Model Guided Specification for Using Compost and Mulch to Promote Establishment of Vegetation and Improvement in Stormwater Quality

FINAL REPORT

April 30, 2010

Contract # 65A0236
Expense Authorization 43 910204

CTSW-RT-10-236.01.1
CA10-0916

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Yard waste composts are commonly utilized for erosion control and for improved revegetation of degraded field sites. Concerns have been raised that field application of composts may contribute additional nutrients to nearby water bodies. The project described here evaluated several erosion control and nutrient-release effects of compost application in the field and in laboratory settings, including numerical modeling of nutrient and metal leaching losses. The basic findings from the 2:1 slope field plots are that yard waste compost treatments lost less than 4% of applied compost nitrogen to nitrate leaching and most application methods lost 1% or less. The most effective treatment (incorporation of yard waste compost into the bare slope plus a surface mulch application) had nitrate losses of only 0.12% of the nitrogen added in the compost amendment, which did not statistically differ from nitrate levels leached from unamended annual grass plots. This result is especially surprising since this particular treatment received twice the amount of compost nitrogen as any other treatment tested. These data indicate that in many cases, degraded, nutrient-poor soils can be regenerated with yard waste compost amendment with minimal risk of nutrient loss, especially if the composts are incorporated into the slope surface and covered with a mulch layer.
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Project Summary

Yard waste composts are commonly utilized for erosion control and for improved revegetation of degraded field sites. Concerns have been raised that field application of composts may contribute additional nutrients to nearby water bodies. The project described here evaluated several erosion control and nutrient-release effects of compost application in the field and in laboratory settings, including numerical modeling of nutrient and metal leaching losses. The basic findings from the 2:1 slope field plots are that yard waste compost treatments lost less than 4% of applied compost nitrogen to nitrate leaching and most application methods lost 1% or less. The most effective treatment (incorporation of yard waste compost into the bare slope plus a surface mulch application) had nitrate losses of only 0.12% of the nitrogen added in the compost amendment, which did not statistically differ from nitrate levels leached from unamended annual grass plots. This result is especially surprising since this particular treatment received twice the amount of compost nitrogen as any other treatment tested. These data indicate that in many cases, degraded, nutrient-poor soils can be regenerated with yard waste compost amendment with minimal risk of nutrient loss, especially if the composts are incorporated into the slope surface and covered with a mulch layer.

This project contained several different sections that addressed the field impact of yard waste compost materials from commercial producers in Northern California. First, published literature was reviewed, which documents the generally positive benefit of compost use for erosion control. Next, several combinations of yard waste compost materials and incorporation treatments were tested on a 2:1 slope on a degraded substrate at a landfill location on the UC Davis campus. A selected set of plot treatments was also established on a 2:1 embankment slope at the Kidwell overcrossing along Interstate 80. Several laboratory or field-station experiments were also developed.
to test materials with greater experimental control than was possible with the field sites. These activities involved measurement of infiltration rates following compost incorporation on three different substrate types and also involved measurement of reduced evaporation from soils after coarse organic materials were applied as surface mulches. Lastly, the nutrient and metal contents measured in runoff during simulated rainfall were used to generate numerical models to predict nutrient release during a single rain event as well as during successive rains of a multi-day storm series.

Weather during the project period varied from extremely high rainfall amounts (landfill plots) to below normal rainfall (Kidwell overcrossing plots). As a result, the measured results represented responses to extreme weather patterns rather than average patterns. Because the high rain volumes overwhelmed the infiltration capacity of the landfill plot treatments, storm-by-storm analysis was not possible. Annual sediment and nutrient losses in surface runoff were successfully measured from nine potential types of compost treatments under these high rainfall conditions. These treatments included testing of differences between two types of yard waste compost (mature and immature) as well as various methods of compost application, including compost incorporation, surface blankets or both. Over the entire rain season there were no significant differences in sediment and nutrient losses from nitrate (NO₃⁻), ammonium (NH₄⁺) and phosphorus (P) between the two compost types when they were applied as surface blankets, although initial losses are expected to differ. Decomposition or stabilization processes of these two different types of materials were evidently shorter in duration than the season-long measurement interval. Annual sediment loss was significantly reduced in treatments where a compost blanket was applied over the top of incorporated compost compared to treatments where compost was just tilled into the soil without a surface mulch overlay. This treatment (tilled compost plus mulch) reduced sediment loss to a level that was comparable to well vegetated treatments, which in this
case was an annual grass cover. Although the tilled plus mulch treatment had twice the amount of compost and total nitrogen as the treatments with just a surface blanket of compost, it lost less than a fourth as much nitrate in its runoff over the year compared to treatment having compost applied as a blanket over bare soil. The greatest sediment loss came from treatments in which compost was tilled into the soil with no additional compost surface blanket. The Kidwell plots, in contrast, experienced so little rain that little or no runoff was recorded. In these droughty conditions, the soil treatment with the greatest tillage and greatest infiltration had less perennial grass establishment, perhaps due to less water availability during the first summer.

From the landfill plot results, a recommendation was generated for field slope treatment with compost to reduce overall runoff, sediment loss and nitrogen loading. This recommendation is to amend compost to a graded surface and then to rough incorporate it into the soil, with an additional mulch cover applied on top. Rates will vary with site conditions, but a common application would include 1 inch of fine (3/8” minus) yard waste compost plus one inch of coarse woody fragments (chips or overs) that are roughly tilled to 10 inches. This should be followed by an inch of coarse woody material over the top as a surface mulch. Rototilling should be avoided because it pulverizes the soil and reduces pore space.

Short-term release of N from compost (weeks- to months-long periods) can be estimated by “available N” testing methods commonly available from commercial soil testing firms. But, the medium-term release patterns (perhaps one to several years) that are important for regeneration of vegetative communities are more difficult to estimate. These release rates are determined by compost characteristics, including the decomposition rate of the woody, high carbon-content proportions remaining in the compost versus N-containing materials and humified compost residues. In the long-term
(perhaps three or four years and longer), most plant-based composts appear to develop similar rates of N release that are generally similar to soil organic matter.

Commercially available short-term N release tests suggest that less than 2 % of the total N loaded onto the site will be found in “available” pools that can be rapidly leached or taken up into plants. This low fraction of available N compared to total N content is an inherent characteristic of many organic sources of N amendments. General literature values suggest that plant-based composts may release approximately 10 - 20 % of their total N in the first season, but this is strongly dependent on compost processing method and degree of post-thermophilic process curing. Nutrient loading to degraded substrates for sustainable revegetation, should account for both short term available N levels and long-term N release amounts.

Composts were also analyzed in lab conditions by Simultaneous Thermal Analysis (STA) in order to identify, if possible, indicators of compost curing state. These tests revealed several chemical differences between products that were thermophilically composted and cured (aged) versus material that was only thermophilically composted (but not cured or aged). These measured differences are also expected to relate to long-term nitrogen release patterns. Although these indicators correspond to compost age or sieved fraction, more experimental work is needed to make this testing method practical for tracking of compost product quality before or after application to field sites. Our current results indicate that fresh applications of fine (10 mm (3/8”) minus) screened composts should be viewed as a more likely source of available N for plant growth or leaching losses than whole compost or coarse woody blends. An immediate application of this finding is that utilization of fine compost materials for pneumatic application has the incidental effect of selecting for more N rich, faster release fractions than does the use of whole composts.
Incorporation of coarse compost or woody fragment materials to construction-impacted substrates generates increases in infiltration of between 20 and 90 % in the months after incorporation, depending on substrate geological type and texture. Incorporation of fine (< 10 mm (< 3/8)) composts provides minimal effect, although these materials provide other benefits that should be considered along with infiltration rates. The type of coarse woody fragments (compost “overs” versus wood chips 10 to 75 mm (3/8 to 3 inches) in length) did not have a significant effect on infiltration. Surprisingly, there was no consistent increase in infiltration from increasing amounts of woody incorporation (1 versus 2 or 4” overlay, incorporated) or type (compost overs versus 3” minus wood chips). These measurements were done in controlled bins about 18 inches square, but additional tests in field conditions with deep matric drainage would be useful to improve understanding of the effect of compost application on infiltration.

Wood fragment and straw mulches both reduced evaporation, but the effect was only detectable for approximately 2 to 4 week periods after the last wet-up event or rain. Thicker mulch layers (2 or 4 inch layers) had minimal improvement in evaporation reduction, but they would be expected to last longer in field conditions. These tests were designed to evaluate non-irrigated conditions, but would function similarly under irrigation.

The chemistry of leached solutions from rainfall simulation on young and old composts added to experimental soil plots was evaluated for a single modeled storm event and also for repeated storms on successive days for each compost age material. Nutrients and metals in the leachate were measured. Measured data were found to fit well with first order kinetics model predictions. Because compost quality changes with age, however, different model parameters may be needed for composts with different maturity, curing or field incubation times.
When these results are integrated with other soils and revegetation studies on degraded substrates, a common picture develops for treatment, regeneration and revegetation of harsh sites: 1) increase infiltration rates to capture rainfall from design storm events without overland flow and sediment loss; 2) increase infiltration capacity (depth) to retain the rainfall volume of a multi-day design storm event and to provide adequate moisture for summer plant growth; 3) mulch the substrate surface to reduce short term evaporation losses (less than a month), to reduce surface crusting and to aid seed germination; 4) provide total N levels of approximately 1,000 - 2,000 kg total N/ha, while limiting available N to perhaps 50 to 70 kg N/ha/yr, depending on location and plant growth potential and risk of leaching losses.
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1.0. Literature review of Compost Use for Erosion Control and Improved Stormwater Quality

Chapter synopsis

Composts are commonly applied in field revegetation and erosion control situations, but they have been suspected of causing nutrient addition to local watersheds. This chapter cites examples that were located in peer reviewed, agency report and trade literature that document the positive benefit of compost use for erosion control. Site conditions of soil compaction and slope conformation also influence how a particular compost or mulch application will perform in field conditions and should be considered as part of field erosion control planning and implementation.

The recommendation is to amend and incorporate yard waste compost into the soil, with an additional mulch cover on top. Application thicknesses appropriate to California conditions are addressed in subsequent chapters.

Social, political and regulatory environment

Under Phase II of the National Pollution Discharge Elimination System (NPDES) 2003, a storm-water management plan must be in place to acquire a permit for any land disturbing activity over 1 acre. In California, the SWRCB is the responsible agency for granting these permits. The primary objectives of the general permit plan (California Storm-water BMP Handbook, 2003, 1.3.2) are several:

+ reduce erosion
+ minimize or eliminate sediment in storm-water discharges
+ prevent materials used at a construction site from contact with storm-water
+ implement a sampling and analysis plan if storm-water does come in contact with construction materials
+ implement appropriate measures to reduce potential impacts on waterways both during after construction of projects
+ eliminate unauthorized non-storm-water discharges from the construction sites
+ establish maintenance commitments on post-construction control measures

The BMPs that the handbook lists include hydraulic mulch, hydro-seeding, soil binders, straw mulch, geotextiles and mats, and wood mulching. Thus, using compost, though not explicitly stated, appears to fit to the extent that it has fibers like hydraulically applied mulch, coarse fragments similar to wood mulch (if unscreened yard waste composts are used) and the humified plant material can act as a soil binder.

Large scale utilization of composts has an intrinsic benefit for the state of California in that it helps reduce the volume of the waste stream going to landfills. The California state legislature passed AB939 in 1989. This act required the state’s landfills to reduce their incoming volume by 50% by the year 2000. County landfills reduced the inflow volume into the landfills by composting organics. Thus, the use of these composted materials for erosion control and soil restoration benefits the landfill waste stream reduction efforts. The use of composted organics for erosion control and storm-water management is not unique to California. In 1997 it was reported that departments of transportation (DOTs) in 34 states were either studying and / or utilizing composts for erosion control purposes (Mitchell, 1997).

Field effects of compost use for sediment reduction

Numerous studies have shown that composts and non-composted woody materials applied as surface blankets, or mulches, can be very effective in reducing
runoff and sediment losses from disturbed slopes when compared to bare slopes or when compared to treated slopes without a mulch cover (Demars et al., 2000, Persyn et al., 2004; Faucette et al., 2004; Grismer and Hogan, 2005). All cover treatments protect the soil surface from the kinetic impact energy of rain, which reduces the potential for sediment detachment and surface crusting, they roughen the surface, which impedes overland flow and they slow surface flows, which allows greater time for percolation of rain down into the soil. Persyn et al., (2004) presented portions of Table 1 that outlines the results of past studies concerning varying surface protection amendments.

**Compost use in urban settings**

The Portland Metro project demonstrated that yard trimmings compost can be used effectively to control nonpoint-source pollution in urban environments (Ettlin and Stewart, 1993; Metro, 1994). The project used both "coarse" compost materials (containing chunks of wood and branches up to 152 mm [6 in] in length) and "medium" compost materials, the fraction remaining following screening of the coarse compost through a 16 mm (5/8 in) trommel screen. Leaf compost was collected from residential streets in the city of Portland.

Eight erosion control treatment plots were established at sites located at St. John's Landfill, Portland, OR. These sites measured 2.74 x 9.75 m (9 x 32 ft) on slopes of 34 percent (19 degrees). Surface runoff was collected on plastic sheeting at the base of the slope and collected in barrels. Treatments included three compost treatments applied as 7.6 ± 2.5 cm (3 ± 1 in) surface mulch layers: 1) 15 cm (6 in) minus "coarse" mixed yard debris compost, 2) 1.6 cm (5/8 in) minus "medium" screenings of the same material, or 3) 1.6 cm (5/8 in) screened compost made from leaf materials only. In an additional treatment, the "medium" and "leaf litter" composts were also shaped into 45
### Table 1. Summary of results of compost use.

<table>
<thead>
<tr>
<th>Citation</th>
<th>Experimental Conditions</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meyer et al., 1972</td>
<td>Slope: 12%. Simulated rainfall: 63 mm h(^{-1}). Straw mulch of 2.3 t ha(^{-1}), 10 cm topsoil application.</td>
<td>Straw mulch soil loss &lt;22 t ha(^{-1}). Topsoil soil loss of 69 t ha(^{-1}).</td>
</tr>
<tr>
<td>Storey et al., 1996</td>
<td>Slope: 33%. Simulated rainfall of 1, 2, and 5 year storms. Compost and wood mulch with chemical tackifiers applied between 76 to 101 mm depth.</td>
<td>Compost and wood mulch plots met Texas sediment loss standards on clay (12.21 kg 10 m(^{-2})) and sandy soil (0.34 kg 10 m(^{-2})).</td>
</tr>
<tr>
<td>Agassi et al., 1998</td>
<td>Slope: 5%. Simulated rainfall: 40 mm h(^{-1}). Solid waste compost, soil control.</td>
<td>85% infiltration for compost, &lt;52% for control</td>
</tr>
<tr>
<td>Demars et al., 2000</td>
<td>Slope: 50%. Natural rainfall. Wood waste materials.</td>
<td>Effective at reducing runoff for storms &lt;12.7 mm h(^{-1}), effective at controlling erosion for mulch thickness of 1.9 cm or greater.</td>
</tr>
<tr>
<td>Risse et al., 2001</td>
<td>Slope: 10%. Simulated rainfall: 167 mm h(^{-1}). Compost, wood mulch, poultry litter at 5 cm depths compared to bare soil.</td>
<td>Total solids loss significantly less on compost treatments (between 96 and 215 g) and on mulch treatments (71 to 124 g) compared to soil (766 g).</td>
</tr>
</tbody>
</table>
| Persyn et al., 2004 | Slope: 33%. Simulated rainfall: 100 mm h\(^{-1}\). Yard waste compost, yard waste compost mixed with a biosolid sludge, and yard waste compost mixed with bio-industrial sludge. Applied at 5 and 10 cm. | All compost treatments exhibited significantly lower steady state inter-rill rates as control and topsoil treatments.  
The yard waste compost had the lowest steady state erosion rate. No statistical difference between compost depths. |
| Faucette at al, 2004| Slope: 10%. Simulated rainfall: 77.5 mm h\(^{-1}\). 11 treatments (3 poultry litter composts, a municipal solid waste compost, a food waste compost, a yard waste compost, a biosolids/peanut hull compost, 3 grades of wood mulches). Applied to a depth of 5 cm. Soil depth (in flume) was 10 cm. | All of the treatments tested, except for the poultry litter treatment, reduced total solids lost compared to bare soil.  
The mulch treatments had lower total solids loss and less runoff than most of the composts (not statistically significant). |
| Grismer and Hogan, 2005 | Slope: 50-60%. Simulated rainfall: 60 mm h\(^{-1}\). Pine needle mulch.                  | 50% decline in sediment concentration, and 30% decline in sediment yield compared to bare soil. Sediment values still greater than from undisturbed sites. |
cm high and 100 cm wide berms (18 x 39 inches) to act as sediment control barriers. A conventional treatment used a sediment fence (Amoco 2122 fabric) and a hydromulch treatment (wood fiber/tackifier mixture; Silva-Fiber Plus, Weyerhaeuser Co. Tacoma, WA), which were compared to an unamended control plot. The hydromulch was specified at 120 gal ac⁻¹ of 36 – 48 lb of product per 100 gallons water, but on these field plots it was applied at an extra heavy rate by the contractor. During and after three storm events in March 1993, 364 samples were collected and tested for suspended solids, settleable solids, turbidity, total solids, metals, nitrate N, total N, and chemical oxygen demand. Total suspended solids are stated to be the most important single parameter to measure in evaluation of erosion control efficiency.

The untreated control and the sediment fence yielded the highest average total suspended solids (8442 and 6348 mg L⁻¹). The compost barrier and the coarse-screened compost yielded 562 and 436 mg L⁻¹. The "leaf litter" compost (7.6 cm blanket application) yielded 380 mg L⁻¹ and the hydromulch treatment yielded 341 mg L⁻¹. The "medium" mixed yard debris compost blanket yielded the lowest total suspended solids for the test period, producing 147 mg L⁻¹. Other compost effects, such as metals adsorption and other water quality data are also evaluated. The need for high-quality, mature compost was noted.

After this study, field plots were constructed in the Portland area utilizing compost as erosion control material. Objectives were to demonstrate use and to increase the market demand for yard trimmings compost materials. Three field sites were established on roadside, housing development, and mobile home park projects. All compost materials were applied to a depth of 76 to 102 mm (3 to 4 in). Materials were brought to the top of the slope by tractor bucket or backhoe. Materials were then spread by hand. The first site (Springwood Drive, Beaverton) had a 14-degree slope at the bottom and a 7.6 m (25-ft) slope length. The slope drains into an existing wetland. At
the second site (Marylhurst, Lake Oswego), slopes ranged from 0 to 30 degrees. The third site (McLoughlin Boulevard, Portland) contained two areas with slope angles of 35 degrees and slope lengths of 3 to 18.3 m (10 to 60 ft). A third area had a slope angle of 15 degrees and a slope length of 4.6 m (15 ft), and a fourth area had a 1- to 5-degree slope and a slope length of 48.8 m (160 ft).

Results from the three demonstration projects suggest the following beneficial uses from compost application. A thick compost layer can provide a surface covering for foot or vehicle traffic onto soils that are otherwise too muddy and wet to support traffic. A compost layer at the exit of a site will reduce mud tracking onto local streets and into storm drains. A 76-mm (3-in) layer of compost was found to be effective. One demonstration site coordinator suggested using a specification of a “minimum” of 3 inches. Compost screened to 38 mm (1½ in) or less is recommended for erosion control on steeper slopes. Slopes of up to 35 degrees were effectively treated. The compost layer should be extended over the top of the slope for 0.6 to 1 m (2 to 3 ft) at a 300- to 450-mm (12- to 18-in) depth to diffuse ponded water entering the top of the slope. Compost that has been screened to 19 mm (¾ in) or less is recommended for slopes that are to be landscaped. A moisture content of less than 25 percent makes application most efficient and enables the compost layer to readily adsorb larger amounts of rainfall immediately after application. Mature compost (interpreted to mean “cured” or stabilized for several weeks after hemophilic composting) will function to release nutrients into the soil more readily than immature compost. Contaminants (plastic, glass, undecomposed plant material) detract from the aesthetic benefits of compost amendment. As a result of the study and field plots, members of several local governments incorporated the use of compost into their specifications.
Use of compost for soil restoration and revegetation

In addition to surface protection, compost treatments can restore disturbed soils and facilitate revegetation by increasing levels of organic matter (OM). Increasing or restoring soil OM increases soils’ water holding capacities (WHCs), cation exchange capacity (CEC), and nutrient levels while decreasing soil bulk density ($\rho_b$) (Munshower, 1994). In addition, compost amendments have been shown to improve soil aggregate stability as well as slowing soil crusting effects. In 2001, researchers amended a silt loam that was prone to crusting and slumping by incorporating municipal waste compost (50 Mg ha$^{-1}$) to a depth of 25 cm. The study showed that the amended soils maintained aggregate stability (and, therefore, infiltration capacity), thereby delaying the onset of surface crusting and runoff (Bresson, L. et al., 2001). The improved infiltration in the treated soils was attributed to the increased levels of organic C. Consequently, the amended soil plots lost about a third as much sediment due to reduced surface runoff compared to the compost amended soils.

Re-establishing vegetation on disturbed soils provides long term soil erosion protection and stormwater buffering. In 1998 the Texas DOT approved specifications for compost to be used for erosion control and vegetation establishment (Block, 2000). The DOT found that compost applications of up to 3 inch blankets were required to re-establish grasses on drastically disturbed slopes. The Texas DOT requires the compost particle sizes to be no more than 3 inches, with 70% being less than 2 inches. The compost must contain 40 to 60% organic content and no more than 5 mmohs cm$^{-1}$ of soluble salts. This use of compost coupled with site specific mixtures of woodchips or other mulches has allowed for successful revegetation projects on previously, believed to be un-restorable sites.

In 2006, another study addressed whether compost and the method in which it is applied to construction embankments affects water content and native plant
establishment. Singer, et al. (2006) applied yard waste compost (143.1 Mg ha\(^{-1}\)) as either a 5 cm blanket, or incorporated to a depth of 5 cm to a “moderately coarse glacial till” slope. The soil’s initial organic matter was 1.6% and initial N content was 0.06% in the top 15 cm. The researchers monitored the test site for three years. The study found that both compost treatments decreased the soil’s bulk density and increased the soil’s moisture retention. Water storage was found to be greater in the incorporated compost treatments than the compost blanket treatments when rainfall exceeded 2 cm. There was no significant difference in native plant density or diversity amongst the two compost application methods. The compost treated plots did produce 2.5 times more shoot biomass than the control (unamended) plots.

**Texas Transportation Institute field facility**

The Hydraulics and Erosion Control Field Laboratory at the Texas Transportation Institute, affiliated with the Texas Department of Transportation and the Texas A&M University system, provides large, full scale experimental slopes for uniform testing of erosion control materials under field and controlled rainfall conditions. A study on compost application (Storey *et al.*, 1996) tested three amendment materials on 1:3 slopes with both clay and sandy loam textured soils. Plot size was 6.1 m wide by 21.35 m downslope (1:3 slope plots). These materials included co-compost (mixed yard trimmings and municipal sewage sludge), shredded wood with polyacrylamide tackifier (6.75 kg/ha), and shredded wood with a hydrophilic colloid tackifier (56 kg/ha).

The different treatments were amended with organic materials to a depth of 76 to 101 mm (3 to 4 in) over the plots. Soil textures on the plots were either clay or sandy loam (Storey *et al.*, 1996) to sandy clay. Slopes were constructed at 2:1 and 3:1 (run:rise) angles. Soils were seeded with a standard warm-season revegetation grass mix selected for the central Texas area. Vegetation establishment criteria were to
achieve a minimum coverage of 80 percent for the clay soils and 70 percent for the sandy loam soils within 6 months of seeding. Simulated rainfall was used to test for sediment loss from the plots at rates representing 1-, 2-, and 5-year storm events. These rates were designed to model events within the Houston/Dallas/Austin region and are equivalent to 30.2 mm hr\(^{-1}\) (1.2 in hr\(^{-1}\)), 145.5 mm hr\(^{-1}\) (5.7 in hr\(^{-1}\)) and 183.6 mm hr\(^{-1}\) (7.2 in hr\(^{-1}\)) (Landphair and McFalls, 2000b). The erosion control objectives were that the treatment should protect the seed bed from a short-duration, 1-year return frequency event (99 percent probability of occurrence within a given year) within the first month after installation, from a 2-year return frequency event (50 percent probability) within the first 3 months following installation, and from a 5-year return frequency event (20 percent probability) within the first 6 months of installation. To be included in the Texas Department of Transportation-approved Material List for Standard Specification Item 169 (Soil Retention Blanket), the sediment loss had to be 0.34 kg 10 m\(^{-2}\) or less from the clay soils and 12.21 kg 10 m\(^{-2}\) or less from the sandy loam soils.

Sediment losses from the compost-amended plots during simulated rainfall tests were measured that were close to the cutoff level of 0.34 kg 10 m\(^{-2}\) from the clay plots. They were 3.88 kg 10 m\(^{-2}\) for the sandy loam plots (Storey et al., 1996), which was within acceptable limits. Vegetation cover was 99 percent on the clay and 92 percent on the sandy loam. The two tackified wood chip treatments produced 0.15 and 0.30 kg 10 m\(^{-2}\) sediment loss on the clay soil and 11.27 and 10.97 kg 10 m\(^{-2}\) sediment loss on the sandy loam. Vegetation establishment was around 50 percent for several of the tackified wood chip treatments, disallowing them from approval under Texas Department of Transportation standards. The fact that much of the vegetative cover established in the compost treatment came from weed seed, not the applied seed mix, points out the need for quality control in compost products. Costs for the compost were below the average cost of synthetic or organic blankets tested by the facility.
In 2007, Birt et al., conducted a study considering runoff and erosion rates, as well as inter-rill erodibility factors on a sandy loam using compost BMPs that were adopted by the Texas DOT in 2004. The authors state that the Texas DOT BMP for compost application was to amend slopes with a maximum steepness of 3:1 with a 5 cm blanket. The compost materials used are required to meet requirements set by the U.S. Compost Council Seal of Testing Assurance. These specifications require that 95% of a compost material pass through a 15.9 mm sieve, and that 70% passes through a 9.5 mm sieve. Birt et al. utilized a rainfall simulator to test varying compost amendments added to a sandy loam slope constructed in aluminum pans. Treatments included compost blankets at 5 cm, compost and woodchip mixtures (1:1) applied to 1.3 and 5 cm depths, as well as topsoil and compost mixtures. The results of this study indicated that there was no significant difference between the two compost treatment depths. The compost blanket was found to have greater erosion potential than the compost / woodchip blends. The authors attribute these characteristics to the smaller and more uniform particle sizes of the compost and that it may be hydrophobic until it reaches a moisture content threshold. The suitability of these treatments as a revegetation amendment was not considered in this study.

In 2006, other researchers successfully revegetated a sandy clay loam slope (highly erodible soil, high K factor) in Athens, GA using compost treatments. Seven treatments (4 composts, 2 hydro-seeds, and bare soil) were applied and seeded with common Bermuda grass. The compost treatments included: 1) biosolids compost blanket; 2) a yardwaste compost blanket; 3) a municipal solid waste compost (MSW) and mulch blanket (2:1 compost to mulch ratio (by volume); and 4) a poultry litter compost, mulch, and gypsum blanket (2:1 compost to mulch by volume with five percent gypsum addition by volume). The composts were all applied as blankets at a depth of 3.75 cm. The two hydroseed treatments included: one with a filter berm, and one with a
silt fence. The hydroteam consisted of water, seed, paper fiber, lime, nitrogen, phosphorus, and potassium from 10-4.4-8.3 mineral fertilizer (commercially recognized as 10-10-10). This study found that the compost blanket treatments averaged 2.75 times more vegetative cover than hydroteam after three months. After one year, the compost and hydroteam treatments had similar cover percentages, but the hydroteam had significantly greater weed biomass than compost and a greater ratio of weed biomass relative to Bermuda grass biomass (Faucette et al, 2006).

Effect of compost quality or feedstock

Compost treatments have a potential to leach nutrients into stormwater runoff. The type of compost utilized (i.e. feedstocks, maturity, curing) greatly affects nutrient leaching potentials. Faucette et al. (2005) presented the cumulative losses in total N and P amongst four composts added to unvegetated test plots (aged poultry litter, biosolid treated, municipal waste, and yard waste). After three rainfall simulations, over a 12 month period, total N and P losses were approximately: 61 and 3.4 kg ha⁻¹ for the biosolid, 27.1 and 0.75 kg ha⁻¹ for the municipal waste, 13.6 and 1.7 kg ha⁻¹ for the aged poultry litter, and 6.8 and 1.4 kg ha⁻¹ for the yard waste. The authors state that compost curing levels and differences in organic versus inorganic N content most likely explain N and P loss differences among the separate treatments (Faucette et al., 2005). Glanville et al (2004) measured nutrient levels in runoff from compost treated slopes (vegetated and un-vegetated) in a similar type of study. The compost treatments were yard waste compost, yard waste compost mixed with a biosolid sludge, and yard waste compost mixed with bio-industrial sludge. All composts were applied as blankets at 5 and 10 cm depths. The study found that the soluble concentrations of P, K, and Zn were significantly (p < 0.05) greater in runoff from one or more of the composts than from the control plots. The N species, as well as 9 other metals, concentrations were below
detection. The study also found that the control plots lost more total mass of nutrients than the compost treated plots. This is due to the control plots having much greater volumes of runoff.

Field application methods

The method of application (blanket or incorporation) and soil preparation (tilled or non-tilled) influences the overall performance of compost treatments. Tillage treatments fracture soil crusts and soil compaction layers, thus allowing for deeper infiltration and rooting depths. Incorporating compost into soil helps to stabilize soil structure by preventing packing and reconsolidation. Tillage management practices (0-10 cm) have been shown to increase surface pore size distribution, increase infiltration and water holding capacities (Lipiec et al., 2006). This combined with surface roughening decreases overland surface flow. Compost incorporation also generates soil surface roughness, which increases depression storage and causes a delay in runoff (Govers et al. 2000).

Although compost incorporation treatments create adequate infiltration capacity, field applications without a mulch or surface cover do not have a physical barrier to intercept raindrops and diffuse the associated kinetic energy. Thus, splash detachment of sediment and subsequent crusting may still be prevalent. Reinsch et al. (2007) studied the effectiveness of yard waste compost in controlling erosion and establishing vegetative cover in a clay sub-soil. Compost blankets of 5 cm depth were added as either surface amendments, or incorporated into the soil. Their results showed that after two growing seasons the compost blanket treatment produced 0.65 kg of total eroded sediment, as compared to 6.4 kg of total eroded sediment produced by the incorporated compost treatment. The control (or bare) treatment produced 493 kg of sediment. Further, the study found that both compost treatments produced 8 times more plant
biomass than straw mat test plots. Shear strength measurements on the plots indicated that the compost blanket treatment produced greater root development and was stronger than the incorporated compost treatments. It should be noted that there were no treatment replications in this study. Therefore there is no statistical analysis and the results from this study can only be viewed as qualitative. Further, the results only pertain to a single soil texture.

In contrast, Muzzi et al. (1997) found that surface amendments alone were not adequate to stop erosion and that, in most cases, tilling the ground before mulch application produced the most effective erosion control and plant growth. When soils are compacted during disturbance, treatment by ripping improves hydraulic conductivity and reduces surface runoff and erosion (Luce, 1997). This type of physical treatment may not restore the natural hydraulic conductivity of an undisturbed slope, however, because the pores formed may not be continuous or may not persist through multiple soil saturation cycles such as with winter rains. Mulches protected the surface of a metamorphic geological material from sealing during rain events during this study, but did not prevent surface sealing of a granitic substrate. Water-stable aggregates, formed from organic matter and microbial residues, would help reduce the tendency to form surface seals and settling (subsidence and close packing) of the near-surface strata. Compost and mulch application and incorporation were recommended to preserve the open soil structure generated by ripping treatments (Luce, 1997).

Surface mulch studies

A study of surface applied composts used as mulches was compared to hydromulches (Morris, 2007). Composts perform at least as well as hydromulching, and significantly lowered runoff. Compost produced higher concentration of TSS, total N, total P, but because of the low runoff, the total load was estimated to be lower from
compost treatments than from hydromulch. Binders in the hydromulch made no
difference in performance. Some decrease in plant density was noted, although the
decrease was not of concern.

The use of shredded brush as erosion control mulch was reviewed by Texas
Transportation Institute staff (Storey et al., 1996). Shredded wood mulch provides
physical benefits because it was reported to adsorb rainfall energy, slow water flow over
the surface, reduce crusting allowing increase infiltration, moderate soil temperature and
wind speeds at the soil surface, and reduce evaporative loss of soil moisture. The
decomposable carbon materials in the compost were reported to stimulate microbial
activity, facilitate generation of water-stable aggregates, and provide a variety of
microclimates for improved seed germination. Fiber lengths of 10 to 20 cm (4 to 8 in.)
were stated to be adequate for loose straw, while wood fiber lengths for coarse compost
mulches were about 7.6 cm (3 in), with application rates of 9 to 13.5 Mg/ha (8,000 to
12,000 lb/ac) for composts or 0.9 to 1.3 kg/m² for wood chips.

Caltrans tested surface mulch applications of composted mulch/chipped green
waste in a study in District 3 (Sacramento area) and District 11 (San Diego area)
(Pollock and Moreno, 1993). Mulch depths evaluated included 15, 30, and 45 cm (6, 12,
and 15 in). The mulch layers did not completely control weeds, even at the 30 cm depth
at the Sacramento (District 3) location, but in the San Diego trials (District 11) weed
growth on the 30 cm deep mulch plots was suppressed. The shallower 15-cm depth
plots had 50 to 60 % of the weed growth as the control plots, which were densely
covered with weeds. A lag time between the start of rainfall and the moistening of the
soil was observed, with a greater lag time associated with greater mulch depths.
Pooling of water at the soil level killed some of the trees on the plots. Drainage and
weed growth is somewhat dependent on the percent of fine materials in the compost.
The best material of those used was stated to be that with uniform sized 6 mm (1/4 in)
particles with fewer larger and smaller sized particles. At the San Diego site, illegal dumping of chipped material from private contractors increased as soon as chipped material for the project began to be delivered to the site. Wood waste chips were recommended to be less than 15 cm depth.

The most efficient method of application turned out to involve five or six workers and a single tractor with a front bucket. Using this combination, a field crew could place 80 to 100 cubic yards of compost per day. Larger crews increased potential for accidents because of crowding and reduced productivity because of worker inactivity. Bed widths of 10 m (30 feet) were able to be constructed with the most even depths. Use of larger equipment (articulated front loader) had the effect of incorporating soil into the compost during loading and moving, which increased weed growth the subsequent season.

Overall, plant growth was improved with mulch treatment, as a result of greater retained moisture, less extreme temperatures and improved soil conditions. The green waste compost was noted as providing little, if any nutrient benefit during the period of the study. The study period was noted as being too short to evaluate the long-term effects of compost mulch treatments on landscape plantings and soil chemistry.

Another study titled "Evaluation of Compost and Co-compost Materials for Highway Construction" was completed by Caltrans (Schollenberger, 1987) but the materials actually tested were at least 80 % municipal solid waste derived materials mixed with biosolids, not yard waste composts, as is the focus of the current study. No tests of erosion control effectiveness were made in this study.
Conclusions

Composts have been well documented to provide excellent erosion protection and reduction in sediment loss, and they typically have low nutrient losses relative to the total amount applied. Sustainable revegetation of degraded slopes, however, also includes regeneration of soil hydrology (infiltration and rooting depth) and soil nutrient content. Therefore, use and evaluation of compost amendments should be considered in the context of the site substrate, slope conditions and project goals. This means that if composts are applied as a surface mulch on top of an impermeable substrate, the water flow through the compost layer may more extensively leach out nutrients and dissolved organics than if the soil had greater infiltration rates. Subsequent plant growth of roots into the compacted substrate could also be limited, and resulting long-term vegetation could be thin or absent. The type of material, feedstock source and curing state, greatly influences the potential for nutrient loss, which may or may not be realized depending on site conditions, especially plant nutrient uptake and soil infiltration rates.

Few studies integrate organic amendment with site components such as infiltration, rooting depth and substrate nutrient content, which are none-the-less often limiting characteristics of many field sites. Regenerating a functioning soil with organic amendments will strongly determine the cover and sustainability of the revegetation stand and the ultimate performance of a compost application under storm conditions. These various conditions should be at least be evaluated during test construction, if not also controlled or manipulated.
References


Schollenberger, D.A. 1987. Evaluation of compost and co-compost materials for highway construction. Phase I. Office of Transportation Laboratory, California Department of Transportation. FHWA/CA/TL-87/04


2.0. Field plot construction

2.1. Field plot construction (UCD landfill site): Cumulative sediment, nitrogen and phosphorus losses from bare and compost-amended fill slopes.

Chapter Synopsis:

Constructed slopes are often amended with compost in order to reduce erosion and improve vegetation establishment. These composts could potentially contain soluble nutrients which may become a source of enrichment to nearby water bodies. The nutrient loss effects of application type (surface versus tilled) versus compost type in degraded substrate conditions and weather patterns was not known.

This study examined annual sediment and nutrient losses in surface runoff from nine potential types of compost treatments. Treatments included tested differences between two types of compost (mature and immature) as well as various methods of compost application, including compost incorporation, surface blankets or both. Over an entire rain season there were no significant differences in sediment and nutrient (NO$_3^-$, NH$_4^+$ and P) losses between the two compost types when they were applied as surface blankets. Sediment loss was significantly reduced in treatments where a compost blanket was applied over the top of compost tilled into the soil compared to treatments where compost was just tilled into the soil without a blanket overlay. This treatment reduced sediment loss to a level that was comparable to vegetated treatments. Although this treatment had twice the amount of compost as the treatments with just a surface blanket of compost, it lost less than a fourth as much nitrate in its runoff over the year than either compost type when they were applied as a blanket over bare soil. The greatest sediment loss came from treatments in which compost was tilled into the soil
with no additional compost surface blanket. Effects of different treatments were confounded by a gradient in slope hydrology that resulted in a relationship between runoff volume and plot position along the slope. Our statistical analysis took this into account and the data presented represent our attempt to control for this nuisance variable. Our findings suggest that compost can be used as a soil amendment and as an erosion control measure on constructed slopes at a minimal risk of nutrient loss if it is done in the proper manner.

We recommend that compost be incorporated into the soil to facilitate greater infiltration and also that a blanket of compost or woody mulch be placed over the soil to provide surface erosion protection. The amendment levels used at this site were inadequate for the site and weather conditions that occurred in this study, but the results did show the value of field treatments including both tilled compost incorporation and application as a surface mulch.

**Introduction:**

Composted organics can be used as a soil amendment along roadways in order to reduce erosion, facilitate revegetation and promote soil regeneration. Numerous studies have shown that composts and mulches applied as soil surface blankets can reduce runoff and sediment loss from slopes as compared to bare slopes or treated slopes without a mulch cover (W&H Pacific, 1993 / Portland Metro, 1994; Demars et al., 2000; Glanville et al., 2001; Faucette et al., 2004; Grismer and Hogan, 2005). Cover treatments protect the soil surface from the dispersive force of raindrop impact on bare soil. Tillage of the surface soil roughens the surface so that overland flow is impeded, allowing more time for percolation of rain down into the soil. In addition, compost treatments can restore disturbed soils and facilitate revegetation by increasing levels of organic matter (OM); which increases soils’ cation exchange capacity and nutrients.
levels while decreasing soil bulk density (Munshower, 1994, Curtis and Claassen, 2007), all of which improve revegetation of disturbed soils, providing long term protection against soil erosion. In some conditions, however, compost treatments have the potential to leach nutrient into stormwater runoff, creating a source of stormwater pollution (Faucette et al., 2005).

The type and production method of compost that is utilized (i.e. feedstocks, maturity, curing) may also influence nutrient leaching potentials. Faucette et al. (2005) compared N and P losses in runoff amongst four composts added to unvegetated test plots (aged poultry litter, biosolid treated, municipal waste, and yard waste source materials) using rainfall simulation. Nutrient losses under simulated rainfall following plot construction were significantly different between composts. The authors stated that compost curing levels and differences in organic versus inorganic N content explain much of the N and P loss differences among the separate treatments.

In a similar type of study, nutrient levels in runoff from slopes with blanket treatments were higher in unvegetated plots as compared to vegetated (Glanville et al., 2004). Plant nutrient uptake throughout the season can be expected to vary. The rate of nutrient uptake during the winter months is considerably reduced in northern California due to cooler temperatures that slow plant growth. This is also the time of year when rains are the heaviest and slopes experience the highest probability of surface runoff events. Thus, plants may not be able to take up the available nutrients from compost amendments and the slopes may leach nutrients and become a potential point source in terms of stormwater quality. Compost materials need to be produced and applied such that they minimize the risk of nutrient leaching.

Nutrient leaching is not only influenced by compost type but also by the method of application (blanket or incorporation) and soil preparation (tilled or non-tilled). Tillage treatments disrupt soil crusts and soil compaction layers, thus allowing for deeper rainfall
infiltration and plant rooting, although it may also pulverize weak soil aggregates. Incorporation of compost into soil helps to stabilize the structure of disturbed soils by preventing reconsolidation and packing (Bresson et al., 2001). Compost incorporation also generates soil surface roughness, which increases depression storage and causes a delay in runoff (Govers et al. 2000). Furthermore, Muzzi et al. (1997) found that surface amendments alone were not adequate to stop erosion and that, in most cases, tilling the ground before mulch application produced the most effective erosion control and plant growth.

Many studies that evaluate erosion abatement treatments or best management practices (BMPs) rely heavily on rainfall simulators to mimic precipitation events. Rainfall simulators can be an effective research tool in such studies because they allow the researcher to control rainfall durations and intensities that may provide useful information concerning the relative differences between erosion treatments. However, there are several major limitations to such experimental designs. Often the data from such studies only offer a “snapshot” of how erosion treatments perform over time. There are several significant variables that are often not addressed by rainfall simulator studies, such as variations in soil moisture, soil consolidation, soil temperature, time since previous rainfall event, and distribution of rainfall intensities. These temporal variations can significantly affect observed treatment effects. Further, experimental plot sizes are restricted by the relatively small size of rainfall simulators. Thus, the inherent variability of the soil across the site and the cumulative effect of rainfall across the whole site may not be adequately characterized.

The goal of this study was to evaluate the annual sediment yield and nutrient losses from nine compost treatments utilizing natural rain events throughout the winter of 2005/2006, which includes Northern California’s Mediterranean cool rainy season. This rainy season period generally runs from early November until April. This study
compares different yardwaste compost types (screened or unscreened and mature (completed thermophilic composting) versus mature and also cured (non-thermophilic aerobic processing), as well as compost application methods (blanket, incorporated, or a combination of a blanket over incorporation). Measured parameters include total suspended solids, and nutrient losses (NH₄-N, NO₃-N, and total P) from 2:1 bare slopes on disturbed earth fill materials that were either tilled or planed smooth to emulate a freshly constructed slope.

**Materials and Methods:**

The study site was located at the University of California, Davis landfill. Research plots were installed on the west-facing slope of a constructed debris cell (~5 acres; ~2 ha in area). The debris cell had been constructed three years earlier and had a temporary 60 cm (2 foot) silt loam cap of soil placed over the debris. The soil had been compacted by being repeated track-walking with a bulldozer after construction.

**Research plot construction:**

Thirty six plots were constructed in October 2005, each measuring 1 m (39") wide by 10 m (33 feet) long (Figures 1 - 9). The average slope of the plots was 2:1 (horizontal:vertical). Edging boards (9 cm x 1 cm; 3.5 x 3/8 in) were placed around the plots so that ~6 cm (4.5 in) of the edging was below the soil surface to prevent run-on from the adjacent slope. A galvanized metal runoff collection device was placed at the base of each plot. Runoff entering the collection devise was funneled into a 17 liter (4 gal) bucket located below the collection device. When runoff volumes exceeded the container capacity of the primary bucket, one third of the overflow was diverted into a 128 liter (28 gal) bucket to acquire a sub-sample of larger flow events.
Descriptions of the nine treatments examined in this study are shown in Table 1. Plot position was randomly assigned for all treatments using Excel (Microsoft, 2003). All treatments were kept free of vegetation using glyphosate (Roundup®) herbicide unless noted. All plots, with the exception of the annual grass treatments (AG), had all the pre-existing vegetation and duff layer removed prior to plot construction in order to expose the bare soil. The AG plots represent the ambient condition of the slope, on which vegetative cover was approximately 80%. Compost mulch (CIB, CMB and CGB) plots were constructed using a 3.5 cm (1.4 in) deep layer of compost over the entire plot. Plot treatments that tested compost tilled into the soil (CMT and MCT) were constructed by applying a 3.5 cm (1.4 in) deep layer of compost over the entire plot, which was then tilled into the soil to a depth of 15 cm (6 in) with a rototiller. Some treatments had an additional layer of compost applied over the tilled surface as a blanket (MCT and MT). The native annual grass *Vulpia microstachys* (small fescue, Six weeks fescue) was used to seed the vegetated plot, to test mature compost over bare ground. This treatment was completely vegetated within 3 months of construction.

The mature compost consisted of screened, windrowed yard waste from the Redding Municipal Composting Facility, Redding, CA (RMC). This material was produced by a 15 day, 55 °C (131 °F), thermophilic process followed by approximately 90 days of turned, aerobic curing. The material had passed through a 125 x 75 mm (5 x 3 in) grate during the initial tub grinding and was further screened to 19 mm (3/4 inches) after composting. The ‘immature’ compost consisted of unscreened, windrowed yard waste from Browning Ferris Inc, Milpitas, CA (BFI). This material was produced according to the US EPA regulations (40 CFR, Part 503c Appendix B), which for windrow piles includes at least a 15 day period with at least 55 °C (131 °F) thermophilic process during which the material is turned at least 5 times. Typically, this is followed by a period of aerobic curing, and contained undecomposed, woody shred materials that
may or may not be screened before application. Our experimental material was selected
to be unscreened and with minimal post-thermophilic curing. Physical and chemical
properties of both composites and the soil are presented in Table 2. This facility
participates in the US Composting Council’s Seal of Testing Assurance Program.

**Table 1.** Experimental treatments at landfill site to test the influence various composites and compost application methods on nutrient loss.

<table>
<thead>
<tr>
<th>Treatment ID</th>
<th>Treatment description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG</td>
<td>Annual grass</td>
</tr>
<tr>
<td>BP</td>
<td>Bare planed soil</td>
</tr>
<tr>
<td>BT</td>
<td>Bare tilled soil</td>
</tr>
<tr>
<td>CIB</td>
<td>BFI † blanket over bare soil (70 Mg ha )-1 ‡</td>
</tr>
<tr>
<td>CMB</td>
<td>RMC †† blanket over bare soil (175 Mg ha )-1</td>
</tr>
<tr>
<td>CGB</td>
<td>RMC over bare soil with grass (175 Mg ha )-1</td>
</tr>
<tr>
<td>CMT</td>
<td>RMC tilled into soil (175 Mg ha )-1</td>
</tr>
<tr>
<td>MCT</td>
<td>RMC blanket over RMC tilled into soil (350 Mg ha )-1</td>
</tr>
<tr>
<td>MT</td>
<td>RMC over tilled soil (175 Mg ha )-1</td>
</tr>
</tbody>
</table>

† BFI-compost from Browning Ferris Inc.; ‡ Compost application rate
†† RMC-compost from the Redding Municipal Compost Facility

**Table 2.** Selected physical, chemical and biological properties of soil at the landfill and the compost used as erosion control.

<table>
<thead>
<tr>
<th></th>
<th>Soil</th>
<th>RMC‡</th>
<th>BFI††</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density Mg m-3</td>
<td>1.44</td>
<td>0.513</td>
<td>0.192</td>
</tr>
<tr>
<td>Total Nitrogen %</td>
<td>0.06</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>Ammonia mg kg-1</td>
<td>0</td>
<td>12</td>
<td>24</td>
</tr>
<tr>
<td>Nitrate mg kg-1</td>
<td>4</td>
<td>351</td>
<td>3.1</td>
</tr>
<tr>
<td>Organic Carbon %</td>
<td>&lt;0.1</td>
<td>25.2</td>
<td>29.2</td>
</tr>
<tr>
<td>Phosphorus mg kg-1</td>
<td>10.9</td>
<td>3097</td>
<td>2367</td>
</tr>
<tr>
<td>pH</td>
<td>7.6</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td>EC</td>
<td>2.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stability Rating-Respiration-BAC†</td>
<td>stable-stable</td>
<td>moderately unstable-unstable</td>
<td></td>
</tr>
</tbody>
</table>

† Stability rating is based on 1) Respiration rate (CO2 evolution) under optimized moisture, temperature, 2) BAC-Biologically Available Carbon-Respiration under optimized conditions except for a carbon source. Results were interpreted and compost stability was determined by Soil Control Lab, Watsonville, CA.‡RMC-Redding Municipal Compost Facility, ††BFI-Browning Ferris Inc.
Figure 1. Runoff test plots in late fall during construction on 2:1 (H:V) silt loam slopes at the UCD landfill located west of the UCD main campus.

Figure 2. Close-up of runoff / sediment collector. An overhanging lip prevented rainfall from entering and being counted as runoff volume. The collector was keyed 10 cm into the soil by a buried flange on the collector base. The five gallon plastic bucket collects runoff and sediment. A spill-over pipe is fitted to the bucket and led to a 28 gallon plastic trash can (not shown) to allow capture of high runoff volumes.
Figure 3. (left photo) Bare-planed (BP) soil treatment (vegetation removed) with no tillage (looking up-slope).

Figure 4. (right photo) Annual grass treatment, with no tillage (AG).

Figure 5. (left photo) Rototilled soil treatment, with no amendment (BT).

Figure 6. (right photo) Rototilled soil, with cured compost incorporation (CMT).
Figure 7. (left photo). Mulch / blanket cover treatment, using cured compost over various tillage treatments (CMB, MCT or MT) depending on plot design. The treatment with compost mulch cover over compost incorporated (MCT) had twice the nitrogen loaded but lost the least nitrogen of all compost-only treatments.  
Figure 8. (right photo) mulch blanket treatment using coarse, unscreened uncured compost (CIB).

Figure 9. The runoff plots after winter rains started, germinating the annual grasses. Plot spacing and orientation angle was determined by the fall line of the local slope topography, which was irregular.
Runoff collection and measurement:

Precipitation events were defined as storms with more than 12 mm (1/2 in) of cumulative precipitation and that were also separated by more than six hours without rain. Figure 10 shows the cumulative precipitation over the rainy season at the landfill and the dates that samples were collected. Runoff from 19 precipitation events was collected between December 2005 and April 2006. After a precipitation event, the constituents of each runoff bucket collector were homogenized by stirring, and a 250 ml (1 cup) sample was removed from the center of the collected runoff volume. The interior area of each container was then multiplied by the measured runoff depth in that container to calculate the total runoff volume. The volume of runoff in the secondary runoff collector was multiplied by three to account for the uncollected portion (2/3) of the runoff. For each plot, the concentration of each nutrient in the primary container was multiplied by the volume in that container to determine the mass of nutrient in that container. This same procedure was done for the secondary container. The sum of nutrient masses in the primary and secondary containers were determined to be the total mass of nutrient loss from that plot for that precipitation event. Runoff samples were stored at 4°C (40 °F) within two hours after collection until they could be analyzed.
Figure 10. Cumulative precipitation for Davis, CA from 12/1/05 through 05/01/06. Large rainfall events in late December, 2005 and early January, 2006 saturated the soil and created heavy runoff.

Sample analysis:

Runoff samples were filtered using pre-weighed 1.5 micron (0.059 thousandths inch) pore size glass fiber filters (Whatman 934-AH). Filters and sediment were dried at 40°C (104 °F) for 24 hours (1 day), placed in a desiccation chamber to cool to room temperature and then weighed. The sediment concentration (mg/L) (parts per million) was calculated from the mass of sediment collected on the filter divided by the volume of runoff filtered. Total sediment from each plot was then calculated by multiplying the sediment concentration of the runoff sample times the total volume of runoff measured from its corresponding plot.
The filtrate of each sample was analyzed for NH$_4^+$, NO$_3^-$ in a continuous flow, conductimetric analyzer (Carlson et al. 1990). A 20 ml (1.3 tablespoon) sample of unfiltered runoff was used to measure total phosphorus (Murphy and Riley, 1958). The mass of nutrients lost from each plot was determined by multiplying the measured concentration of each constituent by the runoff volume for each respective plot. The annual cumulative mass lost for each measured constituent was the sum of the results for all the precipitation events. During some precipitation events, the runoff volume exceeded the storage capacity of the secondary collection containers on a few plots and so the cumulative values represent a minimum. Most sediment was located in the primary collector so that overflow loss from the secondary collector represents only a minor underestimation of total sediment loss.

**Statistical Analysis:**

Statistical analysis was performed using JMP® statistical software (JMP, version 6, SAS Institute, Inc., 1989-2005), using the JMP “Fit Model” platform. Inspection of the annual runoff data revealed a nuisance variable with a significant spatial influence upon runoff response, expressed laterally across the experimental hillslope. Multiple linear regression of total runoff volume vs. plot treatment and plot spatial position along the hillslope face (modeled as a continuous variable) identified a significant (F=13.47, p=0.001209) linear relationship between plot position (the nuisance variable) and runoff volume, which was independent of treatment effects. In other words, after controlling for treatment differences in runoff, a significant increase in annual runoff was observed with increasing plot number. This was thought to occur because of the slope length above the plots were longer at one end of the slope face versus the other. Because of the perimeter border, overland flow onto the plots was not observed, but subsurface seepage occurred during larger rain events. However, no interaction was detected.
between plot position and plot treatment; i.e., the effect of plot spatial position upon runoff volume did not significantly vary between treatments. Not surprisingly, this nuisance variable was found to show a similar effect with regard to the other response variables, all of which depend on runoff volume.

To control for the effect of this nuisance variable, single-factor analysis of covariance (ANCOVA) was employed for factor level mean comparisons, with the nuisance variable (spatial position) included as the model covariate. This test compared treatment means after correcting for the observed increase in runoff volume with increasing plot number. Post-hoc multiple-pairwise comparisons of the ANCOVA least-squares means were performed in JMP using the Tukey-Kramer HSD test (to control for experiment-wise Type I error inflation). The ANCOVA assumptions of homoscedasicity and residual normality were tested according to the Levene and Shapiro-Wilk tests, respectively. The assumption of homogeneity of slope was verified by failure to detect a significant interaction between the plot position and treatment effects. For all tests, statistical significance was determined at the alpha = 0.10 confidence level (comparisons were initially made at the alpha = 0.05 level; however, many differences were significant at the alpha = 0.06 to 0.08 level, so the 90% confidence level was selected in order to report these differences).

If a significant departure from normality or homoscedasicity was detected, a data transformation was attempted in order to meet these assumptions. Selection of an appropriate power transform, \( Y' = Y^\lambda \), was aided by inspection of a Box-Cox plot of the residual sum of squares (RSS) as a function of \( \lambda \), from which a convenient transformation (e.g. \( \log_e[Y] \) or \( \sqrt{Y} \)) was selected based on the location of the RSS minimum. Treatment means presented in tables are the back-transformed means. Possible outliers were identified by analysis of their deleted studentized residuals, with significance determined using a Bonferroni critical \( t \)-value of \( t(0.10/(2 \cdot n_T); n_T - r - 1) \).
where \( n_T \) and \( r \) are the total number of observations and factor levels, respectively. Observations meeting this criterion were considered candidates for exclusion if their associated Cook’s D statistic (a measure of the influence of the observation on the estimated parameters) exceeded the critical value \( F(0.5, p, n-p) \). One observation was ultimately excluded from analysis according to this screening procedure. In addition to this data point, plot 29 was excluded from all analyses because the total runoff volume of this plot exceeded the total volume of rain falling within the plot, indicating a large contribution of subsurface return flow to plot runoff.

Data are presented such that each treatment value is corrected as if it were spatially positioned at the center of the field plot (plot #18). Thus, the absolute values reported in Table 4 are relative to the runoff levels from plot #18. This was done to control for the nuisance variable of runoff as it relates to plot position.

**Results:**

Overall precipitation during this rainy season was 25 % greater than normal (Figure 1). The cumulative storm events for the first part of the rainy season, the month of December, equaled 221 mm (8.7 inches), which is 275% greater than the historical December average (California Department of Water Resources). Further, on 12/30 through 12/31 there was a 25 year rainfall event that delivered 84 mm (3.3 inches) of precipitation in a 24 hour period. This unusual weather pattern provided much greater than average seepage through the subsoil horizon, but it provided a good test of the ability of the treatments to perform in a high rainfall year. The nutrient loss data, which are normalized to account for the ambient hydrologic gradient on site, are presented in Table 3. The highest sediment losses occurred from the bare planed soil, the bare tilled soil and the compost mulch tilled into soil (BP, BT, and CMT respectively).
Table 3. Annual runoff (L ha-1) and nutrient (kg ha-1) loss data from compost treatments at landfill.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Runoff (L)</th>
<th>Sediment</th>
<th>NO$_3^-$</th>
<th>NH$_4^+$</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG†</td>
<td>1968</td>
<td>a</td>
<td>737.4</td>
<td>3.8</td>
<td>c</td>
</tr>
<tr>
<td>BP</td>
<td>2918</td>
<td>a</td>
<td>3554.2</td>
<td>12.1</td>
<td>abc</td>
</tr>
<tr>
<td>BT</td>
<td>1702</td>
<td>a</td>
<td>4216.1</td>
<td>10.2</td>
<td>bc</td>
</tr>
<tr>
<td>CIB</td>
<td>2946</td>
<td>a</td>
<td>1740.9</td>
<td>35.8</td>
<td>a</td>
</tr>
<tr>
<td>CMB</td>
<td>2208</td>
<td>a</td>
<td>1346.0</td>
<td>41.3</td>
<td>ab</td>
</tr>
<tr>
<td>CGB</td>
<td>2351</td>
<td>a</td>
<td>614.2</td>
<td>4.0</td>
<td>c</td>
</tr>
<tr>
<td>CMT</td>
<td>1588</td>
<td>a</td>
<td>6516.8</td>
<td>14.9</td>
<td>abc</td>
</tr>
<tr>
<td>MT</td>
<td>2186</td>
<td>a</td>
<td>1772.6</td>
<td>37.9</td>
<td>a</td>
</tr>
</tbody>
</table>

† AG-annual grass, BP-bare planed soil, BT-bare tilled soil, CIB-BFI compost blanket over bare soil, CMB-RMC compost over bare soil, CGB-RMC compost over bare soil with grass, CMT-RMC compost tilled into soil, MCT-RMC compost blanket over RMC compost tilled into soil, MT-RMC compost blanket over tilled soil. ‡ values in vertical columns followed by differing letters are significantly different using a Tukey Test to separate means, where p<0.1.

These were treatments that had either bare soil or had only fine (< 3/4 inch) compost fibers that did not hold the soil well after tillage. The incorporation of compost into the soil may have increased sediment loss due to loss of soil cohesion by mechanical fracturing during tillage. The AG, CGB and MCT treatments lost significantly less sediment than the CMT treatment. No other treatments attained statistical significance for sediment loss in this experiment. The excessive rainfall, interacting with ambient site conditions such as shallow limiting layer in the subsoil and subsurface saturation, created extreme conditions for erosion processes. Under these conditions, however, the AG, CGB and MCT treatments produced only 10 to 20 % of the sediment coming from the BP, BT and CMT treatments.

The treatments that produced the lowest NO$_3^-$ in runoff were the vegetated treatments (AG and CGB) and the MCT treatment. These treatments performed similarly because either they 1) did not have soil NO$_3^-$ available for loss because of rapid uptake by vegetation or 2) the infiltration was evidently great enough to infiltrate available NO$_3^-$ in the soil rather than to lose it to overland flow. The highest losses of NO$_3^-$ came from compost applications to plots with low infiltration rates (CIB, CMB and MT). Nitrate
losses in the AG, CGB and MCT treatments differed statistically from the CIB, CMB and MT treatments, but there was no difference seen between the other treatments.

Ammonium losses were lowest from the AG and CGB treatments. The \( \text{NH}_4^+ \) losses were highest from plots having a compost blanket application over soil with reduced infiltration, either from lack of tillage, or from tillage without organics incorporated into the soil, or from bare soils with no composts added at all. Though the variance disallowed assignment of statistical significance, the immature compost had about 20 % of the \( \text{NH}_4^+ \) loss as the mature compost in a paired set of treatments. The presence of grass cover or improved infiltration (treatments with tillage) was associated with reduced \( \text{NH}_4^+ \) losses in surface runoff.

Leaching losses from nitrate and ammonium were a small percentage of that applied as organic N. Table 4 shows that all treatments were less than 4 %, and the best treatment (MCT) lost only 0.12% of the nitrogen applied nitrate through leaching losses.

### Table 4. Compost treatment and leaching losses (as kgN/ha or percent of N applied)

<table>
<thead>
<tr>
<th>Compost treatment and leaching losses</th>
<th>N applied kg/ha</th>
<th>NO3 lost kg/ha</th>
<th>NH4 lost kg/ha</th>
<th>% loss nitrate</th>
<th>% loss ammonium</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG ann grass</td>
<td>0</td>
<td>0</td>
<td>3.8</td>
<td>3.5</td>
<td>na</td>
</tr>
<tr>
<td>BP bare planed</td>
<td>0</td>
<td>0</td>
<td>12.1</td>
<td>25.9</td>
<td>na</td>
</tr>
<tr>
<td>BT bare tilled</td>
<td>0</td>
<td>0</td>
<td>10.2</td>
<td>22.6</td>
<td>na</td>
</tr>
<tr>
<td>CIB immature comp blanket</td>
<td>70</td>
<td>1050</td>
<td>35.8</td>
<td>11.9</td>
<td>3.41</td>
</tr>
<tr>
<td>CMB mature comp blanket</td>
<td>175</td>
<td>3500</td>
<td>41.3</td>
<td>55.0</td>
<td>1.18</td>
</tr>
<tr>
<td>CGB compost grass blanket</td>
<td>175</td>
<td>3500</td>
<td>4.0</td>
<td>6.6</td>
<td>0.11</td>
</tr>
<tr>
<td>CMT compost mature tilled</td>
<td>175</td>
<td>3500</td>
<td>14.9</td>
<td>24.1</td>
<td>0.43</td>
</tr>
<tr>
<td>MCT mulch compost tilled</td>
<td>350</td>
<td>7000</td>
<td>8.1</td>
<td>24.5</td>
<td>0.12</td>
</tr>
<tr>
<td>MT mulch tilled</td>
<td>175</td>
<td>3500</td>
<td>37.9</td>
<td>108.3</td>
<td>1.08</td>
</tr>
</tbody>
</table>

*na: compost not applied*
Phosphorus losses were also lowest with grass cover or improved infiltration although statistical differences were not detected in this location and rain year (Table 3). The highest losses occurred with compost blankets over bare, untilled soil (CIB, CMB).

Discussion:
The overall observed trends from this study are similar to those previously published and help to provide more insight into how to best use compost on constructed slopes. Khaleel et al. (1980) reviewed the nutrient losses from studies that examined animal waste application. They stated that incorporated waste decomposed faster and did not lose as much nutrients in the runoff as areas with surface applied waste. They partially attributed this to the increase in surface hydraulic conductivity in the soil that had waste incorporated within it. We also found that, on average, the treatments that had compost tilled into the soil lost fewer nutrients in surface runoff than the treatments where compost was applied as a mulch. In fact, the compost mulch tilled into the soil (CMT) treatment lost 36, 44 and 66 % of the NH$_4^+$, NO$_3^-$ and P that the compost mulch over bare soil (CMB) treatment lost in runoff. Although incorporating the compost into the soil seems to minimize nutrient losses in runoff, this practice alone did not reduce surface erosion. When a mulch blanket was placed over the compost tilled in the soil (MCT), however, there was a significant reduction in sediment loss compared to the CMT treatment. The MCT treatment (mulch applied over compost incorporated by tillage) lost to nitrate leaching only 0.12% of the nitrogen that was amended in the compost. When ammonium and nitrate leaching losses were added together, the loss was only 0.47% of that applied. The application combination of mulch cover and incorporation made these treatments very resistant to nitrate loss.

There was no significant difference between the two compost types (RMC vs. BFI) in terms of nutrient loss (Table 3). The higher ammonium loss in the mature...
compost compared to the uncured compost was, none-the-less, non-significant. Faucette et al. (2004) found that total nitrogen and nitrate loss in runoff significantly differed between three compost types (excluding biosolid treatment) under rainfall simulation at the time of slope construction, but after three months there was no longer a significant difference. Since our measurements were an average of nutrient losses over the entire year, significant treatment differences existing early in the experiment may have not been expressed in this data set. Grass cover caused a significant reduction in NO$_3^-$ loss (CMB vs. CGB). Erosion control plans for slope construction designs typically specify revegetation cover, but plants may be slow to establish. For this reason it is good to have structural safeguards such as compost incorporation and mulch amendments in the slope design so that erosion and nutrient losses will be minimized if revegetation should not occur within the first year.

Conclusions:

Runoff in this experiment was strongly influenced by slope position and subsurface seepage. This was an unforeseen variable in this study, even though the slope construction and slope were visually uniform. Treatments should have placed in a randomized complete block design, rather than randomly situated across the entire slope (i.e. single block). Despite this, our data suggest that a greater reduction in sediment, nitrate, ammonium and phosphorus losses will occur when applying compost to constructed slopes as a surface blanket in combination with tillage of compost into the soil, when compared to either a surface blanket alone or compost incorporation alone.

Acknowledgements:
We would like to thank the staff at the University of California Landfill for their permission to construct our field plots at their facility. This project was funded by California Department of Transportation RTA# 65A0236, Doug Brown, Caltrans contract manager.
References:


California Department of Water Resources Data Exchange Center. http://cdec.water.ca.gov/cgi-progs/profile?s=DVS&type=precip


2.2. Field plot construction
(Kidwell interchange demonstration plots)

Chapter synopsis:

The effect of several developmental compost incorporation and tillage methods was not known for existing right of way slope (2:1) conditions using typical erosion control specifications as a comparison.

Field calibration plots were installed across a whole slope cross section (top to the toe) of an existing slope at Kidwell Interchange located 2 miles west of the intersection of I-80 and Hwy 113, just west of Davis, California. These plots provided an opportunity to up-scale treatments from experimental plots to whole slopes and they demonstrated compost amendment methods and outcomes. Five of the six plots were fitted with flumes to collect runoff. Rainfall volumes were very low in 2006 - 2007, resulting in no runoff from any plots. Rainfall in the 2007- 2008 rain season was sporadic but yielded three storms with runoff, after which rains effectively quit at the end of February. These storms showed that all compost treatments produced less runoff than the Type D erosion control treatment. Data were very general, however, given the low number of rain events and lack of replication. Establishment of native grasses was greatest on the Type I (Incorporate) plot with 50 mm (2") whole compost amended to the surface followed by tillage to 150 mm (6") (200 mm (8 ") total depth). This plot also produced some of the lowest runoff amounts. The most intensive treatment (dig and replace) had zero runoff, but lower grass establishment, perhaps due to lower water availability in the deeply tilled soil during the first summer drought.

The recommended slope treatment for low fertility soils is a 50 mm (2") coarse, unscreened compost amendment to the surface and rough tilled (disked or ripped, but
not rototilled or blended) to 250 mm (10 inches). This soil treatment should be followed by hydroseeding of native grasses, followed by a 25 mm (1") wood chip mulch in good growth areas (lower elevations) or 50 mm (2") wood chip mulch in areas with slower growth (colder or drier or steeper or more erosion-prone areas).

**Problem statement:**

Compost amendments have been used in lab experiments to test various components of organic amendment to soil function, but real world applications are needed to integrate all existing environmental effects and to demonstrate an "on the ground" perspective of compost application for erosion control.

**Introduction:**

Field plots at the Kidwell interchange were constructed to show compost surface treatment methods on a roadway embankment site. This site was chosen because of proximity to the UCD campus, and because the overcrossing provided access to a site that was somewhat removed from the busy I-80 trafficway. The site also represented a common, finer soil textured slope material that is commonly found in embankments in the central valley.

**Materials and Methods**

At this site, a wildfire had burned off the mustard and annual grasses the previous summer. Small areas were graded to remove ground squirrel mounds and fill burrows. Then all areas were track walked with an agricultural crawler tractor. Six plots were designed to demonstrate general compost use on for erosion control and revegetation treatments. Two were left as trackwalked surfaces, but the remaining four plots had a compost blanket / mulch surface treatment, the same compost volume that
was incorporated, and the same compost volume that was roughly incorporated by an excavate and replace (bench/step) method.

The specific treatments are:

(south end near I-80; left side of photos)

**Bare (Plot 6)** which was cleared of dead or burned vegetation and graded slightly to flatten undulations and then trackwalked with a small crawler tractor. Seed was hydraulically applied with a small amount of carrier fiber but no other amendments or treatments were applied.

**Type D (Plot 5)** is the conventional Caltrans hydroseed and erosion control treatment over trackwalked soil. Native grass seed (28 kg/ha; 25 lb/ac) were hydraulically applied with 800 kg/ha (714 lb/ac) of < 3/8 fibers that served as a carrier or bulking agent. Next, 3/8"minus fibers were applied 1500 kg/ha (1200 lb/ac) and tackified. This was intended to be the standard control comparison treatment rather than the zero (bare) control slope, since projects are not intentionally left barren.

**Buffer plot**

**Type M (surface mulch) (Plot 4)** uses a 25 mm (1") coarse (<3") compost mulch as a surface treatment with no tillage.

**Type I (Incorporate compost #1) (Plot 3)** utilized a 50 mm (2") coarse compost surface amendment that was then tilled in by rototiller to the surface 150 mm (6") of soil, for a total of 200 mm (8") of tillage depth. Native seed and carrier were then surface applied, and a 1500 kg/ha fiber mulch was applied over the top and tackified.

**Buffer plot**

**Type I (Incorporate #2 grassed) (Plot2)** is a trial of a compost incorporate treatment, but using incorporation with a backhoe bucket as a rougher, less finely mixed incorporation method. The bucket was used to create a diamond pattern of 300 - 500 mm (12 - 18) steps with a horizontal base under the tilled and compost incorporated substrate. Native seed and carrier fiber was then surface applied and a 1500 kg/ha (1200 lb/ac) fiber mulch was applied over the top and tackified.

**Type I (Incorporate #2 no grass) (Plot 1)** is the same as Plot 2 except no grass seed was applied and the plot was kept bare. This plot demonstrated the erosion control ability of the soil treatment by itself without plant cover.

(north end, away from I-80, lower on the ramp)
Figure 4. Construction (top photo), surface appearance (middle photo) and seeding treatment of the dig and replace (bench/step) treatment (lower photo). This soil treatment had the lowest runoff, but also had reduced grass regeneration and cover.
Figure 1. Kidwell soil treatment plots. Tillage treatments are 10 m wide and include two 5 m plots with different seeding treatments. A 3 m access buffer is located between every pair of plots.

Figure 2. Kidwell soil tillage treatment plots looking south towards I-80 and the Kidwell overcrossing.
Figure 3. Close-up views of Kidwell plot soil treatments (left to right in the field): track-walked surface (top photo), compost blanket (left half, middle photo) or compost incorporated (right half, middle photo); dig and replace (bench/step) (lower photo).
and are used for access up and down slope without walking on the plots.

Plots were constructed in Fall, 2006 using a commercial erosion control applicator. The plots were observed for two rain seasons (11/06 – 04/08). Rainfall amounts were checked after significant storms and runoff volumes were measured. Because of the lack of replication, no other water quality measurements were taken.

Results:

The plots produced no runoff during the first season. There are two factors that help explain the lack of run-off. First, the 06/07 season was unusually dry across the valley. There were only 4 significant rain events throughout the season, and there were significant periods with no precipitation between rain events. Thus, the soil never received enough precipitation to reach saturation and create runoff. Cumulative precipitation is graphed for that period in Figure 1.
The other reason that runoff did not occur may have to do with the recent construction of the surface treatments. Most erosion control studies show that varying treatment effects diminish over time due to the soil re-settling after numerous wetting and drying events, formation of surface crusting, and the physical breakdown of the amendment material. These recently constructed plots, especially with their compost incorporation, would have distinct tillage effects of heightened infiltration and reduced runoff.

The 07/08 rain season produced many more rain events and the plots did produce limited runoff. Figure 2 shows cumulative precipitation graph for that period.

Plot Type I (#1, with grass) did not produce any runoff over the two season span. The two precipitation events of interest were 12/7 and 01/27. These events produced runoff from multiple plots. The 12/7 sampling was preceded by 48 hour precipitation event that produced 1.6” of rain; which is a common rain event in terms of amount and frequency for the Davis area.

What is not known are the actual short term rain rates during this time interval. The runoff was most likely produced by a shorter interval of more intense rainfall within the 48 hours. In other words, the rainfall rate was probably not uniform over the specified time. The incorporated compost treated slope produced half the amount of runoff as the non-compost amended slope. The 1/27 precipitation event produced runoff in 4 of the 5 treated slopes. The precipitation event that preceded the site sampling lasted for 6 days, producing 95 mm (3.73”) of rain; which again is a common precipitation pattern for the Davis area. The two incorporated compost treatments produced an intermediate amount of runoff (13.5 L / plot), the mulch compost blanket
Figure 1. Cumulative precipitation for the Kidwell area from November 2006 to April, 2007.

Figure 2. Cumulative precipitation for the Kidwell area from November 2007 to April, 2008. Runoff was collected from the plots on: 12/17/07, 01/05/08, and 1/27/08.
Table 3. Runoff volumes for Kidwell plots at three dates in the 2007-2008 water year.

<table>
<thead>
<tr>
<th>dates of runoff</th>
<th>Bare</th>
<th>Plot 6 Type D</th>
<th>Plot 4 Type M</th>
<th>Plot 3 Type I (#1)</th>
<th>Plot 2 Type I (#2 grassed)</th>
<th>Plot 1 Type I (#2 no grass)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/7/07</td>
<td>nd</td>
<td>27 L</td>
<td>0</td>
<td>13.5 L</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1/05/08</td>
<td>nd</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>13.5 L</td>
</tr>
<tr>
<td>1/27/08</td>
<td>nd</td>
<td>54 L</td>
<td>27 L</td>
<td>13.5 L</td>
<td>0</td>
<td>13.5 L</td>
</tr>
</tbody>
</table>

resulted in 27 L / plot of runoff, and the non-compost amended slope produced the most runoff of all the treatments (54 L / plot). The deeply tilled (dig and replace; bench/step) treatment produced no runoff, but also had lower perennial grass establishment than the Type I incorporated compost.

Discussion:

The plots were constructed and monitored in what turned out to be several years of below normal rainfall. This reduced revegetation establishment of the native grasses somewhat, but mainly it reduced the runoff needed across the plot face to compare treatment effectiveness. Never the less, several rains occurred that confirm the finding from the landfill that compost tilled plus a coarse mulch over the surface is the best overall compost treatment to reduce surface flows. The type D erosion control gave twice the runoff as any other treatment, although sediment and nutrients were not measured from this demonstration type plot installation. The compost mulch (Type M) treatment appeared to not produce sediment (the overland flow was not muddy) but the packed soil under the mulch treatment appeared to sheet water off and infiltrate less than on the Type I treatments. This finding also confirmed observations of mulch performance over untilled soil.
The demonstration format also suggested that hydroseeding may be less effective on upper slope regions than lower on the slope due to low seed delivery to the upper slopes. This trend should be confirmed with a seed count from high and low slope positions on hose-applied hydroseed. The soils were uniformly moist from frequent, if small, rains, but germination density was much higher on the lower slopes.

The upper area of all plots showed cracking and slumping from runoff from the road crown. Slopes must be designed and treated to not only handle their own rainfall erosion loads, but also the flow from offsite, which in this case was the road. These observations of whole slope (top to toe) field calibration plots were the first attempt at upscaling research plots along a roadside. These demonstration plots indicate a need for tillage that can be done on-slope rather than reaching from top or bottom, as well as for seedbed preparation and potentially seed and mulch application.

Conclusions:

The recommendation from these demonstration-style plots is to amend the final grade surface with coarse compost 25 to 50 mm (1 to 2”) thick, and then coarsely till it in with ripping or coarse tillage, but not rototilling or extensive digging with an excavator to the extent that the soil is disaggregated. Then, after seeding, apply 25 to 50 mm (1 to 2”) of coarse mulch. Control annual grass the first year by mowing between late flowering and the milk stage of seed maturity. Run-on of drainage onto the slope should be treated by diverting the flow or by hardening slope sections to conduct moisture away or by bioengineering the slope sections that will experience increased flows. In urban areas or near roadways having high atmospheric nitrogen deposition, less compost should be used, or a blend of woody material with a low proportion of compost, in order to reduce nutrient availability and weed growth.
3. Nutrient content and release from composts

3.1. Nutrient content and release from composts for baseline estimates of nutrient release

Chapter synopsis

The amount of nutrient release from composts after application to field sites is hard to estimate because composts continue to decompose at various rates depending on substrate, production methods, carbon ‘quality’ and inherent N content. But, this information is needed to understand the risk to local water bodies. Currently, soil extraction methods are used to estimate “available” nutrients for crop production, but much of this amount would not be released during a leaching event. Composts applied to field situations undergo extensive decomposition over several years, during which the release of nutrients is determined by net mineralization (nutrient release) and immobilization (uptake) processes. Information that could predict nutrient release during these long-term trends would improve use and management for widespread field application of composts so that nutrients are not lost to local watersheds.

Compost materials are a complex combination of organic substances, some of which are readily released into the environment (mineralization), some of which are taken up into living microbial or plant tissues (immobilization) and some of which are organically bound to the substrate and are not available for leaching or plant or microbial uptake. Estimates of the size of these nutrient pools are generally estimated by chemical extraction, using methods that are developed to represent amounts proportional to plant uptake. Most of these methods have used developed with agricultural systems and are less well understood for wildlands systems such as road edges. But, they are a common starting place for estimating what proportion of the total
nutrient content of a compost amendment will be “available” for leaching or uptake in field situations, and are available from commercial testing laboratories. These lab data show that a small proportion (< 2 %) of the total nitrogen (N) is measured in “available” pools. This is a desirable characteristic, since some of these available N forms are easily leached from the soil or promote rapid weed growth. A larger proportion of phosphorus (P) is in “available” pools, but this indicator is more subject to errors for being representative of availability for this nutrient. Further, because soil mobility of this nutrient is low, the nutrient does not move as far in soils as nitrate does. This reduces the potential for P to produce impacts to water bodies unless the whole soil particle is mobilized as sediment.

The recommendation from this work is that yard waste composts can be applied to field sites can be used with little risk of nutrient loss. Subsequent research (Chapter 3.2) on N release from compost fractions indicates that the finest particle fraction has the most releasable N. This means that a 3/8 inch minus application will have a greater potential for loss in a sudden rain than a whole compost or a coarse fraction compost. A combination of 1 inch deep application of fine (3/8 minus) compost that is then tilled to approximately 10 inches, and also is overlaid with a coarse compost or wood mulch delivers the maximum nutrient but yields the lowest N loss of any method of compost amendment (Chapter 2). Field amendments should be integrated with long term nutrient dynamics, including nutrient uptake for revegetation and incorporation into plant tissues and soil organic matter. Recently, urban areas and road edges have been documented to be receiving excessive atmospheric N deposition. This chronic input may be as large or larger than the compost N inputs. Long term dynamics are expected to be predictable from compost chemical and physical characteristics, but this is not possible with current methods.
Problem statement

Predicting nutrient release from compost amendments is complicated by the occurrence of several chemical forms of any given nutrient that have different levels of being “available” for plant or microbial uptake or for leaching by rainfall. So, the total amount of nutrient needs to be apportioned into “stable” forms that are not released to the environment and “available” forms that are released. These availability indexes are empirically developed for agricultural applications, which can be used as a starting point for understanding nutrient release in wildlands systems.

Introduction

Analysis of organic materials starts by doing a “total” digest and elemental analysis of nutrient contents. This indicates the elemental content, but not how much of these elements is able to move in to other pools versus being organically and chemically bound in insoluble or unavailable forms. The “available” forms are evaluated by a number of methods, each specific to the element or to the environmental processes of concern. For example, a nutrient may be “available” to a microbe producing enzymes to acquire the nutrient, but the same nutrient may be unavailable for dissolving in rainwater. For these two examples, an enzyme digest or bioassay would be used to estimate the biological availability, while a hot or cold water extract would be used to estimate leaching potential. In this case, the leachable fraction would probably be available to the microbe also, but the enzyme accessible material would not be available for leaching. For these estimates, every element and every “availability” indicator should be critically evaluated for its relevance to the situation being characterized. In the case of compost analysis, “availability” indicators are often developed for understanding uptake by crop plants, but these tend to measure short term patterns of “availability” and not the years-
long processes that will occur with a revegetation project. Long term nutrient release patterns remain difficult to predict.

**Materials and Methods**

Compost materials that were analyzed were selected from well mixed amendments used on the landfill erosion control plots and on the Kidwell Interchange demonstration plots and on Brockway summit revegetation projects that occurred the same time as our field work. These materials included a coarse (unscreened) (BFC) material from Browning Ferris in Milpitas, CA and fine (sieved) produced from the same facility (BFF). A fine (3/8 minus) product (RCF) was produced by the City of Redding Municipal Compost Facility, Redding, CA. The Brockway material was attained from Full Circle Farms and was a coarse (unscreened) material (FCC).

All composts were well mixed, carefully composited and sub-sampled and sent to two compost testing laboratories in northern California, including Soil Control Lab, Watsonville, CA and Soil and Plant Laboratory, Inc, Santa Clara, CA. Because larger compost particles are relatively inert, these lab tests represent materials sieved before analysis to 1/2 or 3/8 inch. Only the nitrogen (N) and phosphorus (P) data are reported here since these are the primary elements of concern for a field use and management of compost applications.

**Results**

As expected, the "available" N was a small fraction of the “total” N pools. Data are presented Table 2.1. Nitrogen levels in “available” pools that would be potentially available for plant or microbial uptake or for leaching losses, represent less than 2 % of the total N applied in the compost (center and right hand columns). All compost materials released less than 3 kg/ha (3 lb/ac) except the Redding material, which
released 14 to 18 kgN/ha (13 to 16 lbN/ac). Common plant uptake rates for grass growth can run 50 kg/ha or more, so these levels are not excessive unless the rains come early in the fall when plants are small. As compost decomposition proceeds, the organic compounds will continue to degrade and more N will be released (mineralized) as carbon is oxidized away. The pattern of the subsequent delayed release is unknown, and needed for use and management.

Table 1. Estimated total and available levels of N and P nutrients in four compost materials.

<table>
<thead>
<tr>
<th>Plant and Soil Lab</th>
<th>test results</th>
<th>available</th>
<th>N added</th>
<th>&quot;available&quot;</th>
<th>Soil Control Lab</th>
<th>test results</th>
<th>available</th>
<th>N added</th>
<th>&quot;available&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>nutrient</td>
<td>as % of 25 mm</td>
<td>as % of 1 inch</td>
<td>ppm</td>
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Table: Estimated total and available levels of N and P nutrients in four compost materials.

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<td>%</td>
<td>kg/ha</td>
<td>lb/ac</td>
<td>ppm</td>
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The phosphorus (P) levels that are “available” differed according to lab analysis. One lab estimated 12 to 23 kgP/ha (11 to 20 lbP/ac) from using a dilute chemical extract to represent “available” P. The second lab analysis used an empirical estimation factor, and using this value, an estimated 59 to 93 kgP/ha (53 to 83 lbP/ac) were released. Agricultural crops often receive fertilizer rates of 100 kg P/ha, so the rates estimated here are not atypical for agricultural regions.

Conclusions:

Use of conventional soil tests for plant nutrient availability from comports indicates that only a small proportion of the total N that is applied to a field site would be available for leaching or uptake as ammonium or nitrate. This small “leachable” pool also means relatively low levels of plant available N occur. This characteristic is countered by loading on relatively large amounts of compost volume, creating an amendment with perhaps 1000 kg total N/ha, but having only 20 kg available N/ha, for example.

The proportion of total P that is estimated to be “available” is larger, but most of these forms of P adsorb quickly to soil particles. This means that the nutrient loss to local watersheds would not occur from leaching waters in most substrates but rather from mobilized and transported sediments. Reduction of sediment losses will stop P translocation to water bodies. Longer term estimates of N loss over several years is needed.
3.2. Estimates to develop indicators of compost curing to predict nutrient dynamics

Chapter Synopsis:

Compost nutrient release varies between different ages of composts, even when from the same producer and feedstock. Because composts can either release (mineralize) nutrients or immobilize (withdraw) nutrients from the soil, a method to predict the current or future behavior of a compost amendment would be beneficial and would improve field use and management of these materials.

This chapter explores several instrumental methods to evaluate compost chemical structure, offering clues to predict the nutrient behavior under field amendment conditions. These methods used thermal analysis and thermal gravimetry to detect more stable compounds forming during the composting process. This chemical stability is what makes composts acquire the "cured" characteristics of slower decomposition and greater N availability. Distinct age-related differences were identified in compost materials, but a critical indicator, respiration, remained highly variable and unresolved as to its relationship to the chemical indicators that predict nutrient release. Efforts to develop a more perceptive indicator of nutrient availability for rapid, dependable screening of yard waste compost batches before field application were not completed within this project period. But, information from this research has confirmed that the finer sized materials in composts are the source of N leaching losses, that composts can be evaluated as mixtures of at least two very general stability groups of organic compounds, and that non-organic (mineral) materials accumulate in composts and may influence the measurement of chemical trends when samples are standardized on a weight basis.
These results suggest that finer composts will be more liable to release N, while coarser compost mixtures should be seen as having a non-composted fraction remaining as well as an already composted fraction. Appropriate utilization of these different types of compost materials may include application of less well cured materials to areas with the greatest sensitivity to N impacts, or to areas with heavy atmospheric N inputs. Well cured composts (extensive aerobic decomposition period after thermophilic composting phase) may be more productive when applied to very nutrient poor substrates with little ambient soil nitrogen content. Long-term prediction of N release needs to account for the fraction of residual plant tissue compounds in the compost versus decomposed organic residues versus the mineral (ash) content of the compost material.

Introduction:

Nutrient release from organic materials such as composts is not a static, inherent characteristic of the material, but a dynamic and variable process influenced by time and field conditions. In composts with abundant and decomposable organics (high wood chip or straw content), microbes often rapidly take up available nutrients, especially nitrogen (N), and can sequester available nutrients into their biomass (called immobilization). These materials may actually withdraw N from the soil. As these energy-rich substrates are depleted, however, the microbial population declines and the N rich organic compounds in the microbial biomass starts to decompose, releasing much of the accumulated organic N. The early stages of composts, having a greater amount of cellulose, are characterized by a high C:N ratio (> 25). After further decomposition, this pattern generally reverses. Carbon losses create a lower C:N ratio (< 15) and further decomposition release nutrients, especially in a process called mineralization. This general process results in release of N as ammonium and especially nitrate in the
compost. An extended period (weeks to months) of aerobic decomposition after the thermophilic stage of composting is known as curing and produces a yard waste compost material that has a higher rate of nutrient release than comports that have completed thermophilic processes (i.e. are mature) but have not been cured.

Problems arise with field performance of comports when relying on the C:N ratio relationship during non-routine uses. For example, if compost use and management is developed around application to fertile, biologically rich agricultural soils, which can capitalize the decomposition process with ambient nutrient availability, similar rates of decomposition may not occur when the same materials are applied to sterile, low organic carbon, droughty, degraded substrates. These materials may have no surplus nutrients to spare or decomposition is too slow to make them available. Soil moisture and temperature conditions may also vary and change the net decomposition process. Other problems arise with this general relationship when materials of unusual particle size distribution or decomposition are used. Larger wood fragments or bark chips or decay-resistant wood types (heartwoods, redwood, cedar) may have high C:N ratios (indicating immobilization conditions), but because decomposition is so slow, little decomposition occurs. A blend of a resistant organic material (such as bark chips or heartwood) and a very decomposable high-N material (biosolids sludge) may behave in the field as an excessively N rich amendment even when the C:N ratio appeared proper, since the carbon is resistant to decomposition.

Composts generally work and are beneficial when applied to field conditions. Their widespread use is recommended. But, as plant materials and installation projects become more expensive, as revegetation projects are developed on difficult substrates and harsh site conditions and as unforeseen nutrient losses to local water bodies becomes more closely monitored, the field behavior of these large nutrient loadings onto field sites needs to be understood in greater detail.
**Materials and Methods:**

Composts from different commercial producers were analyzed to evaluate potential chemical indicators of compost curing state. Two materials were acquired from ZBest (Gilroy, CA) and Grover Environmental (Vernalis, CA). The ZBest material ages (measured from initial grinding at the start of composting) were 0, 1.2, 3, and 6 months. The Grover materials were 0, 4, and 9 weeks. These times generally include a 15 day period of thermophilic composting with frequent turning, moisture control and temperature monitoring. Following this process the materials are windrowed and turned approximately weekly until they have attained some degree of curing. Composts of varied ages were collected from the producer in 28 gallon plastic trash bins and transported to the UC Davis campus for processing.

Composts were dried to stop decomposition processes. All materials were sieved by hand into three size classes for chemical analysis: 9.5 mm to 2 mm, 2 mm to 0.5 mm, and < 0.5 mm ((3/8" to 5/64", 5/64" to 2/100", and less than 2/100"). Size classes referred to as A, B, and C, respectively. Each age/size class was re-homogenized by gentle mixing with a hand trowel before removing ~5 g subsamples for ball mill grinding.

Total carbon and nitrogen was determined for each ground sample by flash combustion/chromatographic separation using a Costech ECS 4010 Elemental Analyzer.

Thermal analysis of each ground sample was done using a thermal analyzer coupled to an FTIR bench. The instrumentation consists of an STA 409 PC Luxx, furnace type S (temperature range of 25C-1500C) with a TG-DTA carrier, coupled to a Bruker FTIR Spectrometer Tensor 27, Hyperion 1000 microscope, and TGA accessory. All samples were heated at 20K/minute up to 1000K in an oxidizing atmosphere of "zero" air (hydrocarbon-free compressed air). The most typical and illustrative results from the two compost materials are shown below.
### Results:

**Total carbon and nitrogen**

Elemental content of C and N are shown in Table 1. Note that carbon content is greater in larger fragment sizes (woody pieces) and that for any size class, carbon content generally decreases with age from 0 to 1.2 to 3 months. By 6 months, carbon is relatively well stabilized and these decreases slow.

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<th>Nitrogen (%)</th>
<th>Carbon (%)</th>
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Table 1. Elemental content of compost materials of different ages from ZBest facility (top table) and from Grover (bottom table).
Figure 1. Ratios of C:N content for ZBest (upper) and Grover (lower) compost materials at different ages and size fractions. The coarser (A), medium (B) and finest (C) fractions have progressively lower C:N ratios, indicating decomposition of degradable carbon. Further, C:N ratio declines with age of compost, except for the 6 month material in the top graphic, which may result from resistant woody shreds that were fragmented during sample handling.
Particle size analysis

Particle size distribution was calculated based on the mass of each sieved size class related to the total mass of each age. Note that the fresh, chipped material (0 months) starts with a large proportion of large particles but few small particles. By 6 months’ time, a greater proportion of all particles are in the finest fraction. The same general pattern was observed in Grover materials. A question remains about the nature of the remaining large particles. These may be undecomposed remnants of the initial large particles, or they may be extra resistant fractions that remain, or they may be altered from their original form by the composting process (pore plugging, rind formation, salt effects). Further physical fractionation and analysis of the compost would help identify the state of the organics in each particle size fraction.

Ash content was determined from the mass loss data from thermal analysis. This process evaluates the non-organic material (ash) that was not burned off during analysis. Generally, ash content increases with aging time. This trend confirms that organics are leaving the sample matrix and mineral ash is remaining, and accumulating to a greater proportion of the remaining material. The exception is that the finest fraction of the Time 0 material has an elevated ash content, perhaps because of dust and dirt brought in with the plant materials. The role that this may play in influencing the composting process by providing nutrients or some type of particulate is not known.
Figure 2. Particle size distribution of ZBest (upper) and Grover (lower) compost materials at different ages and size fractions.
Figure 3. Ash content as percent of total mass loss by size fractions (A, B, and C). Note that size fractions differ between each facility. Samples with less organic content have more ash. Ash content increases with decreasing size fraction indicating organic matter decomposition and accumulation of mineral fractions.
**Thermal decomposition analysis**

The blue line on each thermogram shows the heat flow through the compost sample as a function of furnace temperature. The significance of this line is that compost particles that release energy do so at different temperatures. The green line in the graphs shows the weight loss from the sample as organics burn off. The development of two energy release peaks is used to track the type of organic compounds that form in the sample as the age increases. As the composts age and as the size of the compost decreases, dual exothermic peaks develop. This is an indication of chemical bond type and bond energies changing as decomposition proceeds. The first exothermic peak consists of the aliphatic compounds (sugars and cellulose type compounds from plant materials). The second peak consists of aromatic compounds, whose stronger bonds require more energy (higher temperature) to be broken. These may be concentrated in the remaining plant tissues as lignin type compounds, or they may be formed by microbial action. As the compost ages the aromatic peak increases in intensity compared to the aliphatic peak. This corresponds with the understanding that as decomposition proceeds there is an increase in the humic material content. Humic materials consist of humic acids and fulvic acids and are thought to be complex aromatic macromolecules linked together by amino acids, amino sugars, peptides, and aliphatic compounds.
Figure 4a,b,c. Simultaneous thermal analysis of thermal gravimetry and differential thermal analysis of uncomposted (0 month) yard waste from (a) 9.5 to 2 mm; (b) 2 mm to 0.5 mm and (c) < 0.5 mm size fractions.

The blue thermogram trace indicates a mix of materials that decompose from 350 to 550 °C at the same time as the green trace shows weight loss. This is a whole compost sample.

When smaller particle sizes are tested at 0 months time, two peaks occur.

At the smallest particle size (<0.5 mm), two peaks (aliphatic and aromatic) are shown, but the first is larger than the second, indicating undecomposed plant material.
Figure 5a,b,c. Simultaneous thermal analysis of thermal gravimetry and differential thermal analysis of composted and moderately cured (1.2 month) yard waste from (a) 9.5 to 2 mm; (b) 2 mm to 0.5 mm and (c) < 0.5 mm size fractions.

At 1.2 month’s time, the aromatic peak is visible in the coarse fraction, with less of the aliphatic peak remaining.

In smaller particle size fractions of the same time period, the peaks sharpen.

In the smallest fraction, the aliphatic peak is the smallest, indicating loss of plant material and gain of aromatic compounds of unknown source (the second peak).

Figure 5a,b,c. Simultaneous thermal analysis of thermal gravimetry and differential thermal analysis of composted and moderately cured (1.2 month) yard waste from (a) 9.5 to 2 mm; (b) 2 mm to 0.5 mm and (c) < 0.5 mm size fractions.
At 6 month’s time, the trend of lower aliphatic and higher aromatic peak continues. Here the coarse fraction shows remnants of plant materials.

The finer fractions have clearer differences indicating more advanced decomposition.

The smallest and oldest samples show the clearest peaks and the greatest weight loss of these compounds (55 %) as shown by the green trace. The large second peak suggests a high level of organic stability.

Figure 6a,b,c. Simultaneous thermal analysis of thermal gravimetry and differential thermal analysis of composted and well cured (6 month) yard waste from (a) 9.5 to 2 mm; (b) 2 mm to 0.5 mm and (c) < 0.5 mm size fractions.
Figure 7. Ratio of aromatic (ring compound) to aliphatic (straight chain) peaks from thermal analysis of the ZBest (upper) and Grover (lower) composts of different ages and size fractions. Lower bars indicate more sugar or cellulose related compounds, while higher bars represent more condensed (humified) compounds. The lower chart covers only about 2 months compared to 6 months in the upper chart.
The plot of the ratio of aromatic peak to aliphatic peak heat flow maximums does show that there is a trend towards increased aromatic character over time and as the size class decreases.

**N release:**

At the end of the three week incubation, the jars were leached with 250mL 0.01M CaCl$_2$ solution three times and the accumulated 750 mL was combined. Two mL aliquots were removed and analyzed on a continuous flow soluble nitrogen analyzer for NO$_3^-$ and NH$_4^+$. The 1C (one month) compost had the highest level of ammonium (Figure 8).

The oldest and smallest compost (2.25C)(slightly over two month), however, had the most nitrate (Figure 9). The bulk of the soluble N (ammonium and nitrate) is available only in the smallest fraction of the oldest material. This suggests that younger composts, which are typically applied to field sites, will release little soluble N, whereas well cured composts, especially if screened to smaller particle sizes, have the most potential for N losses. The total of all soluble nitrogen is graphed in Figure 10. This shows that the bulk of all soluble N will be in the oldest and finest fraction.
Figure 8. Ammonium release by dilute salt extract from Grover compost materials.

Figure 9. Nitrate release by dilute salt extract from Grover compost materials.
Composts were incubated and a time course of extractions were made to determine the effect of testing air dried versus moist, incubated compost volumes (Table 11). The comparison data between incubated and unincubated composts shows that further decomposition of the oldest compost material draws down the leachable nitrate in the woody fraction (upper graph) compared to extraction of unincubated compost samples (lower graph). The short term “availability” assay (salt extract) (as used in extraction nutrient availability tests) shows much higher nitrate proportion in the coarse fraction of the oldest material. This trend shows that further decomposition of compost coarse fragments in field situations continues to draw down available nitrate, reducing leaching potential. It also shows the difficulty of interpretation of test results of short-term processes such as leaching events.

Figure 10. Total soluble N (ammonium plus nitrate) by dilute salt extract from Grover composts.
Figure 11. Proportion of nitrate and ammonium leached from compost samples with (upper chart) and without (lower chart) a three week aerobic incubation period.
Conclusions

Soluble N extraction measurements confirmed that the smallest and oldest fractions are primarily responsible for much of the N mineralization (release) from composts. The proportion of this fraction in a bulk mixture of compost, along with the decomposability of the other fractions is expected to determine potential risk of N loss after field application.

Compost organic characterization methods confirm that the non-organic ash component increases in smaller size fractions and with time of aging. This biases evaluation of decomposable C organic content and N mineralization or immobilization dynamics and may account for some of the inaccuracy in predicting N release from composts.

Thermal gravimetry confirms that straight chain (cellulosic; plant based) materials decrease (the first, aliphatic peak becomes smaller with time) while condensed ring compounds increase (second, aromatic peak becomes larger) as compost curing time increases and as smaller size fractions accumulate or are selected. This is shown in the “aromatic to aliphatic ratio” and indicates that cellulose and sugar compounds are decomposing while less easily decomposable ring-containing organic compounds increase or accumulate. These chemical changes are the basis of organic stability and humification characteristics. These data indicate that composts change in chemistry by both size and age, with small fractions being more extensively processed or cured than larger fractions. This suggests that even moderately aged compost should be regarded as a mix of different organic material types, and that different compost fractions may be more indicative of curing status and field behavior of a compost batch than an overall bulk sample, especially if screened during production. The proportions of decomposable versus stabilized compounds would then be used to predict future nutrient release or
organic stability behavior of the bulk material. This methodology is not ready for field implementation but analytical components have been developed and are in place.

The present research has confirmed an unequal aging sequence in bulk composts. The next step is to develop ways to fractionate compost and measure each fraction separately, or alternatively to develop a prorating method for bulk composts to account for the fraction that is more decomposed (more stabilized) versus less decomposed (less stabilized, but potentially size inhibited) fractions in a whole compost. Creation of a more uniform experimental compost material for sample analysis may allow identification of key indicators of organic stability without the heterogeneity of samples that are mixtures of whole shredded or chipped bulk compost material.

Physical and/or chemical fractionation are needed so that the more decomposed or microbial residue portions are separated from the as-yet undecomposed plant material fractions remaining in the sample. Once the chemical tests for plant versus microbial residues or stabilized, humified materials have been developed, these indicators can be used on whole composts to evaluate curing state and future N mineralization or immobilization potential.

Use of conventional N availability tests also has limitations. For example, the proportion of leachable nitrate is high in an extract from a dry compost, but is much reduced during incubation processes with coarse woody material in the same sample. This indicates that operational tests may provide results that do not reflect what occurs in field situations. Until the chemical components of composts are understood, tests must be carefully selected to represent field conditions.

At this time, composts remain a recommended soil amendment that provides positive benefits to degraded soils over several-year periods. But, during the first few years after application, compost nutrient release remains variable and unpredictable as the different compost fractions interact with each other and the soil environment. For
example, a well cured compost product with high nitrate content may produce small leaching losses if saturating rains come before plant growth starts, although these amounts are still a small part of the total N content applied. Conversely, a poorly cured compost product may create a lack of nutrients that can reduce growth of revegetation species in nutrient poor substrates during the first season or two of growth. Use of larger amounts of finer screened compost products (< 3/8 in) are more likely to provide relatively greater amounts of leachable N, especially if they are from older, more cured materials. Use of C:N ratios for predicting N release may well be confounded by the presence of undecomposed plant-based coarse materials with high C:N ratios within a matrix of more decomposed residues of low C:N ratio. Analytical tests to predict nutrient release from composts before field application can be developed using the tools generated in this project, but further field validation is needed.
4.0. Rainfall simulation, field monitoring and demonstration plot construction

4.1 Infiltration effects of compost incorporation: Use of compost materials on drastically disturbed, sandy substrates to improve short to medium term infiltration and reduce sediment mobilization.

Chapter synopsis

Degraded or construction-impacted substrates are often compacted and have low infiltration. This leads to overland flow and surface erosion. The effect of compost tillage into soils on infiltration rates has not been measured in controlled trials. This information is needed for improved design of field projects.

This chapter evaluates the use of incorporation of compost and woody materials to increase and maintain infiltration, for the reduction of sediment mobilization and for improved revegetation. Incorporation of compost or woody fragment materials to construction-impacted substrates generates 20 to 90% increases in infiltration at the time of incorporation, depending on type of geological substrate and texture. Incorporation of fine (< 10 mm (< 3/8)) comports provides minimal effect, although these fractions are useful for improving nutrient availability. The type of coarse woody fragments (compost “overs” versus wood chips 10 to 75 mm (3/8 to 3 inches) in length) did not have a significant effect on infiltration in these test conditions. Surprisingly, there was not consistent increase in infiltration from increasing amounts of woody incorporation. A 50 mm (2 inch) layer tilled to 10 inches did not consistently outperform a 25 mm (1 inch) layer, although it may last several years longer in the field soil. With
approximately one season’s time after amendment, some substrate types re-settled and infiltration decreased by about 50 %, while infiltration in others maintained or increased approximately 10 %. Unanswered questions involve the effect of a more uniform coarse fragment size (all 50 to 75 mm (2 to 3 inch) size, for example) and effects on fine textured substrates rather than the sandy materials tested here. Within a few years, these woody fragments will decompose, by which time the infiltration of the substrate must be maintained by stabilized organic matter and soil aggregates.

The recommended amendment to improve infiltration, if needed, is 1 or 2 inch layer of coarse woody material, tilled to approximately 10 inches. The desired thickness depends on objectives for longevity and the tillage depth depends on regional weather patterns.

**Problem statement**

Newly constructed or barren, erosive sites often have substrates that pack and settle and have low infiltration. Rainwater on these sites tends to flow overland rather than infiltrate, increasing sediment mobilization. At the time of construction, tillage can greatly increase infiltration. But, the substrates often “melt” and settle and repack, quickly reducing tillage-generated infiltration characteristics. A method for keeping infiltration rates up during the few years of plant establishment is needed in order to reduce sediment generation and to provide moisture for plant growth, which will eventually protect the site and maintain the soil structure.

**Introduction**

Rainfall infiltration rates that are adequate to minimize overland flow during storm events are needed both for source control of sediments and for sustainable revegetation growth during droughty summer months. The rate that is ‘adequate’ depends on target
storm intensity, slope and existing substrate textures or geology. Erosion and sediment mobilization results when excess rainfall is shunted to overland flow by inadequate infiltration, but from the plant’s perspective, low infiltration rates are a negative effect because they reduce the amount of rainwater that enters the soil and reduce the moisture that is stored and available for summer growth. Revegetation cover thins out with time, exposing the substrate to more erosion and the process continues.

Organic matter deposition from plant growth can rebuild soil aggregates, but this is a lengthy process that can take longer than a decade (SRE II results). This means that the first seasons of a revegetation process are when the site is at the greatest risk because there is the least amount of plant growth and soil organic material and the greatest tendency for substrate particles on the slope to settle, pack and decrease in infiltration capacity. Surface erosion control blankets and mulches only protect against rain-drop impact, so any accumulated water that is not infiltrated gathers on the surface and gains speed until the surface erosion control treatment is floated off, undercut or eroded. Mats that are keyed into the slope can withstand greater flows, but the service life of many products is only a few years, and then the strength decreases. Sooner or later a storm provides sufficient intensity to overwhelm the surface erosion control treatment, unless revegetation has already well colonized the site.

Shallow-rooted annual grasses, often used as erosion control species or occurring as the dominant invader to a site, only root in the top few inches of soil. Although this is a “revegetation” cover, the depth to which moisture can percolate into the soil is often so shallow that larger storms generate sufficient water flow to wash out or cause shallow slips even in established stands of these shallow-rooted annual grasses.

The infiltration trials described here are intended to evaluate whether yard waste composts or coarse organic amendments can be used to improve infiltration immediately
at the time of incorporation on construction-impacted project substrates. The goal is to regenerate temporary conditions that facilitate infiltration for the first few years of a revegetation project, and that then sustain a site until natural soil aggregates are regenerated over the following decade or so. The target substrates are coarse textured (sandy) substrates from Caltrans rights-of-way that are commonly observed to be erosive and difficult to revegetate. Information from these trials will be used to recommend changes to Caltrans erosion control specifications.

**Materials and Materials:**

Rainfall simulations were conducted on three substrates collected from actively eroding sites, two from northern California and one from southern California. The first substrate was a decomposed granite (DG) material collected from a Caltrans right-of-way on the west side of Lake Tahoe, Hwy 89, near Bliss State Park. A second Tahoe Basin material was a saprolytic volcanic lahar (VL) (solidified mud flow) collected from the north side of Lake Tahoe, Hwy 289, from a cutslope at Brockway Summit. The third substrate was an erosive, sandy, magnesium-rich marine sediment (MS) that was collected along I-15, in San Diego County, east of Marine Corps Air Station at Miramar, CA. These sites are characterized as being drastically disturbed, meaning all topsoil and organic material was removed from the soil sites (Box, 1978), resulting in low OM levels, low levels of aggregation, and minimal soil structure. These characteristics all contribute to low infiltration rates.

The soils were sieved to 10 mm (< 3/8") and air dried. This is a larger size than the conventional 2 mm sieve fraction used for soil analysis and was selected to avoid pulverizing remaining soil or geological structure. The particle size distributions of these materials are listed in Table 1. All soils were packed into experimental bins 50 x 40 x 40 cm (18 x 16 x 16") to attain an air dried bulk density of 1.35 g cm\(^{-3}\), a standard degree of
soil density. The bins were perforated at the bottom by drilling 6 mm (0.25") holes on a 50 mm (2") spacing grid pattern to allow for drainage. Prior to packing the soils, water was added (5% by mass) to make the soils “tilthy” and easier to mix (Klute, 1986, pg 619).

Table 1. Particle size distributions of study soils. DG, decomposed granite; VL, volcanic lahar; MS, marine sediment.

<table>
<thead>
<tr>
<th>Substrate type</th>
<th>Sand %</th>
<th>Silt %</th>
<th>Clay %</th>
<th>texture classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG</td>
<td>92.9</td>
<td>6.5</td>
<td>0.6</td>
<td>sand (S)</td>
</tr>
<tr>
<td>VL</td>
<td>80.7</td>
<td>17.1</td>
<td>2.2</td>
<td>sandy loam (SL)</td>
</tr>
<tr>
<td>MS</td>
<td>64.5</td>
<td>12.7</td>
<td>22.8</td>
<td>sandy clay loam (SCL)</td>
</tr>
</tbody>
</table>

Compost Treatments

Different compost treatments were generated by mixing various amounts of fine or coarse compost or woody materials into the three sandy textured substrate materials. These amounts are calibrated to be equivalent to a given thickness of the amendment material applied to the substrate surface before incorporation. In this way, they can be visualized to represent a conventional field application of some amendment thickness followed by tillage and incorporation. For this experimental work, however, the appropriate amount of material was calculated by weight and mixed uniformly throughout the depth of the substrate in the bin. Treatment mixtures were uniformly packed by 50 mm (2") layers during construction.

Treatments included 1) bare (control); 2) an amendment equivalent to 2" surface application of fine compost (screened to < 10 mm; < 3/8 inch); 3) 2” of fine plus 1” of coarse woody amendment; or 4) 2” fine plus 2” of coarse amendment. The coarse woody amendments were either compost overs or wood chips that were 10 mm to 75 mm (3/8 inch to 3 inch) screen size.
Compost that passed through a 3/8” sieve was considered “fine”, and the fraction that could not pass through was considered coarse. Two separate coarse amendments were studied (coarse compost and coarse wood chips). The particle size distributions of the two coarse composts are presented in Figure 1.

The compost amendment rates are listed in Table 2. Each treatment was replicated 3 times per soil type. A coir fabric erosion mat was added to the surface of each bin to prevent splash detachment and to simulate the field condition of having a mulch or erosion control blanket as a cover.

### Table 2. Compost treatment volumes

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Fine compost (&lt; 3/8 inch)</th>
<th>Coarse compost (&gt;3/8 inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fine</td>
<td>11% by volume 2 inch layer, incorporated</td>
<td>0</td>
</tr>
<tr>
<td>Fine compost plus 1” coarse amendment (compost or woodchips)</td>
<td>11% by volume 2 inch layer, incorporated</td>
<td>5.5% by volume 1 inch layer, incorporated</td>
</tr>
<tr>
<td>Fine compost plus 2 inch depth of coarse amendment (compost or woodchips)</td>
<td>11% by volume 2 inch layer, incorporated</td>
<td>11% by volume 2 inch layer, incorporated</td>
</tr>
</tbody>
</table>
Figure 1 (a,b). Particle size distributions (volume and length) of coarse amendments.
The fine compost addition (11% v/v) is equivalent to a 1500 kg N ha\(^{-1}\) amendment, if it were added as a 20 cm (8 inch) incorporated layer in a conventional revegetation project that is tilled to a conventional depth. The greater depth (to 50 cm (18 inches)) was used in these experimental bins because the focus was on accounting for the infiltration characteristics of the amendment, not nutrient contents or the volumetric water storage characteristics. The total N of the fine compost was 1.4% as measured by dry combustion / gas chromatography (Bremner and Mulvaney, 1982; Carlo Erba NA 1500 elemental analyzer (Fisons; Milan, Italy)). The volumes of the coarse amendments are equivalent to 1 or 2 inch of surface mulch layers. The bulk densities of the compost fractions were found to be 0.48 g cm\(^{-3}\) for the fine compost, and 0.4 g cm\(^{-3}\) for the coarse amendments.

**Rainfall Simulations:**

A 1 m\(^2\) (39” square) rainfall simulator was used to provide controlled experimental rainfall events. The simulator is similar in design as described by Battany and Grismer (2000a), with modifications to simulator height to improve portability (reduced from 16 feet to 4 feet) and the use of generator-driven submersible pumps to improve pressure control. The soil bins were loaded in late January, 2008. Rainfall simulations were performed on all bins at this time. The rainfall rate was 120 mm/hr, and the duration was 30 minutes. No data was collected during this first rain event; rather, the rain event was performed in order to allow the soil and compost amendments to “settle” after construction. Three other rainfall events followed. The first was performed 02/02-02/05, the second was 04/09-04/12, and the final simulations were 05/17-05/20, 2008. Data was collected during the February and May rainfall simulations. The April simulation (at the same rate and duration as the initial) was performed in order to allow the soils to saturate and expand, and then subsequently dry and contract, in
order to examine how the treatments were performing both as a function of time, drying processes and subsequent storm events.

The rainfall rate of the February and May rainfall simulations equaled 120 mm/hr. This is an intense rain rate for California. In fact, the estimated 100-year 15-minute storm in the Tahoe Basin equals 60 mm/hr. The higher experimental rate was chosen in order to overwhelm the infiltration potential of the soils and to produce saturated conditions, under which steady state saturated conductivity (Ksat) occurs. The excess moisture that ran off the surface was subtracted from the applied volume of simulated rainfall, thus allowing measurement of the experimental Ksat for the substrate and treatment. The duration of the rainfall events varied by soil and treatment, and simulated rainfall continued until steady-state Ksat was reached. This generally required 30-45 minutes per run. Surface runoff volume samples were collected every two minutes from the onset of overland flow until steady state was reached.

**Pilot Study:**

A preliminary pilot study was conducted in order to refine methods and scope initial data trends. Where appropriate, some of this preliminary data is included in the overall results. Smaller bins (30 x 30 x 40 cm; 12 x 16 x 16") were used in this pilot study, and were packed with either a decomposed granite (similar to the one previously described) or a Yolo loam (USDA texture classification), at a bulk density of 1.35 g cm$^3$. Compost treatments were divided into two groups, either fine or whole and were applied at either 10 or 20% (v/v); again, compost that passed through a 3/8” sieve was considered “fine”. A one-time rainfall simulation event was conducted at a rate of 60 mm/hr and the saturated conductivity was measured.
Statistics:

Data from different soils and treatments were evaluated for significant differences by analysis of variance with separation of means using Least Significant Difference methods at a $p = 0.10$ level of significance. (StatSoft, Inc. Ver 5, Tulsa, OK).

Results:

The results of the pilot study showed that compost treatments always increased saturated conductivity (Ksat) compared to the bare treatment in both the coarse and finer textured soils, and whether measurements were at initial or final time of measurement. Table 3 lists the comparisons of increases relative to the bare, unamended substrate. All treatments generated positive values, indicating increases in infiltration (Ksat).

Table 3. Increases in saturated conductivities (%) of compost amended soils as compared to untreated, bare control treatments.

<table>
<thead>
<tr>
<th></th>
<th>Large Bins (18&quot;x16&quot;x16&quot;)</th>
<th>Small Bins (12&quot;x16&quot;x16&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DG</td>
<td>MS</td>
</tr>
<tr>
<td>Amendment (v/v%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fine (11%)</td>
<td>1.8</td>
<td>6.0</td>
</tr>
<tr>
<td>Fine + 1&quot; compost overs (16.5%)</td>
<td>15.6</td>
<td>7.0</td>
</tr>
<tr>
<td>Fine + 2&quot; compost overs (22%)</td>
<td>24.3</td>
<td>1.1</td>
</tr>
<tr>
<td>Fine + 1&quot; woodchips (16.5%)</td>
<td>26.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Fine + 2&quot; woodchips (22%)</td>
<td>18.2</td>
<td>3.3</td>
</tr>
<tr>
<td>Fine + 4&quot; compost overs (33%)</td>
<td>51.3</td>
<td>na</td>
</tr>
</tbody>
</table>

Even the initial measurement, made after wetting and settling, shows increases in infiltration compared to unamended substrates. This makes these trends
representative of compost incorporation effects, not just the obvious improvements from “tillage” effects of mechanically opening the soil. The “whole” compost from the pilot study (small bins) has similar larger fragments compared to the coarse compost treatments, and was generally more effective than the fine treatment in increasing infiltration. Generally, 20% amendments of either fine or whole compost were more effective than 10% amendments. But, the experimental variability was high for the shallow 30 cm (16”) bins, so the size was increased to 50 cm (18”). Also, an issue arose regarding the difficulty of getting coarse woody shreds (tub ground wood, often from seasonally available, orchard removal grindings) throughout the year and throughout the state. This suggested that the study would be more relevant to current use and management if the coarse woody ‘shreds’ were replaced with compost overs or wood chips. These more conventional materials were used for the second set of experimental measurements, which also utilized larger bins that were expected to have lower experimental variability.

In the second round of tests, all soils amended with coarse fraction treatments (compost overs or wood chips) exhibited greater infiltration (Ksat) rates than bare treatments regardless of soil type, amendment volume, or time (Table 4). The fine compost treatments produced small and generally non-significant increases in Ksat. Because of the combination of effects of compost amendment, soil type and aging time, the data trends were arranged into a flow chart to visualize the combined effects (Figure 1). For the decomposed granite (DG) substrate, the passage of time is associated with a natural increase in infiltration at all treatment levels from bare to maximum amendment, as shown by the right pointing ‘time’ arrow. This process of increasing porosity is not understood, although it is known not to be “reaggregation” because there is no increase in organic content or sufficient clay percentage. It is suspected to result from migration of the small amount of (relatively uncharged) clay in
Table 4. Average saturated conductivities (n=3) of amended and bare study soils. Values in vertical columns within each substrate type that are followed by differing letters are significantly different at p < 0.10. The right hand column shows significance between initial and final Ksat values within each row.

<table>
<thead>
<tr>
<th>Saturated Conductivity mm/hr</th>
<th>p &lt; 0.05</th>
<th>+ = significant difference between initial and final Ksat</th>
</tr>
</thead>
<tbody>
<tr>
<td>DG</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bare</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial (Feb.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1&quot; over</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2&quot; over</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4&quot; over</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final (May)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>110.7</td>
<td>ns</td>
<td>+</td>
</tr>
<tr>
<td>117.3</td>
<td>ns</td>
<td>+</td>
</tr>
<tr>
<td>118.4</td>
<td>ns</td>
<td>+</td>
</tr>
<tr>
<td>111.9</td>
<td>ns</td>
<td>+</td>
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<td>112</td>
<td>ns</td>
<td>+</td>
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<tr>
<td>115.5</td>
<td>na</td>
<td></td>
</tr>
<tr>
<td>bare</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial (Feb.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>fine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1&quot; over</td>
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<tr>
<td>2&quot; over</td>
<td></td>
<td></td>
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<tr>
<td>4&quot; over</td>
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<td></td>
</tr>
<tr>
<td>Final (May)</td>
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</tr>
<tr>
<td>68.7</td>
<td>c</td>
<td></td>
</tr>
<tr>
<td>109.7</td>
<td>ab</td>
<td>+</td>
</tr>
<tr>
<td>103.2</td>
<td>b</td>
<td></td>
</tr>
<tr>
<td>100.9</td>
<td>b</td>
<td></td>
</tr>
<tr>
<td>113.3</td>
<td>ab</td>
<td></td>
</tr>
<tr>
<td>115.6</td>
<td>a</td>
<td></td>
</tr>
<tr>
<td>101.1</td>
<td>a</td>
<td></td>
</tr>
<tr>
<td>bare</td>
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<tr>
<td>Initial (Feb.)</td>
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<tr>
<td>fine</td>
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<td></td>
</tr>
<tr>
<td>1&quot; over</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2&quot; over</td>
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</tr>
<tr>
<td>4&quot; over</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final (May)</td>
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<td></td>
</tr>
<tr>
<td>18.2</td>
<td>b</td>
<td>+</td>
</tr>
<tr>
<td>23.3</td>
<td>b</td>
<td>+</td>
</tr>
<tr>
<td>30.5</td>
<td>b</td>
<td>+</td>
</tr>
<tr>
<td>32.4</td>
<td>b</td>
<td>+</td>
</tr>
<tr>
<td>30.3</td>
<td>b</td>
<td>+</td>
</tr>
<tr>
<td>37</td>
<td>a</td>
<td>+</td>
</tr>
</tbody>
</table>
this substrate out of the larger pores and by cementing them into smaller pores by hardsetting processes.

This DG soil type represents one of the larger challenges for regenerating stable organics and aggregates since the particles are smooth sands and low charge (non-sticky) clays. The substrate responds well (+ 20 - 30 %) to compost amendment in general, but subsequent changes in infiltration of amended materials with time are small (+ 10 %). These data suggest that organic amendment is effective on newly constructed DG substrates. A secondary effect is that compost incorporation will greatly increase plant growth to provide surface protection for these same materials, providing a different type of beneficial effect.

The volcanic lahar (VL) substrate (Figure 1, lower left) shows very different effects. In this substrate, the passage of time is marked by a drastic and significant decrease in infiltration. This is suspected to result from the higher clay content of the volcanic (2.2 %) versus the DG (0.6%) and possibly the type of clay mineralogy (low weathering state (lower charge) vermiculites in the DG compared to short range (higher charge) oxyhydroxide clay materials in the lahar). This infiltration decrease occurs with time whether the substrates were amended or not. This suggests that amendment-generated improvements in infiltration will be very effective initially, but will not have lasting effects in this substrate type.

The marine sediment (MS) showed improvement with amendment only, but did not change with aging time. The treatment (amount amended, wood fragment type) appeared to not matter as long as some organics were added. Gains in infiltration from amendment were maintained with time and infiltration did not decrease.
Figure 2. Effect of incorporation of coarse woody fragments and time on infiltration rates of three substrates. DG = decomposed granite; VL = weathered volcanic lahar; MS = magnesium-rich marine sandstone saprolute. Wood fragments are 1 or 2 inch layer of compost ‘overs’ or wood chips incorporated to 18”. The upper and lower and left arrows are literal paths that could occur by amending or not, and monitoring with time in both cases. The right arrows are a hypothetical case contrasting no amendment with time versus amendment with the passage of time. This could not literally be implemented in the field, however, and so is a conceptual “what if” contrast.

The effect of compost or organic fragment type on substrate infiltration was generally that fine composts had little improvement effect. Differences in type of coarse woody material added (compost overs versus wood chips) or amount (1” vs 2” vs 4”) showed little consistent improvement in response. This suggests that an economical 1” amendment that is tilled in is as effective in a few months time (perhaps representing the first season) as a higher amendment rate. This lack of effect on increasing volumes is counter-intuitive and may still occur in field situations or with other substrate types. But,
in these controlled conditions, no effects of higher amendment rates with tillage were detected. A hidden effect, however, may be that a greater amendment rate with incorporation may have a longer service life as the smaller of the particles decomposes and fewer numbers of particles are left physically intact.

The general conclusions from these data are that coarse woody fragments are more effective at increasing infiltration than fine composts, but the relative amounts of 1, 2, or 4 inches rates of amendment are less important than the amendment of at least some woody fragments in the substrate. In general, coarse woody fragment amendments tilled into the soil can be expected to increase infiltration rates 15 to 30 mm/hr from their unamended rate. This is about a 20 to 30 % increase in DG and MS and approximately a 50 to 90 % in VL at the initial time of measurement. The DG and VL showed smaller increases in infiltration with compost amendment after aging, but the aged MS substrate maintained a 50 to 60 % increase in infiltration compared to the bare, unamended substrate.

The substrates also differed in their physical structure during the aging and drying process. The VL and MS substrates showed visible signs of settling during drying. The soils settled into the bins 1-3 inches down from the initial packing height, with some drying and cracking visible in the upper 5 cm. This contracting with drying could account for the large infiltration decrease in the VL soil with time (44.6 mm/hr down to 18.2 mm/hr), during which the soil particles are pulled tightly together by drying water films that can exert compressive pressures of several hundred pounds per square inch. Such packing decreases pore volume and connectivity, reducing infiltration rates. Amended substrates maintained somewhat higher infiltration levels during this process, but infiltration still decreases by 50 % or more with time.

The MS substrate did not decrease infiltration when dried, and no explanation is known for this lack of an effect, which would be expected given the high clay content.
No cracking was visible immediately after rainfall events, so this effect is not expected to influence measurements. The DG substrate showed no physical volumetric effect of aging and drying.

**Discussion**

Another essential aspect of site erosion resistance is to integrate the effects of infiltration rate with substrate depth. A high rate of infiltration must be coupled with adequate depth to imbibe the total volume of rainwater for a given storm, since underlying layers often have lower infiltration rates.

To evaluate the amount of tillage depth that would be needed in a field site to reduce or eliminate overland flow, computer simulations were performed using Hydrus 1D ver 4.06 hydrologic modeling software. Data from the initial VL soil was used for this exercise. The top soil was assigned a Ksat value equaling the value from the 1” wood chip treatment (77 mm/hr) and a bulk density reflecting the coarse amendment (1.23 g/cm$^3$). The data from the bare VL soil was used for the sub-soil boundary: Ksat = 44 mm/hr and bulk density was 1.35 g cm$^{-3}$. We modeled the soil water characteristics of substrate treatments with different soil tillage and amendment depths for a Tahoe basin 100 year storm (60 mm/hr; 2.4”/hr) (Tahoe City (DWR # G70 875800) (Table 5). The output of the model predicted the time to runoff, as well as the time to saturation at the soil / sub-soil interface. Note that for modeling purposes, the rainfall was considered constant and that there was no depth restriction drainage into the sub-soil. The model results indicate that the 200 mm (8”) tillage depth treatment would require almost 3 hours (173 minutes) of precipitation at this rate to produce surface runoff. The model also shows that by simply increasing the tillage depth from 4 to 8 inches, the time to runoff is delayed by 72 minutes. A 12” tillage depth increases time to runoff to 238
Table 5. Predicted times to runoff and soil / sub-soil interface saturation using simulated rainfall data collected from bins packed with Volcanic Lahar.

<table>
<thead>
<tr>
<th>Tillage depth of treatment</th>
<th>4” 100 mm</th>
<th>8” 200 mm</th>
<th>12” 300 mm</th>
<th>18” 450 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to run off (minutes)</td>
<td>101</td>
<td>173</td>
<td>238</td>
<td>336</td>
</tr>
<tr>
<td>Time to sub-soil interface saturation (minutes)</td>
<td>79</td>
<td>126</td>
<td>166</td>
<td>224</td>
</tr>
</tbody>
</table>

minutes, nearly four hours. Storms of this intensity (15 minutes or 1 hour duration) are highly unlikely to occur for the times needed to saturate the subsoil as listed in Table 5. To be more realistic, more complex models need to be used, incorporating ambient moisture content, sub-soil percolation, evaporation and variable rainfall rates. Hydrus 2d is an example of this type of soil hydrologic model.

What is more likely to occur than a hypothetical “15 minute” storm of several hour’s length, is a more moderate rain event lasting all day or longer. This slower but steady rainfall could be able to produce sufficient volume of water required to saturate the treated tilled depths. This scenario is illustrated in Table 6, based on the same weather and soil data for the previous model (VL with coarse woody amendments). The table shows that as the depth of tilled, amended soil increases at each step (4, 8, 12, 18”) the precipitation required to saturate the depths increases by 1.5 – 2” per step. The return frequency for a storm of sufficient size to produce enough precipitation to saturate the amended tilled layer becomes very large, and such storms are predicted to occur much less frequently (2 year return period to > 250 year return period). The slope becomes erosion resistant for a longer predicted period of time.
Table 6. Predicted one day storm return frequency required to saturate depths of coarse amendment treated (11% v/v) Volcanic Lahar in the Tahoe Basin.

<table>
<thead>
<tr>
<th>Tillage depth of treatment</th>
<th>4&quot; (100 mm)</th>
<th>8&quot; (200 mm)</th>
<th>12&quot; (300 mm)</th>
<th>18&quot; (450 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One day storm return frequency (years)</td>
<td>2</td>
<td>10</td>
<td>60</td>
<td>&gt; 250</td>
</tr>
<tr>
<td>Precipitation required to saturate tilled depth (inches)</td>
<td>3.1</td>
<td>5</td>
<td>6.5</td>
<td>8.8</td>
</tr>
<tr>
<td>Surface layer of compost to be tilled (in) to attain 11%</td>
<td>3/8</td>
<td>7/8</td>
<td>1</td>
<td>3/8</td>
</tr>
<tr>
<td>Surface layer of compost to be tilled (cm) to attain 11%</td>
<td>1</td>
<td>2.5</td>
<td>3.5</td>
<td>5</td>
</tr>
</tbody>
</table>

Additional work needed

The next tasks needed for improving infiltration with coarse woody fragments are evaluation of fragment size distribution and effects in field situations. The materials used here are produced to a current specification of 10 mm to 75 mm (3/8 to 3 inch) length. But, little control was placed on the size of these materials, as shown in Figure 1. A restriction of particles to 50 to 75 mm (2 to 3"), for example, may create a larger average particle size material. A consistent, nearly 3 inch long amendment would be expected to provide more infiltration (through creating more continuous pore spaces) compared to a specified “3/8 to 3 inch” woody material that may be 50 % or more fragments of less than an inch in length. This added study would directly apply to development of Caltrans specifications to guide improved materials for revegetation use.

Secondly, there are several important field effects that influence infiltration rates that were not measured in these controlled conditions. Effects of aging are greatly determined by wet/dry cycles. Field installations will have underlying soil that will pull moisture out of the amended layer, and causing more rapid removal of pore moisture. Field sites also show day/night moisture and temperature effects that differ from bin studies. These carefully designed and constructed experiments did, however, have
more control over experimental conditions than will be available in field situations, and therefore are a good method to compare effects of small treatment differences.

Another effect would relate to the effective infiltration capacity (rate and volume combined) of a horizonated field soil. Soil layers below the tillage depth may have different textures, soil structure and permeabilities. This bin study standardized these variables for better comparison of compost amendment effects. These effects will vary and influence the best use and management in field situations.

**Conclusions and Recommendations:**

1). Fine compost is not recommended as an effective treatment to increase infiltration. Fine compost fractions, however, may be needed for soil fertility purposes. Fine composts did not plug pores and reduce infiltration, as could potentially occur. Rather, in these test conditions, there was not a measurable increase in infiltration.

2). Infiltration was increased by 15 to 30 mm/hr (0.6 to 1.2”/hr) on sandy substrates by amending a 25 or 50 mm (1 or 2”) overlay of coarse woody material that is tilled to 230 to 460 mm (9 to 18”) depth. Increases in infiltration rate compared to bare substrates were variable but ranged from 20 to 30% (DG, MS) to 50 to 90 % (VL) increases. Volcanic lahar (VL) substrates lost about half of this improvement within a few months, but decomposed granite (DG) and marine sediment (MS) did not significantly change. This study has clearly shown that coarse amendment materials, as opposed to fine compost fractions, are critical to improving infiltration rates of soils.

3). There did not appear to be a significant difference in infiltration effects between the two types of coarse materials used (wood chips or coarse compost).

4). The effect of increasing levels of coarse woody amendment with incorporation did not seem to have a strong influence on infiltration in these experimental conditions. None of the substrate types or times of measurement showed consistent trends of increased
infiltration with increasing amendment amount, from 25 to 100 mm (1 to 4”) of surface amendment thicknesses. The recommendation from these experimental results would be to use only 25 mm (1”) woody material to increase infiltration, but the practical aspect of increasing the amendment to 50 mm (2”) before tillage may be made to provide longer service life as fragments degrade, as much as to insure that infiltration was increased.

5). Tillage depth greatly influences infiltration capacity. As shown in computer model outputs, the capacity of soils to hold a given amount of water, and the ability of the site to produce no overland flow in higher intensity storms increases as soil amendment/tillage depth increases. Recommendations for effective amendment and tillage depth depends on the target storm event that the site needs to be designed for, which is an agency decision.

References:


4.2. Effectiveness of mulch covers for moisture retention

Chapter synopsis

Mulches are assumed to reduce evaporative water loss from substrates in addition to controlling rain drop splash detachment, but information on the performance of different thicknesses or mulch types to reduce soil water evaporation in California environments was not known.

Straw and wood chip mulches were applied to three erosive substrate types (serpentine, decomposed granite and volcanic lahar) to test the ability of type and thickness of mulch to retain soil moisture during an early summer dry-down period. The serpentine substrate with mulch cover retained more moisture between 2 days and 4 weeks compared to bare soil, but after that there was no difference. The mulched granite and volcanic substrates retained more moisture than the bare soil between 2 days and 2 weeks, after which all treatments were uniformly dry. The mulch appeared to act by shading the soil, keeping it cooler and less evaporative. These data show that mulch cover acts to retain soil moisture for a two to four week period after the last wetting rain, but not for rest of the summer season. Moisture retention differences were small between 25 or 50 mm (1 or 2 inch) amendment thickness and between straw or chips. Both mulch types and application depths are beneficial for short term function, but wood chips will last longer on the site. A larger wood fragment size (4 to 6 inches, for example) is expected to provide longer service life of the mulch fibers without resorting to a thicker amendment layer.

The recommended material is a 25 mm (1 in) layer of coarse wood chips. For longer duration of the mulch layer in the field, a thicker, 50 mm (2 in) depth can be used,
or potentially a 1 inch layer of coarser materials, as long as the ground surface remains shaded.

**Problem statement**

Soils and substrates that are left exposed to the elements are susceptible to conditions that enhance erosion. Rain drops impact soil particles and disperse them (break aggregates), after which they settle, pack and hardset (partial cementation). This reduces infiltration. A single layer of mulch material is sufficient for this purpose. Two other mulch functions have a more indirect influence on erosion. Thicker layers of mulch may block heat or cold losses in soils. Heat increases breakdown of organics and drying and hardsetting. Cold can freeze the soil, which, if wet, also breaks apart soil aggregates. This study does not address heat effects. Another potential effect of thicker mulch layers is their ability to reduce moisture loss from the soil, potentially improving plant growth. The unresolved question is whether mulch layers effectively or functionally reduce moisture loss, and whether the thickness or mulch material type is important to achieve this particular effect.

**Introduction:**

Mulch covers help protect soil surfaces by several well characterized processes, including dispersing the kinetic energy of rainfall impact, roughening the soil surface, improving soil structure, and by slowing surface water flow to compensate for slower infiltration rates of rain to the soil surface (Bond and Willis, 1969). Mulches also reduce evaporation losses from soils by forming a thin air-dry layer on the soil’s surface, which disrupts capillary rise (Melloui H, et al. 2000) and by decreasing soil temperature. The dynamics of reducing evaporative losses with mulch coverings can be better understood if the mechanics of the process are considered.
The evaporation of soil water has been explained as a two-phase process. The initial phase is linearly related to energy and is related to air temperature and solar input. This phase of moisture loss increases in direct proportion to season (air temperature) and to incident sunlight (solar angle or slope angle). The second phase is slower and is related to diffusion processes within the soil. This phase of moisture loss is limited by soil moisture levels and will vary according to the soil moisture content. The process will be fast in damp soil and slow to negligible in dry soil volumes. Soil characteristics that govern the second phase are similar to those that govern soil water holding capacities, such as soil texture, bulk density, and soil pore size distribution. Mulch covers are effective at slowing the first phase because they shade the soil surface from direct solar radiation, thus reducing the energy input into the soil. Mulches have a limited effect during the second phase if their large pores allow ready passage of water vapor. An impermeable plastic sheet, for example, would stop movement of water vapor into the air and would remove the concentration gradient that drives evaporation. A mulch layer that is thick enough to hold a non-mixing layer of air in its pores would work somewhat like the sheet, but the loss of moisture would be only slowed, not stopped. During extended periods (weeks and months) soil under this mulch would reach the same dryness as an unmulched soil (Hanks and Woodruff, 1958; Bond and Willis, 1969; Unger and Parker, 1976; Ji and Unger, 2001; Taban and Naeini, 2006).

Melloui H, et al. (2000) examined the effects of straw mulch treatments on evaporation rates from sandy soils after a single wetting event. The researchers filled soil containers with either a loamy sand soil or a stony soil and applied a 3 hour precipitation event at a rate of 20 mm hr⁻¹ (0.78”). The straw mulch treatment (450 g m⁻²) (1.1 lb/sq yd) was shown to be effective at reducing evaporation during the first phase, but had little effect during the second phase. After the 46 days, the final soil moisture content of the mulch treated soils was not significantly different than the control soils.
However, the time required to reach the second phase was considerably longer in the
mulch treated soils than the bare. It required 15 days for the mulch treated soil to
evaporate 50% of the cumulative evaporation of 46 days as compared to 9 days for the
bare soil.

The soil water conservation benefits of mulches may be more realistically by
examining studies that utilize multiple wetting events that mirror natural rainfall events.
Researchers studying the relationships between straw mulch treatments and
evaporation, soil temperature, and winter wheat yields from the North China plain found
reduced seasonal evaporation rates with increasing mulch treatments. Chen et al.
(2007) monitored experimental field plots of a well drained loamy soil for 5 years. Wheat
straw was applied at 0, 3000, or 6000 kg/ha (0, 2679, 5375 lb/ac). The study found that
the total seasonal evaporation under winter wheat from the control soil was 137 mm.
This was reduced by 29 mm (21%) at the 3000 kg/ha rate, and by 56 mm (40%) at the
6000 kg/ha rate. During the 5 seasons, the mulched plots consistently had higher levels
of top soil moisture. A shorter-term field study was conducted on a silty loam in
Hohenheim, Germany (Dahiya et al., 2007). Field plot treatments included bare, rotary
hoeing, mulch blanket, and mulch incorporated by rotary hoeing. The wheat mulch
blanket treatment was 2 cm (0.79") in depth, and the lengths of the straws ranged from
10 to 15 cm (4 to 6"). The volumetric soil water was recorded daily for 15 days. The
blanket mulch treatment reduced daily evaporation by 0.39 mm/day (0.015"), as
compared to the bare treatment. Daily weather data was not given for either of the two
previous studies.

The purpose of the study reported here was to examine the effect of varying
mulch treatments (mulch type and thickness) on soil water evaporation losses from three
coarsely textured soils under local California climatic conditions, for the purpose of
understanding mulch function and for refining specifications for field amendment.
**Materials and Methods:**

Three sandy sub-soils, containing varying levels of clay, from actively eroding slopes were used in this experiment. The three soils were: 1) Decomposed granite collected from the west side of Lake Tahoe, Hwy 89, near Bliss State Park, 2) Volcanic collected from the north side of Lake Tahoe, Hwy 267 at Brockway Summit, and 3) Serpentine sub-soil collected from San Benito county. These soils can be characterized as being drastically disturbed, in which the top soil was removed from the soil sites, resulting in low OM levels, low levels of aggregation and biological activity, and limited soil structure. The soils were sieved to < 3/8”, and air dried. The particle size distribution and water holding capacities of these materials are listed in Table 1. Two mulch materials were tested. The first was wheat straw that was cut to lengths of 30 - 50 mm, and wood chips that would pass through a 50 mm (2 inch) sieve but not a 10 mm (3/8 inch) sieve.

The dry soils were packed into polyvinyl chloride tubes (10.16 inner D X 30 cm L) (4 x 12”) at a bulk density = 1.4 g / cm³. Substrate materials were loaded to different heights (30 cm, 27.5 cm, and 25 cm; 12, 11, and 10”) so that the appropriate mulch thickness could be added and all surfaces would be level with the top of the tube. Tubes of this diameter and length have been used in other mulch studies measuring evaporation (Ji and Unger, 2001) from clay soils. Mellouli et al. (2000) conducted a mulch study on sandy soils, and found that the change in volumetric water content after a 60 mm rainfall event was most prominent in the 10 - 25 cm depth. Thus, the height of the tubes was set at the lengths listed. Nylon screens (1 mm; 1/32 mesh opening) were glued to the bottom of the tubes prior to loading. The substrate-filled tubes were then saturated with H₂O by placing the screened end of the tubes in water pans. After saturation, the tubes were allowed to drain by gravity indoors for approximately 24
hours. The mulches were added to the tubes at either 2.5 or 5 cm (1 or 2") amendment thicknesses bringing all of the tubes up to 30 cm (12") total filled height. Each soil consisted of two mulch material types (wheat straw or wood chips) and three treatments (0, 2.5 and 5 cm of mulch’ 0, 1 and 2") mulch thickness, and each treatment was replicated three times.

After measuring the initial wet weight, the study tubes were placed in a box that was buried to be flush with the ground surface in a fallow field without vegetation near the University of California, Davis’ CIMIS (California Irrigation Management Information System) station, which was located approximately 200 m to the south. This site was chosen to ensure there would be no influence of increased local humidity from evapotranspiration of nearby vegetation. Netting was placed over the tubes in order to prevent loss of mulch materials to winds, and the tubes were wrapped in reflective foil in order to decrease soil temperature fluctuation. The tubes were weighed every 48 hours for 28 days, and then weighed every 96 hours for an additional 12 days. The daily mean temperature, potential evaporation, relative humidity, and wind-speed values were noted from the UCD CIMIS station.

All of the tubes were brought indoors for approximately 72 hours due to an unusually early rainfall event. This was between the hours of 507-578 of the experiment. Further, the tubes containing the 1” straw treatment on the serpentine soil were accidentally destroyed at the 409 hour sampling event. Thus, this treatment for the serpentine soil was no longer considered after 409 hours.
Statistics:

Weight loss data from different soils and treatments were evaluated for significant differences by analysis of variance with separation of means using Least Significant Difference methods at a $p = 0.10$ level of significance. (StatSoft, Inc. Ver 5, Tulsa, OK).

Results:

After initially saturating the soils and allowing 24 hours for the excess water to drain, the initial soil water contents did vary by soil type. The volcanic soil contained the most water ($0.3 \pm 0.007$ g/g), followed by the serpentine ($0.23 \pm 0.017$ g/g), while the decomposed granite contained the least ($0.13 \pm 0.005$ g/g). The final water contents at 867 hours exhibited the same trend as the initial levels, with the volcanic being highest ($0.15 \pm 0.005$ g/g), then the serpentine ($0.067 \pm 0.005$ g/g), and the decomposed granite being driest ($0.043 \pm 0.004$). The total water loss after 867 hours did vary by soil type, but did not significantly vary by treatment.

The cumulative evaporation loss rates, expressed as a percent loss of the initial water content, from all the soils and all the treatments exhibited two distinct phases. The initial rate was always greater than the second rate, in all the soils and treatments (Figure 1). The initial evaporative rates of the bare soils were consistently faster than the mulch-treated soils. The bare soils exhibited a 25% water loss after 3 days, and a 50% water loss after 6 days. The mulch treatments required 6 to 7 days to lose 25% of their initial water content. They required 10 to 14 days (depending on treatment) to lose 50%. These results are in good agreement with literature values of the coarse soil mulch studies previously mentioned.
Figure 1(a). Cumulative water loss, as a percent of the initial water content, versus time.

Figure 1(b). Cumulative water loss, as a percent of the initial water content, versus time.
Figure 1(c). Cumulative water loss, as a percent of the initial water content, versus time.

Figure 2 (a). Cumulative water loss, as a percent of the initial water content, versus time.
Figure 2 (b). Cumulative water loss, as a percent of the initial water content, versus time.

Figure 2 (c). Cumulative water loss, as a percent of the initial water content, versus time.
Table 2. Days required for soil treatments to lose 25, 50, and 75% of initial water content.

<table>
<thead>
<tr>
<th>Soil + treatment</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>serpentine (bare)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1&quot; straw</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>1&quot; chips</td>
<td>7</td>
<td>14</td>
<td>21</td>
</tr>
<tr>
<td>2&quot; straw</td>
<td>7</td>
<td>14</td>
<td>24</td>
</tr>
<tr>
<td>2&quot; chips</td>
<td>7</td>
<td>14</td>
<td>26</td>
</tr>
<tr>
<td><strong>volcanic (bare)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1&quot; straw</td>
<td>6</td>
<td>10</td>
<td>19</td>
</tr>
<tr>
<td>1&quot; chips</td>
<td>6</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>2&quot; straw</td>
<td>6</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>2&quot; chips</td>
<td>7</td>
<td>14</td>
<td>21</td>
</tr>
<tr>
<td><strong>decomposed granite (bare)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1&quot; straw</td>
<td>6</td>
<td>10</td>
<td>17</td>
</tr>
<tr>
<td>1&quot; chips</td>
<td>5</td>
<td>10</td>
<td>17</td>
</tr>
<tr>
<td>2&quot; straw</td>
<td>6</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>2&quot; chips</td>
<td>6</td>
<td>12</td>
<td>19</td>
</tr>
</tbody>
</table>

Discussion:

Reductions in evaporative rates based on mulch type do not seem to vary significantly. Increasing mulch thickness from 1" to 2" does seem to provide some modest evaporative reductions in the times required to reach 50 and 75% losses but these increases are small compared to the difference between mulch and bare. The service life of a mulch layer may be greatly increased by type (chips lasting longer than straw) and by thickness (more material to decompose before the surface again becomes bare). Mulch decomposition of a variety of agricultural crop byproducts generally followed first order kinetic models (initially rapid, then slowing) regardless of mulch thickness, or season (Dahiya et al., 2001). Wheat straw mulches were applied to a field soil at thicknesses of 2 and 4 cm. The half lives of the mulch treatments (the time required for 50% of the mulch to decompose) were 217 days at 2 cm, and 330 days at 4 cm. The researchers speculate that the thicker mulch treatments had less actual mulch to soil contact, thus resulting in lower microbial activity. Wood chips have larger internal volumes (less exposed surface area) and have slower observed decomposition rates.
Conclusions:

Mulches show functional improvement of soil moisture retention between 2 days and 2 weeks in the decomposed granite and volcanic substrates and between 2 days and 4 weeks in the serpentine substrate. After these times, there was no improvement in soil moisture between bare and mulched substrates. This suggests that if rains come in less than 2 or 4 week intervals, mulches will have significant and repeated benefits for reducing evaporation. For periods longer than this, depending on substrate type, the mulches may have other beneficial effects, but will not result in increased soil moisture. The lack of a striking effect of mulch for preserving months-long periods of moisture reiterates that deep soil moisture and deep rooting depth is essential for sustained plant growth and that rapid root growth to these depths is a critical establishment requirement.

Mulch provides other effects that should also be considered, including the effect of mulch thickness to absorb small rains that are prevented from wetting the soil, but this is a site specific effect depending on weather cycle, soil moisture and substrate. Potential thermal effects are shading of seeds and reduced germination (positive or negative effect, depending on seed type), cooler soil temperatures during spring warm up (negative effect for growth) or during summer (positive effect for reduced thermal stress) and prevention of frost heave during winter and maintenance of biological activity through the winter (positive effect).

Recommendation:

One inch of wood chips, applied to the surface is a minimum mulch cover. Areas with greater erosion potential or less revegetation potential should use two inches. Straw mulches are shown to be effective, but are short lived and require tackification or netting to be retained on site. These materials should only be used if revegetation will be rapid.
References


5.0. Literature review (water chemistry)

Introduction and literature review

Stormwater collected from highways and new construction sites often has high total suspended solids (TSS) and other constituents of concern such as nutrients and metals that have negative effects on stormwater quality. In 1987, the Clean Water Act (CWA) led to regulations on erosion, sediment, and stormwater at construction sites in an attempt to control water quality (Glanville et al., 2004).

Compost application as a surface mulch can help control erosion problems by mitigating formation of soil crusts through dissipation of the energy from rain drop impact and because the rough surface microtopography promotes percolation, lowers surface flow velocities, and reduces the shear forces acting on the soil surface. The compost layer applied to the soil surface also reduces evaporation and provides a more suitable environment for root growth and releases nutrients that improve the vegetative cover (Faucette et al., 2004). Improved vegetative cover further protects the soil surface from erosion. Controlling erosion is a critical first step in improving stormwater quality because it can dramatically reduce inputs of suspended solids and associated constituents.

Nitrogen release from compost is important for the growth of the vegetative cover; nitrogen release rates that are too high will lead to the fast growth of undesirable weeds, and may result in other problems such as greater frost sensitivity, increased water stress and increased herbivory. Most importantly, in the context of this report, high nitrogen release impacts the quality of the stormwater runoff.

Soil organic matter releases nitrogen at rates considered to be slow (1-3 % of total N/year) and the leaching process can be extended for many years as the composted organic materials are decomposing. In contrast, the nitrogen release rate
from chemical fertilizers is considered to be high, the release persists for a much shorter time and its nitrogen content is rapidly depleted. Composts are intermediate between soil organic matter and fertilizers in their release rates (Claassen et al., 2006).

Compost is an organic material that has been decomposed by a controlled microbiological process at elevated temperature to reach a biologically stable state (Faucette et al., 2004). In contrast, chipped woody materials are produced from wood waste or yard debris that does not go through a controlled biological heating process and that has a wide carbon to nitrogen ratio and low available nutrient content. Either composted fines or chipped wood products can be used as a surface mulch if they are applied on the ground surface.

Without the experimental testing of a certain type of composted material it is hard to predict the rate and amount of its release of nutrients and metals in runoff. Diversity in the types and sources of raw organic solid waste combined with the various processing procedures used to produce composted materials results in different physical and chemical properties in the composted products. This fact makes it hard to generalize the nutrient and metal leaching characteristics from the different types of composted materials.

Studies have been conducted by several investigators on the use of compost to control water quality and erosion problems, but few have involved quantitative experimental measurements on the release of nutrients or metals from composted materials. Faucette et al. (2004) investigated the impacts of compost and mulch applications on runoff quantity and quality. They compared nutrient losses, total suspended solid release and runoff volume from soils covered with a variety of compost and mulch blankets to those from untreated soils under rainfall simulation (160 ±7 mm/h) and related that to the physical and chemical properties of the organic amendment used. Runoff began 3 to 23 minutes after rainfall started for soil and mulch and a significant
variability was found in runoff volume and total solids loss between the different soil amendments. All of the different types of compost and chipped material applied as surface mulches had runoff volume equal to or less than untreated soil. Partly, this equivalence resulted from heavy simulated rainfall rates that filled the pore space in the mulch layer and overwhelmed the sorptive capacity. Greater treatment differences were expected in smaller storm events. Losses of total solids in runoff were lower for all composts or woody materials than for the untreated soil, confirming their utility in controlling erosion. Nitrate, ammonium and total N release from the soils covered with chipped wood was tended to be lower than the untreated soils, but not significantly so. Compost blanket treatments tended to have significantly higher N losses, but nitrate and ammonium losses, although trending higher, tended to be non significant. Total P and phosphate losses from wood mulches and composts did not significantly differ from soils except with poultry feedstock materials, which were much higher.

Carbon-Nitrogen ratio (carbon content divided by the nitrogen content) controls the duration of the slow nitrogen release. Organic soil amendments with high carbon-nitrogen ratios are expected to hold the nitrogen for longer durations in the soil amendments or in associated microbial biomass until it ultimately gets mineralized and released. This behavior will continue until the bio-available carbon is consumed and the nitrogen available in the biomass of the declining microbial populations is released. This effect delays the nitrogen release at the early stages of growth of the vegetative cover and prevents undesirable weedy species from consuming the excess available nitrogen, thereby promoting the establishment of the desired, slower growing permanent vegetative cover (Claassen et al., 2006).

Glanville et al. (2004) performed a study that evaluated the effects of different compost materials on water quality after field application for rapid control of erosion and runoff on new highway embankments. Runoff and water quality from treatments with
composted biosolids, yard waste, bio-industrial (paper and grain processing sludge) materials were compared to subsoil and topsoil treatments. All treatments were applied as 5 to 10 cm (2 to 4 inch) layers over tilled and culti-packed 3:1 embankments as replacements for conventional treatment methods such as synthetic erosion control blankets or chopped straw. Rainfall simulation (100 mm/hr., a 30 minute, 25 year return frequency storm) was used to test runoff and water quality on the first one hour of runoff volume. Glanville’s study measured and compared the concentration of heavy metals and nutrients in runoff from soils or compost blankets and also the total mass of metals and nutrients lost.

Runoff from the compost blankets had higher concentrations of soluble and particle-adsorbed zinc, chromium, copper, phosphorus and potassium than runoff from the topsoil or subsoil treatments. But, since the compost blanket treatments had significantly higher surface infiltration capacity, much more rainwater was retained in the blanket and infiltrated compared to the two bare soil treatments and less volume ran off. This resulted in lower overall losses of nutrients and metals (3 to 20 %) compared to the bare soil treatments. Yard waste composts were significantly lower in mass losses than the soil treatments for all metals and nutrients, often being below detection limits. Although the composts had higher total nutrient and metal contents than the soils, and the initial runoff volumes from composts often had higher concentrations than from soils, the total mass lost was lowest from compost treated plots.

Biological release (mineralization) rate of nutrients depends both on feedstock and compost curing (aging) stage. Nitrogen mineralization rates were slower from yard waste compost materials than from biosolids / yard waste blends, and nutrient release was greater from well cured composts that were retained after thermophilic composting, than from composts that received no subsequent curing time.
Release rates of organic soil amendments and chemical based nitrogen fertilizers are generally much faster than from composts. Claassen et al. (2007) performed a study that measured and compared nitrogen release rates and patterns from different types of composted organic material and other types of chemical soil amendments in lab incubations and also under field conditions. Chemical soil amendments had a high nitrogen release rate with a short duration, while the composted materials had a lower rate and longer period of nitrogen release rate. Generally, all soil amendments had the same overall pattern of nitrogen release; initial release of nitrogen was fast but was followed by a much slower, steady nitrogen release rate. The difference between the different soil amendment materials was in the proportion of the nutrient released in the early phase and in the rate of release in the slower, second phase. Based on the results of the nitrogen release rates, the applied soil amendments have been divided into four major groups: (1) rapid release rate, (2) slower release rate, (3) rapid release rate followed by a different, slower release rate, (4) slow release rate.

Organic-based soil amendments will continue releasing nitrogen at a low rate for many years unless the temperature drops or the soil becomes too dry. The nitrogen release rate also depends on time of aging. Nitrogen release was different when it was measured after 130 days (0.25 - 2.7 % of total N content per month) compared to 334 days (0.08 - 0.98 % per month), showing the slowing of N release rates with length of aging.

Crop and vegetable production is usually coupled with the use of nitrogen-rich fertilizers that result in high nitrogen release to soil (up to 150 kg-N ha\(^{-1}\)) (Chaves et al., 2005). When organic matter decomposes, nitrogen usually experiences two different stages of mineralization and immobilization. Mineralization of nitrogen means that nitrogen is decomposed into plant accessible forms such as \(\text{NH}_4^+\) (via mineralization) and \(\text{NO}_3^-\) (via nitrification). Immobilization of nitrogen occurs when the accessible
nitrogen species are taken up by microorganisms preventing them from being accessible by plants. Nitrogen immobilization is related to the biochemical composition and decomposability of the compost. A high C/N ratio in compost will promote nitrogen immobilization. The immobilized nitrogen will be available later for the plants after the microorganisms die and the nitrogen is released (Chaves et al., 2007). A model that will be able to predict the nitrogen remaining on compost is important for estimating the need for nitrogen fertilizers to be applied again to support the growth of the vegetative cover (De Neve et al., 1996).
References:


6.0. Rainfall simulation and water chemistry

Synopsis

The aim of the work described in this section is to understand the effect of compost age on the extent and rates of nitrogen and metals release by conducting detailed studies of one compost type at three different ages. The results will be used to construct a mathematical model of nitrogen remaining on compost following repeated storm events (Task 7). Changes in the retention of metals of importance in storm water runoff will also be examined as a function of compost age.

Analytical methods

Compost materials

Three different ages of Grover Green Waste (GGW) compost were tested in this study including freshly ground material at zero weeks age (GGW0) (chipped green waste), 4 weeks (GGW4) (thermophilic process) and 9 weeks (GGW9) (cured). GGW had less than 1% of impurities such as plastic bags, paper, cloth tissues and stones. All materials were collected from the composting facility of Grover Environmental, Vernalis, CA. Samples were air dried within two days of collection and were sieved to < 16 mm (< 5/8 inch) for experimental work.

Moisture content and volatile organic matter were determined gravimetrically for triplicate samples for each compost age and were measured gravimetrically by adding 50 g of compost to a tared metal tray. Weight loss after drying for 24 hr at 105 °C was assumed to be equal to the moisture content. And further loss upon heating at 550 °C for another 24 hr provided the volatile solids content.
Metals content was determined for triplicate samples by nitric acid extraction. Samples were prepared by adding 5 mL of concentrated nitric acid to 0.5 g of fine compost particles and left overnight. The next day, samples were sonicated for 1 hr, diluted to 50 mL, and then centrifuged prior to analysis.

**Batch Experiments**

Samples were prepared for batch experiments by adding 5 g of compost passing a 1.7 mm sieve to 50 mL of Milli-Q water and mixed at 35 rpm for 72 hr to make sure that equilibrium was achieved. After that, the aliquot were filtered using a 0.45 µm filter and acidified. The samples were preserved at 4 °C. The test was done in triplicate for each compost age (GGW0, GGW4 and GGW9).

**Rainfall Simulation**

Rain simulation on samples of each compost age (GGW0, GGW4 and GGW9) was performed repeatedly for three consecutive days with a 24 hr drainage period between each test. The test plot consisted of two 80 × 80cm concrete slabs equipped with a 4 inch surrounding wall on three sides and lined with plastic sheeting to contain the runoff (Figure 1.). The slab was tilted at a 2% slope and the lower edge was equipped with a v-shape channel for runoff collection. The weighed compost was applied in a 4 - 5 cm loose layer to the test plot surface.

Rain intensity was applied at 55 ± 5 mm/hr. Rain intensity was independently estimated by collecting runoff from the test plot over a specified time interval and by dividing the water volume collected by the area of the test plot.

The time interval between starting the rain simulator and the collection of the first 50 mL of runoff was recorded and the first sample was designated the time 0 sample. Subsequent samples were taken after 10, 20, 30, 45 and 75 minutes, after which the
rain simulation was stopped for the day. Each day after the rain simulation ended, the test plots were covered with a plastic cover to keep the compost moist. Runoff samples collected were analyzed for total nitrogen (TN) within two hours of completing the rain simulations. Runoff samples collected for other analyses were acidified and stored at 4 °C.

Figure 1. Drop-forming rainfall simulator with concrete test pad.

Analytical methods

All nitrogen species were measured by colorimetric methods using appropriate HACH test kits and a HACH DR/890 colorimeter. Samples were analyzed for total nitrogen (TN) using method 10071 following 10-fold dilution. All nitrogen species are
converted to nitrate by the alkaline persulfate digestion method. In order to remove the halogen oxide interferences, sodium metabisulfite was added after digestion. Chromotropic acid then reacts with nitrate to form a yellow complex (absorbance near 420 nm). The method has a detection range of 0 to 25 mg/L-N.

Total Inorganic Nitrogen (TIN) concentration in samples was measured using method 10021 following 10-fold dilution. Nitrite and nitrate are reduced by titanium (III) to ammonia in a basic environment. After removing the solids, the ammonia reacts with chlorine and forms monochloramine, which reacts with salicylate to form 5-aminosalicylate. The sodium nitroprusside catalyst oxidizes the 5-aminosalicylate to form a blue compound; this blue color gets mixed with the yellow color from the excess reagent to result in a final green color solution. The method has a detection range of 0 to 30 mg/L-N.

Nitrate+Nitrite (NO$_3$-NO$_2$) concentration in samples was measured using method 10020 with no dilution. Chromotropic acid reacts with the nitrate under a strong acidic condition which results in a yellow compound. The method has a detection range of 0 to 30 mg/L-N.

Ammonia+Ammonium (NH$_3$-NH$_4$) concentration in samples was measured using method 10023 following 10-fold dilution. Ammonia species are detected in the same manner as in method 10021. Ammonia concentrations were measured during the first two days of rain simulation for GGW0. Results indicated that NH$_3$-NH$_4$ measured concentration was equal to the result from subtracting the NO$_3$-NO$_2$ concentration from the TIN concentration. Consequently, ammonia nitrogen was usually obtained by difference during the field experiments.

Metals analysis was performed using an Agilent (Palo Alto, CA) 7500i inductively coupled plasma mass spectrometer (ICP-MS). The ICP-MS uses a peristaltic pump with a flow rate of 0.4 mL/min for sampling through a Babbington-style nebulizer that injects
the sample through a 2°C cooled double-pass spray chamber prior to introducing it to a 1300 W plasma. Standard solutions were prepared from NIST-traceable standards (SpexCertiprep, Methuen, NJ) and verified against a multi-element SRM (NIST-1643e). Elements measured were Phosphorus (P), Potassium (K), Copper (Cu), Chromium (Cr), Nickel (Ni), Zinc (Zn), Cadmium (Cd), and Lead (Pb). Three separate standards were prepared for P (0.01 – 10 mg/L), K (100 – 100000 µg/L), and the six remaining elements (0 – 100 µg/L). The ICP-MS detection limits ranged from 1 µg/L (K) to 0.01 µg/L (Cu, Cr, Ni, Zn, Cd, and Pb). For P, the detection limit was 0.01 mg/L. (Carson et al., 2007)

**Results and Discussion**

**Compost characteristics**

Physical and chemical characteristics of the three different ages of compost used (GGW0, GGW4; and GGW9) are presented in Table 1. As compost age increases, the compost becomes more soil-like as particles break down into smaller sizes. A significant increase is observed in the bulk density, going from 119.7 kg/m³ (201.8 lb/yd³) for GGW0 to 202.28 kg/m³ (341.0 lb/yd³) for GGW9, which was due to the decrease in the average particle size. The GGW9 had more fine particles and fewer coarse particles than the GGW0. Compost was not compacted at any time and was applied loosely to the test plot.

**Table 1. Physical and chemical characteristics of compost.**

<table>
<thead>
<tr>
<th>Compost</th>
<th>N content (%)</th>
<th>C content (%)</th>
<th>C/N ratio</th>
<th>NH₄-N (mg/kg)</th>
<th>NO₃-N (mg/kg)</th>
<th>Moisture content (%)</th>
<th>Volatile solids (%)</th>
<th>Bulk density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GGW0</td>
<td>1.20</td>
<td>32.05</td>
<td>26.82</td>
<td>636.55</td>
<td>13.30</td>
<td>5.76</td>
<td>73.37</td>
<td>119.75</td>
</tr>
<tr>
<td>GGW4</td>
<td>1.31</td>
<td>26.10</td>
<td>19.92</td>
<td>192.70</td>
<td>1.70</td>
<td>7.44</td>
<td>63.11</td>
<td>129.71</td>
</tr>
<tr>
<td>GGW9</td>
<td>1.34</td>
<td>26.05</td>
<td>19.51</td>
<td>19.60</td>
<td>65.55</td>
<td>6.72</td>
<td>55.05</td>
<td>202.28</td>
</tr>
</tbody>
</table>
The N content of the compost increased slightly (~10%) with compost age while the C content, NH₄-N and carbon-nitrogen ratio decreased with the increase in the compost age. The reductions were not significant for the C content and carbon-nitrogen ratio between GGW4 and GGW9, while a significant reduction is apparent for NH₄-N which declined by a factor of 3.3 and 9.8 in going from 0 to 4 and 4 to 9 weeks of age. Volatile solids content also decreased with age. Volatile solids are frequently used as a measure of organic matter content and the organic matter to carbon ratio declines to 2.1 by 9 weeks of compost age approaching the levels typically found in surface soils of 1.8. The increase in compost age generally results in more stable organic matter and as is seen below, lower leachable nutrient and metal concentrations.

**Batch test results**

The results of batch experiments for nutrients and metals release conducted on compost of three ages are presented in Table 2. The increase in compost age is expected to result in more mature compost, and more mature compost is expected to leach fewer nutrients and metals.

<table>
<thead>
<tr>
<th>Compost</th>
<th>Parameter soluble concentration</th>
<th>mg/L</th>
<th>µg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TN³</td>
<td>TIN³</td>
<td>Norg³</td>
</tr>
<tr>
<td>GGW0</td>
<td>171.9</td>
<td>47.8</td>
<td>124.1</td>
</tr>
<tr>
<td>GGW4</td>
<td>127.0</td>
<td>23.9</td>
<td>103.1</td>
</tr>
<tr>
<td>GGW9</td>
<td>60.6</td>
<td>7.6</td>
<td>53.0</td>
</tr>
</tbody>
</table>

³ concentration in mg-N/L.
As compost age increases, the concentration of total nitrogen (TN), total inorganic nitrogen (TIN), organic nitrogen (N_{org}) and NH_{3} leaching out of the compost decreases, as expected from previous research by others. As compost age increases, a higher concentration of NO_{3}^{-} is expected to leach out of compost because of the nitrification process. Nitrification is a microbial process in which ammonia is converted to nitrate and subsequently to nitrate by various bacterial species. The increase in compost age means a longer curing period which provides a longer time for bacteria to multiply. That results in a higher population of nitrifying bacteria in the compost. Nitrate concentration leaching out of the compost increased with greater compost age as expected, although the increase was small.

Field rain simulation

Total nitrogen concentrations in runoff for each of the three simulated storms for GGW0 over time from initiation of runoff are presented in Figure 2 as an example of leaching processes from compost amendments.

![Figure 2. Measured total nitrogen (TN) from sample GGW0 in runoff collected from simulated storms on three consecutive days.](attachment:image.png)
Dry compost is expected to absorb water. For the first day storm (day 1) compost retained water for the first two minutes, which was the time required until the first 50 ml of runoff started to drain from the test plot. This retention time typically decreases for the next two days as compost becomes more saturated with water. The retention times for days 2 and 3 were 1.03 and 1.06 minutes respectively, showing the effect of the initial, first day wet-up process.

**Conclusions**

1. Nitrogen content (%) and bulk density of compost increased with the increase in compost age. On the other hand, the carbon content (%) and volatile solids (%) decreased as compost age increased.

2. Total nitrogen released decreased with older cured (9 week) compost compared to thermophilic mature (4 week) compost. Organic nitrogen and ammonium were the predominant species of nitrogen released. On the other hand, NO$_3^-$ released concentration increased only slightly with the increase in compost age presumably due to nitrification.

3. All metals concentrations in compost leachate decreased with the increase in compost age, and their related $K_d$ values increased with the increase in compost age.

4. The three rain simulations (storms) performed on each of the three compost ages show that nitrogen release declined each day of the repeated daily storms.
7. Model development and validation

Synopsis

Using data from Task 6, Rainfall simulation, a mathematical model is constructed to represent leaching losses from compost materials, both in scenarios of within a single storm event (intra-storm) and between successive days of rain (inter-storm) events. A first order kinetics model gave good fit to measured data. When validated, these numerical models can be used to predict leaching losses in non-measured conditions, such as longer or harder rainfall, or with greater amounts of field-applied compost.

Background

Release of total nitrogen (TN) measured in the previous section decreased as time increased for all three simulated storms. To provide a single number that summarized nitrogen or metal losses during a simulated storm, event mean concentrations were calculated using equation 1.

\[
C_{\text{avg}} = \frac{\sum (C_t \times \Delta t)}{\sum \Delta t}
\]  

(1)

In this equation, \(C_{\text{avg}}\) is the event mean concentration (mg-N / L), \(C_t\) is the concentration at time (t) and \(\Delta t\) is the time segment duration \((t_1-t_2)\) in minutes. Nutrients and metals release are expected to decrease on each subsequent day. Before the first storm, some of the nitrogen and metals in compost will be within pore water associated with the compost surface or loosely adsorbed. When the first storm is applied those labile nutrients and metals will be flushed away from the surface relatively easily. Over
time as more storm water is applied to the compost, additional nutrients and metals will be leached out but not as rapidly. As a result, the event mean concentration decreased over three consecutive days from 53 to 16.2 and then 11.4 mg-N/L, as expected.

Equation (1) was used to calculate the event mean concentration for different parameters presented in Table 3. All parameters presented in Table 3 followed the same behavior as the TN for each individual storm (e.g., Figure 1.) and also for the three consecutive storms for each compost age.

**Table 3. Event mean concentrations for nutrients and metals in rainfall simulation.**

| Parameter soluble concentration (mg/L) | Composts | Day 1 | Day 2 | Day 3 | Day 1 | Day 2 | Day 3 | Day 1 | Day 2 | Day 3 | Day 1 | Day 2 | Day 3 | Day 1 | Day 2 | Day 3 |
|---------------------------------------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Composts                              | GGW0     | GGW4 | GGW9 |
| Day                                   | 1        | 2    | 3    | 1    | 2    | 3    | 1    | 2    | 3    | 1    | 2    | 3    | 1    | 2    | 3    |
| Parameter                              |          |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| TN a                                  | 53.0     | 16.2 | 11.4 | 84.6 | 55.0 | 42.7 | 66.8 | 45.2 | 24.0 |
| TIN a                                 | 19.4     | 1.7  | 1.1  | 18.5 | 9.5  | 5.4  | 11.2 | 5.5  | 4.6  |
| N$_{\text{org}}$ a                    | 33.6     | 14.9 | 10.6 | 66.1 | 45.5 | 37.3 | 55.6 | 39.8 | 19.4 |
| NH$_3$ a                              | 18.6     | 1.2  | 0.8  | 17.5 | 8.9  | 4.9  | 8.4  | 4.4  | 3.9  |
| NO$_3$ a                              | 0.8      | 0.5  | 0.3  | 1.0  | 0.6  | 0.5  | 2.8  | 1.1  | 0.7  |
| P                                     | 16.0     | 2.4  | 2.0  | 12.4 | 5.9  | 3.5  | 4.6  | 4.3  | 3.6  |
| K                                     | 302.2    | 81.9 | 39.2 | 890.9| 316.3| 156.0| 1596.3| 460.3| 239.3|
| Cr                                    | 0.032    | 0.022| 0.018| 0.034| 0.020| 0.015| 0.035| 0.024| 0.020|
| Ni                                    | 0.063    | 0.026| 0.010| 0.057| 0.023| 0.011| 0.033| 0.019| 0.013|
| Cu                                    | 0.073    | 0.039| 0.022| 0.072| 0.042| 0.022| 0.084| 0.073| 0.055|
| Zn                                    | 0.575    | 0.365| 0.250| 0.214| 0.183| 0.116| 0.144| 0.185| 0.171|
| Pb                                    | 0.019    | 0.010| 0.004| 0.010| 0.005| 0.002| 0.007| 0.005| 0.005|
| Cd b                                  | 0.8      | 0.4  | 0.3  | 0.5  | 0.3  | 0.2  | 0.5  | 0.4  | 0.3  |
| TOC c                                 | 1007.7   | 139.6| 43.2 | 384.0| 130.8| 58.9 | 261.4| 124.0| 52.5 |

$^a$ concentration in mg-N/L.

$^b$ concentration in ppb.

$^c$ TOC: total organic carbon.
Event mean concentrations for a 55±5 mm/hr intensity storm with one hour duration, on three consecutive days for each of the three compost ages are presented in Table 3. All test plots had the same area of 0.64 m² (80x80 cm) that was covered with a 4 - 5 cm (1.5-2 inch) layer of compost. Because of the different bulk densities between the three compost ages different weights of compost were used to cover each test plot for each compost age. This fact complicates the comparison between the amounts of nutrients and metals released from the three compost ages (GGW0, GGW4 and GGW9). Nevertheless, results presented in Table 3 are valuable for understanding and modeling the release behavior of nutrients and metals for each compost age, under three consecutive simulated storms. For any compost age, a more significant difference in concentrations between the first day and second day storms is expected in comparison with the difference between the second day storm and the third day storm, since some nutrients and metals will be washed off in each storm and the most labile forms will be removed first. Results presented in Table 3 show that for all nitrogen species and metals, event mean concentrations decreased each day. The concentration values of the different elements presented in Table 3 show more significant differences between day 1 and day 2 values than that between day 2 and day 3 for all three ages of compost GGW0, GGW4 and GGW9 as expected.

**Nitrogen model**

A first-order kinetic model has been used previously to simulate nitrogen immobilization and mineralization (De Neve et al., 1996, Chaves et al., 2005, Chaves et al., 2007). A typical form of this model is:

\[
N_{rel}(t) = N_0 (1 - e^{-kt})
\]  

(2)
Where $N_{rel}(t)$ is the total N that has been released at time (t), $N_0$ is the total amount of N available for release (% of total nitrogen) at the beginning of a storm event (t = 0), $k$ is the rate constant for N immobilization and $t$ is the time from the start of incubation.

In this work we are interested in both the N released at a particular time ($N_{rel}(t)$) and in the amount remaining for release at that time ($N_{rem}(t)$). These two terms are related by:

$$N_0 = N_{rem}(t) + N_{rel}(t) \quad (3)$$

Comparing equations 2 and 3 reveals that:

$$N_{rem}(t) = N_0 \left( e^{-kt^2} \right) \quad (4)$$

In practice it is difficult to define the fraction of total N that is available for leaching and logarithmic fits of equation 4 do not always pass through the origin. The intercept on such a plot represents the amount of N apparently available for leaching. One way to fit such data is:

$$N_{rem}(t) = N_0 \left( e^{-kt^2 + \beta} \right) \quad (5)$$

Where $\beta$ is an empirical constant and $e^\beta$ is the fraction of N available for runoff. Equation (5) was used to model the nitrogen remaining at each time point during each simulated storm on three consecutive days for each of the three compost ages (intra-storm).
Equation (5) was also used to model the change in nitrogen remaining for each compost age after each rain simulation event (inter storm).

**Intra-Storm N Release Model**

**Table 4. Sample of data used in the fitting of the intra-storm N release model.**

<table>
<thead>
<tr>
<th>$T$ (min)</th>
<th>TN (mg/L)</th>
<th>TN$_{avg}$ (mg/L)</th>
<th>Runoff$^1$ (L)</th>
<th>$N_{rel}$ (mg)</th>
<th>Compost weight (Kg)</th>
<th>$N_{rel}$</th>
<th>$N_{rel}$ (t)</th>
<th>$N_{rem}^2$</th>
<th>$N_0$</th>
<th>$Ln(N_{rem}/N_0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.93</td>
<td>48.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.93</td>
<td>30.5</td>
<td>39.5</td>
<td>10</td>
<td>395</td>
<td>6.473</td>
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<td>10</td>
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<td>10</td>
<td>205</td>
<td>6.473</td>
<td>31.67</td>
<td>199.68</td>
<td>12221.5</td>
<td>12421.1</td>
<td>-0.01621</td>
</tr>
</tbody>
</table>

$^1$Runoff was calculated by multiplying the constant flow (1 L/min) by $\Delta t$.

$^2$N$_{rem}$ was calculated by taking the difference between the $N_0$ and $N_{rel}$ (t) columns.

Table 4 represents a sample calculation for GGW9 during the day 3 rain simulation experiment. The values of $Ln(N_{rem}/N_0)$ were plotted with $t$ in minutes. And by rearranging equation (5) we get:

$$Ln\left(\frac{N_{rem}(t)}{N_0}\right) = -k \cdot t + \beta$$  \hfill (6)

where the rate constant for nitrogen release (-$k$) is the slope of the line, and $\beta$ is the y intercept.
The values obtained for the nitrogen release rate constant (-k) and their related regression $R^2$ values for the three storms applied on three continuous days for each of the three compost ages GGW0, GGW4 and GGW9 are presented in Table 5.

Table 5. Fitted parameters for intra-storm model for the nine simulated storm events applied to compost of three ages.

<table>
<thead>
<tr>
<th>Compost</th>
<th>GGW0</th>
<th>GGW4</th>
<th>GGW9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>-k</td>
<td>0.0009</td>
<td>0.0003</td>
<td>0.0002</td>
</tr>
<tr>
<td></td>
<td>(0.0002)</td>
<td>(0.0001)</td>
<td>(0.0000)</td>
</tr>
<tr>
<td>-β</td>
<td>0.0326</td>
<td>0.0076</td>
<td>0.0031</td>
</tr>
<tr>
<td></td>
<td>(0.0079)</td>
<td>(0.0019)</td>
<td>(0.0009)</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.856</td>
<td>0.913</td>
<td>0.973</td>
</tr>
</tbody>
</table>

*a values in parentheses are standard errors of regression coefficients.

It can be seen from Table 5 that as compost age increases and compost becomes more mature and stable, the regression $R^2$ values approach one. No specific trend was observed for the -β values as compost age increased. N release rate
constants (-k) generally decreased across storm events except that GGW4 showed a slightly higher value for -k on day 3 than on day 2.

**Inter-Storm N Release Model.**

**Table 6. Input values used in fitting inter-storm N release model for GGW4 on day 1.**

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>TN (mg/L)</th>
<th>TNavg (mg/L)</th>
<th>Δt (min)</th>
<th>TNavg*Δt (mg.min/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.75</td>
<td>70.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.75</td>
<td>172</td>
<td>121.25</td>
<td>10</td>
<td>1212.5</td>
</tr>
<tr>
<td>25.75</td>
<td>113.5</td>
<td>142.75</td>
<td>10</td>
<td>1427.5</td>
</tr>
<tr>
<td>35.75</td>
<td>81.5</td>
<td>97.5</td>
<td>10</td>
<td>975</td>
</tr>
<tr>
<td>50.75</td>
<td>66.5</td>
<td>74</td>
<td>15</td>
<td>1110</td>
</tr>
<tr>
<td>80.75</td>
<td>41.5</td>
<td>54</td>
<td>30</td>
<td>1620</td>
</tr>
<tr>
<td><strong>∑</strong></td>
<td></td>
<td></td>
<td>75</td>
<td>6345</td>
</tr>
</tbody>
</table>

C_{avg} for GGW4 on the first day rain simulation was calculated using equation (1). By dividing the summation of TN_{avg}*Δt over the summation of Δt, C_{avg} was found to be 84.6 mg-N/L. Event mean concentrations for each compost age for the three consecutive days of rain simulation were calculated following the same procedure and the results are presented in Table 7.

**Table 7. Event mean concentrations.**

<table>
<thead>
<tr>
<th>Day</th>
<th>C_{avg} (mg-N/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GGW0</td>
</tr>
<tr>
<td>1</td>
<td>53.04</td>
</tr>
<tr>
<td>2</td>
<td>16.20</td>
</tr>
<tr>
<td>3</td>
<td>11.44</td>
</tr>
</tbody>
</table>
By removing the TN column from table 4 and replacing $TN_{avg}$ by $C_{avg}$ table 8 was obtained.

Table 8. Sample calculation for the fitting parameters of the (inter-storm) nitrogen runoff model.

<table>
<thead>
<tr>
<th>$t$ (day)</th>
<th>$C_{avg}$ (mg-N/L)</th>
<th>Runoff Vol. (L)</th>
<th>$N_{rel}$ (mg)</th>
<th>Compost weight (Kg)</th>
<th>$Ln(N_{rem}/N_0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>84.6</td>
<td>60.0</td>
<td>5076.0</td>
<td>4.2</td>
<td>1222.8 1222.8 11877.2 13100 -0.09799</td>
</tr>
<tr>
<td>2</td>
<td>55.0</td>
<td>60.0</td>
<td>3299.0</td>
<td>4.2</td>
<td>794.7 2017.6 11082.4 13100 -0.16725</td>
</tr>
<tr>
<td>3</td>
<td>42.7</td>
<td>60.0</td>
<td>2561.0</td>
<td>4.2</td>
<td>617.0 2634.5 10465.5 13100 -0.22453</td>
</tr>
</tbody>
</table>

Table 8 represents a sample calculation for GGW4 on day 3 of the rain simulation experiments. The values of $Ln(N_{rem}/N_0)$ were plotted against $t$ in days, figure 3 was obtained.

![Figure 3. Sample calculation for GGW4 for the inter-storm model.](image-url)
The values for the nitrogen release rate constant ($k$), their related correlation ($R^2$), and $\beta$ values obtained for the three days rain simulation applied on each of the three compost ages GGW0, GGW4 and GGW9 are presented in Table 9.

Table 9. -$k$, $R^2$ and $\beta$ values for the three compost ages.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GGW0</th>
<th>GGW4</th>
<th>GGW9</th>
</tr>
</thead>
<tbody>
<tr>
<td>-$k$</td>
<td>0.0198</td>
<td>0.0633</td>
<td>0.0258</td>
</tr>
<tr>
<td></td>
<td>(0.0019) $^a$</td>
<td>(0.0035)</td>
<td>(0.0044)</td>
</tr>
<tr>
<td>-$\beta$</td>
<td>0.0533</td>
<td>0.0367</td>
<td>0.0242</td>
</tr>
<tr>
<td></td>
<td>(0.0040)</td>
<td>(0.0075)</td>
<td>(0.0095)</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.991</td>
<td>0.997</td>
<td>0.972</td>
</tr>
</tbody>
</table>

$^a$ values in parentheses are standard errors of regression coefficients.

Results obtained show that -$k$ value was the highest for GGW4, GGW9 and GGW0 respectively. High $R^2$ values ($R^2 > 0.97$) were obtained for the three compost ages. -$\beta$ value was decreasing with the increase of the compost age.

**Metals distribution coefficient**

Under equilibrium conditions, the distribution coefficient ($K_d$) is calculated by dividing the element concentration in one phase to the element concentration in another phase. The distribution coefficient is controlled by the relative strength of the intermolecular forces between the element and each of the two phases. The pH has a strong influence on the $K_d$ value, primarily by changing the charge on the surface and the metal ion (Anderson et al., 1988). In our experiments, no significant pH difference was found between the three compost ages, which reduces the potential for pH interference and makes our comparison depend predominantly on the compost age.
where $K_d$ is the distribution coefficient (L/kg), $q_e$ is the solid phase loading of the metal on the compost at equilibrium (mg/kg), and $C_e$ is the measured concentration of metal in solution at equilibrium (mg/L). A mass balance on the metal in the batch reactor, assuming that there are no other losses can be written as:

$$Metal\ in\ reactor = (Metal\ in\ solution + Metal\ on\ compost)$$

$$q_0 \cdot M_{compost} = C_e \cdot V_w + q_e \cdot M_{compost}$$  \hspace{1cm} (8)$$

Where,

$$q_0 = \frac{C_{extract} \cdot V_w}{M_{compost}}$$  \hspace{1cm} (9)$$

By rearranging equation 9 we get:

$$q_e = q_0 - \frac{C_e \cdot V_w}{M_{compost}}$$  \hspace{1cm} (10)$$

Where $q_0$ is the initial solid phase loading of metal on compost (mg/kg), $M_{compost}$ is the mass of compost added to the reactor (kg) and $V_w$ is the volume of water in the reactor (L). Equation 9 was used to determine $q_0$ values and equation 10 to determine the
values of $q_e$ for the metals in the three compost ages and results obtained are presented in Table 10.

Table 10. $q_0$ and $q_e$ values for metals in the three compost ages.

<table>
<thead>
<tr>
<th>Metal</th>
<th>$q_0$</th>
<th>$q_e$</th>
<th>$q_0$</th>
<th>$q_e$</th>
<th>$q_0$</th>
<th>$q_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr</td>
<td>8.89</td>
<td>8.80</td>
<td>11.06</td>
<td>11.01</td>
<td>9.78</td>
<td>9.75</td>
</tr>
<tr>
<td>Ni</td>
<td>8.77</td>
<td>8.30</td>
<td>14.78</td>
<td>14.58</td>
<td>12.28</td>
<td>12.21</td>
</tr>
<tr>
<td>Cu</td>
<td>26.66</td>
<td>25.94</td>
<td>42.43</td>
<td>42.03</td>
<td>46.56</td>
<td>46.37</td>
</tr>
<tr>
<td>Zn</td>
<td>67.75</td>
<td>64.56</td>
<td>95.24</td>
<td>94.53</td>
<td>120.90</td>
<td>120.66</td>
</tr>
<tr>
<td>Pb</td>
<td>41.86</td>
<td>41.76</td>
<td>49.90</td>
<td>49.83</td>
<td>67.91</td>
<td>67.88</td>
</tr>
<tr>
<td>Cd</td>
<td>0.27</td>
<td>0.27</td>
<td>0.39</td>
<td>0.38</td>
<td>0.39</td>
<td>0.39</td>
</tr>
</tbody>
</table>

$K_d$ was calculated using equation (7). $C_e$ values for the metals are presented in Table 2, and $q_e$ values are presented in Table 10. $K_d$ values calculated are presented in Table 11.

Table 11. $K_d$ values for different metals.

<table>
<thead>
<tr>
<th>Compost</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>Zn</th>
<th>Pb</th>
<th>Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>GGW0</td>
<td>923.3</td>
<td>176.8</td>
<td>359.5</td>
<td>202.3</td>
<td>4222.8</td>
<td>531.6</td>
</tr>
<tr>
<td>GGW4</td>
<td>1979.3</td>
<td>716.4</td>
<td>1055.2</td>
<td>1323.9</td>
<td>6733.2</td>
<td>1673.4</td>
</tr>
<tr>
<td>GGW9</td>
<td>4203.4</td>
<td>1745.0</td>
<td>2513.5</td>
<td>4996.2</td>
<td>25809.8</td>
<td>3254.8</td>
</tr>
</tbody>
</table>
A higher $K_d$ value indicates that the metal release from the solid phase to the liquid phase is less preferable, and that the metal tends to stay on the compost. As compost age increases compost releases significant amounts of metals and nutrients that are weakly bound, hence, compost become more stable and is expected to release less metal to the solution. Moreover, and based on the released metals concentration in Table 2, the $K_d$ value is expected to increase as compost age increases. From Table 11, it can be seen that $K_d$ values for all metals (except K for GGW4 and GGW9) increased with the increase in compost age (GGW0, GGW4 and GGW9 respectively).

Organic matter content, structure and specific surface area all change as the compost ages. Functional groups on the organic matter are responsible for much metal retention via surface complexation reactions and structural changes in organic matter may change sorption capacities. Larger specific surface areas are expected to lead to more bonding regardless of mechanism. The change in $K_d$ is larger in magnitude than the change in the organic carbon content or the surface area suggesting that changing organic matter composition may have been most responsible for the increased metal binding effectiveness of the compost organic matter.

Model section conclusions

A first-order kinetics model can be used to estimate the amount of nitrogen remaining on compost after several storms, and a good correlation ($R^2$) was found between the model parameters ($R^2$ values ranged between 0.856 and 0.995 for the intra-storm model, and between 0.972 and 0.997 for the inter-storm model).
7.1. Appendix: Data used to build model parameters

Graphical representation of rainfall simulation data that are used to build the numerical model of leaching losses. These figures are constructed for calculating the values of \( k \) and \( R^2 \) for each rain simulation test applied to GGW0, GGW4 and GGW9 compost materials. In each test case, the ratio of \( \frac{N_{rem}}{N_0} \) or the nutrient remaining on the compost versus the amount contained at starting time 0) (i.e. the amount remaining in the compost that could eventually leach) becomes smaller with time or duration of rainfall.

![Graphical representation of rainfall simulation data](image)

\[ y = -0.0587x - 0.0999 \]
\[ R^2 = 0.994 \]

Figure 4. Sample calculation for GGW0 for the day 1 rain simulation.

![Graphical representation of rainfall simulation data](image)

\[ y = -0.0714x - 1.0953 \]
\[ R^2 = 0.9924 \]

Figure 5. Sample calculation for GGW0 for the day 2 rain simulation.
Figure 6. Sample calculation for GGW0 for the day 3 rain simulation.

Figure 7. Sample calculation for GGW4 for the day 1 rain simulation.
Figure 8. Sample calculation for GGW4 for the day 2 rain simulation.

Figure 9. Sample calculation for GGW4 for the day 3 rain simulation.
Figure 10. Sample calculation for GGW9 for the day 1 rain simulation.

Figure 11. Sample calculation for GGW9 for the day 2 rain simulation.
Figure 12. Sample calculation for GGW0 for the inter-storm model.

Figure 13. Sample calculation for GGW9 for the inter-storm model.
7.2. Indications of qualitative changes in organic matter characteristics and their influence on metal and nutrient losses from compost leachates

Synopsis

Although first order kinetics provide a good fit for measured data during leaching events, the composition of the compost substrate being measured should be viewed as dynamic and changing through time. In particular, plant-based compounds are progressively degraded into microbial biomass and microbial and plant biomass residues and byproducts accumulate in the compost matrix. This section is a general interpretation of measured data with emphasis on changes in substrate quality rather than changes in release kinetics from a given matrix.

Discussion

The data presented on Table 3, Section 6, show declines in leaching losses during each of three successive daily leaching events for organics with different processing times, including 0 weeks (chipped green waste), 4 weeks (thermophilic composting; ‘mature’), and 9 week old (‘cured’) materials. When these leaching data are summed for each age of organic material, some of the characteristics of the organic matter can be qualitatively interpreted and generally related to processes that influence leaching losses. This information can be used to improve compost field performance by selecting proper compost production methods, particularly curing time after thermophilic treatment. These data differ from those presented in Table 3, which presented leaching losses from a uniform thickness applied to an experimental surface area. The values
here have been corrected for changes in bulk density to represent equivalent masses to show differences in leaching losses per standardized unit of compost mass.

When the leaching losses from three simulated rain events are combined, three different trends are observed that relating to age of the organic materials: 1) organic C, P and metal leaching losses steadily decline as compost ages; 2) losses of nitrogen-containing compounds peak with mature compost (4 week) and then decline with curing (except nitrate, which remains at very low levels); 3) potassium increases with compost age, as does nitrate slightly.

The increased retention of metals by older composts is interpreted as indicating increased charge on organic functional group surfaces as they oxidize and become humified, providing negative charges for these predominantly positive ions to adsorb onto. For metal-impacted watersheds, retaining composts longer (more extensive curing) may have practical benefits for reducing metal losses.

The strong decrease in leaching losses of TOC with age suggest that easily soluble carbon materials are rapidly depleted by microbial decomposition, reducing their abundance and converting some of these materials into microbial biomass. Leaching losses decrease by about half in each age interval, while, in contrast, nitrogen leaching losses increase from 0 to 4 week materials, and then decreases with 9 week materials. Microbial activity typically results in organic matter with C:N ratios around 8 to 10, but the C:N ratio of the leached materials, however, declines to below this ratio, indicating other mechanism for generating leachable compounds. C:N ratios decrease steadily with compost age and with leaching event: from 0 weeks (C:N ratio of 19.0, 8.6, 3.8) to week 4 material (4.5, 2.4, 1.4) and to week 9 material (3.9, 2.7, 2.2). This indicates that increasingly N-rich fractions are being lost to leaching from each material. The C:N ratio of the bulk compost, meanwhile, also declines and becomes stable at 26.8; 19.9; 19.5 (for weeks 0, 4, and 9). This raises the question of what produces the leachable
compounds compared to what is occurring in the bulk compost itself. The effect is not caused by inorganic nitrate, which remains at low levels. Compost decomposition is a multi phase process, and each phase is contributing different materials to the decomposition process and to the pool that can be leached if rains occur. As impacts to watersheds become more critical, this may be a useful indicator of potential ways to improve compost retention of N-containing compounds.

Another indicator of plant material decomposition is shown by the increase in potassium (K) levels released from plant tissues as the carbon framework is consumed. Much of the 'salt' measured in compost materials is not sodium chloride, but rather, decomposition products of potassium and other nutrient ions. Characterization of this process is important for regulation of salt loading in the watershed. In this case, the 'salt' is actually a nutrient that would be rapidly taken up into regenerated plant biomass.

Phosphorus losses are about equal for 0 and 4 week materials, but then decline from 9 week materials. The reason for this is unknown, and does not match other patterns of other elements. Phosphate is a negatively charged ion, so would not be expected to be retained on oxidized surfaces. For watersheds critically impacted by P, this behavior is interesting and suggests greater curing times may decrease P losses.

**Conclusion**

The dynamics of nutrient and metal losses are clearly related to compost age as well as leaching events, and leaching patterns of different elements reflect the chemical properties of the different nutrient or metal elements. Management of at least some of these nutrients or metals can be expected to be improved if the characteristics of composts of different ages were better understood.
Table 1. Leaching losses from 1.5 - 2.0 inch compost layer for combined three-day storm series, with mass losses prorated for increased bulk density. Values in mg/L except Cd in ppb.

<table>
<thead>
<tr>
<th>Element</th>
<th>0 weeks</th>
<th>4 weeks</th>
<th>9 weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>TN</td>
<td>80.60</td>
<td>168.30</td>
<td>80.51</td>
</tr>
<tr>
<td>TIN</td>
<td>22.20</td>
<td>30.84</td>
<td>12.61</td>
</tr>
<tr>
<td>Norg</td>
<td>59.10</td>
<td>137.47</td>
<td>67.96</td>
</tr>
<tr>
<td>NH3</td>
<td>57.50</td>
<td>135.53</td>
<td>65.24</td>
</tr>
<tr>
<td>NO3-</td>
<td>1.60</td>
<td>1.94</td>
<td>2.72</td>
</tr>
<tr>
<td>P</td>
<td>20.40</td>
<td>20.13</td>
<td>7.40</td>
</tr>
<tr>
<td>K</td>
<td>423.30</td>
<td>1258.52</td>
<td>1359.18</td>
</tr>
<tr>
<td>Cr</td>
<td>0.07</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>Ni</td>
<td>0.10</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>Cu</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>Zn</td>
<td>1.19</td>
<td>0.47</td>
<td>0.30</td>
</tr>
<tr>
<td>Pb</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Cd</td>
<td>1.50</td>
<td>0.92</td>
<td>0.71</td>
</tr>
<tr>
<td>TOC</td>
<td>1190.50</td>
<td>529.65</td>
<td>259.24</td>
</tr>
</tbody>
</table>

Table 2. N and C leaching losses and C:N ratios of leachates and bulk composts of different ages.
8.0. Project Findings Summary

Composts can be used for field applications with little likelihood of leaching losses of nutrients or metals if appropriately applied to the field site. Many examples of compost application are cited from studies around the country. If losses occur, they tend to happen with thick layers of compost applied as a surface mulch over impermeable substrates. Yard waste composts have less likelihood of losing nutrients than animal source composts.

The lowest nutrient losses were measured from field soils having tilled and incorporated composts plus an application of compost or wood chip as a surface mulch. Suitable incorporation depths will vary with substrate, topography and climatic region, but a general recommendation is to apply one inch of compost tilled to 10 inches, and covered with another one inch surface mulch layer. Tilled soil volumes on slopes should be placed on a horizontal bench to avoid lateral movement when saturated.

Mulches (in this case woody fragments measuring 10 to 50 mm (3/8 to 2 inch) in length) reduce water loss from soils, but the effects are restricted to two to four weeks after a rain, rather than for several months. Because test results and literature information suggests that it is the shading function, not the insulation function that makes mulches work, the particle size is less important for reducing evaporation as long as the ground is shaded. Duration of the material would, of course, be longer with larger or more decay-resistant (bark vs wood chips) materials. If plants are expected to grow through the summer drought in non-irrigated conditions, they need deep rooting and moisture reserves, not more mulch application. Mulches are also valuable for many other field effects, including protection from raindrop splash detachment, protection from excess heat or freezing, slowing surface water flow and reduction in crusting. These effects require long-lasting mulch cover, which is attained by thicker layers of coarser
wood fragments. But, saving moisture is not a long term benefit of these mulch applications for periods greater than one month.

Organic characteristics vary between composts of different ages and between different size fractions within a single compost. Fine (< 3/8 inch) compost particles are more advanced in their decomposition and more likely to release N, especially when screened from older, more extensively cured composts. Less cured composts may immobilize N.

Infiltration on dense or compacted soils with low rates can be increased by application and incorporation of coarse woody chips or shreds. Increases in saturated conductivity between 20 and 90 % were measured. Fine composts (< 3/8 inch) gave minimal improvements in improved infiltration, but also did not plug the pores. The depth of incorporation needed to avoid overland flow and sediment production is determined by rainfall volumes as well as intensity.

Nutrient and metal losses from composts were well fit by first order kinetics models. Data from leaching during a single storm and from repeated storms on successive days were equally well represented. Qualitative differences in compost substrates as they age suggest that different parameters are needed for mature versus well cured composts.