant cover. Therefore, percent cover was not correlated to

loss of sediment or runoff water. Future studies should consider the percent of vegetative cover on the erosion plots and the determine if sediment or runoff loss is correlated to percent cover. Additionally, comparisons could be made between the percent coverage provided by native vegetation versus the percent coverage from invasive species to determine if non-natives may be beneficial in reducing sediment or runoff loss.

This study was conducted on slopes of approximately 27 percent (4:1 horizontal:vertical). Many fill slopes are significantly steeper than 4:1 and often approach 2:1 or 1.5:1. Future studies should be conducted on steeper slopes that are commonly used in road construction such as 2:1 or 1.5:1.

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Photograph 1. Determining rate of water being applied to each plot.

Photograph 2. Water leaving collection tray and entering 5-gallon buckets.

Photograph 3. Water collected in Nalgene bottles for measurement.

Photograph 4. Runoff water carrying sediment from untreated control plot.

Photograph 5. Attaching heavy plastic to determine amount of water applied to each plot.

Photograph 6. Erosion plots covered with plastic and ready for application of water.

Photograph 7. PVC pipe being glued to form collection pipes leading from erosion plots to 5-gallon buckets.

Photograph 8. Runoff water being collected in 5-gallon bucket.

Photograph 9. Performing test to determine equal distribution of water on plots.

Photograph 10. Compost applied in 0.75 inch layer as part of Treatment 1.

Photograph 11. Compost covered by jute netting as part of Treatment 1.

Photograph 12. Straw spread at 1,500 pounds per acre and being crimped into soil for Treatment 2.

Photograph 13. Straw after being crimped into soil.

Photograph 14. Jute netting over upper 75 percent of erosion plot as part of Treatment 3.

Photograph 15. Creeping wild rye (*Leymus triticoides*) installed in lower 25 percent of erosion plot and jute netting over upper 75 percent of erosion plot.

Photograph 16. Runoff and overflow collected from barren control erosion plots.

Photograph 17: Barren control plot. Note deer tracks on surface of plot.

Photograph 18. Irrigation being applied to erosion plots.

Photograph 19. Irrigation being applied to one of Treatment 2 plots.

Photograph 20. Sediment samples in dryer to remove moisture and determine dry sediment yield.

Photograph 21. Dried sediment after sample was removed from oven.

Photograph 22. “Volunteer” vegetation became established in all erosion plots throughout the study, including this untreated control plot.

Photograph 23. Vegetation becoming established among jute netting and creeping wild rye filter strip in Treatment 3.

Photograph 24. Densely established vegetation among crimped straw and seeds.