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GENERATION OF WATER-STABLE SOIL AGGREGATES FOR IMPROVED EROSION CONTROL AND REVEGETATION SUCCESS

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16. Abstract

This project summarizes the mechanism of water-stable aggregate formation and concludes that sustained, vigorous plant growth is essential to maintenance of soil structure. Plants contribute to water-stable aggregates by adding carbon materials to the soil that are decomposed by soil microbes. Exudates from roots and soil microbes contribute to the formation of microaggregates, while fine roots and mycorrhizal hyphae contribute to the stabilization of macroaggregates.

Sustainable, vigorous plant growth, however, is difficult to achieve on degraded soils from which topsoil has been removed by construction or erosion. Previous studies indicate that plant growth on degraded soils is often nutrient limited, and that low soil nitrogen (N) is the most common limiting nutrient (other than water). To evaluate the levels of N needed for sustained plant growth, we surveyed a wide range of disturbed but revegetated sites in the Tahoe Basin, and correlated the percent plant cover with soil N pools. Plant communities with > 40 % ground cover were associated with soil containing an average of 1228 kg total N/ha and 26 kg mineralizable N/ha.

Laboratory incubation experiments using prospective amendment materials indicated that widely differing N release patterns occur. Given the large total amounts of N per ha that are associated with adequate plant growth and cover, the use of amendments with slow N release rates is encouraged, so that the N applied to the site is retained in the soil until it is incorporated into plant tissue. Replicate extraction runs indicate that the incubation method is consistent and is useful for screening amendment materials during selection for field plots.

Placement of the amendment has a strong effect on plant growth. Surface (0-10 cm) applications had significantly higher biomass production than N amendments that were evenly distributed throughout the profile (0-30 cm) or applied deeply within the profile (20-30 cm).

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Implementation Statement

Information from this research activity will be disseminated through distribution of copies of this report, through presentations to technical and general conferences, workshops and through published journal articles and through the Caltrans Publications Unit. Further details are included in Chapter 6, Conclusions, Recommendations and Implementation.

Summary

This project summarizes the mechanism of water-stable aggregate formation and concludes that sustained, vigorous plant growth is essential to maintenance of soil structure. Plants contribute to water-stable aggregates by adding carbon materials to the soil that are decomposed by soil microbes. Exudates from roots and soil microbes contribute to the formation of microaggregates, while fine roots and mycorrhizal hyphae contribute to the stabilization of macroaggregates.

Sustainable, vigorous plant growth, however, is difficult to achieve on degraded soils from which topsoil has been removed by construction or erosion. Previous studies indicate that plant growth on degraded soils is often nutrient limited, and that low soil nitrogen (N) is the most common limiting nutrient (other than water). To evaluate the levels of N needed for sustained plant growth, we surveyed a wide range of disturbed but revegetated sites in the Tahoe Basin, and correlated the percent plant cover with soil N pools. Plant communities with > 40 % ground cover were associated with soil containing an average of 1228 kg total N/ha and 26 kg mineralizable N/ha. When measured on a concentration basis (< 2 mm fraction) volcanic soils had much higher N levels than granitic soils. When measured on a whole soil basis, however, granitic and volcanic soils did not significantly differ.

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materials during selection for field plots. Field release rates from test plots near Livingston, CA were 30 to 40 % slower than laboratory release rates.

Placement of the amendment has a strong effect on plant growth. Surface (0 - 10 cm) applications had significantly higher biomass production than N amendments that were evenly distributed throughout the profile (0 - 30 cm) or applied deeply within the profile (20 - 30 cm).

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Chapter 1. Introduction

OVERVIEW OF THE PROJECT

The project “Generation of Water-Stable Soil Aggregates for Improved Erosion Control and Revegetation Success” was conceived following repeated field observations of hard-setting (partial cementation with drying) on scree slopes formed from decomposed granite (DG) materials. In particular, the DG materials near the Buckhorn summit realignment project in northern California were observed to hard-set to depths of 10 cm or more. Root penetration is very poor when these materials hard-set and revegetation success is low. Low soil organic matter content was identified to be a contributing factor to both plant nutrition and soil physical condition ("Soil Conditions and Mycorrhizal Infection Associated with Revegetation of Decomposed Granite Slopes." FHWA-CA-TL 96/1. Claassen and Zasoski, 1995).

Harvesting, stockpiling and reapplication of topsoil on project sites on DG materials is strongly encouraged ("The Effects of Topsoil Reapplication on Vegetation Reestablishment. FHWA-CA-TL-94/18. Claassen and Zasoski. 1994)). However, because topsoils are frequently very shallow on DG parent materials or in mountainous terrain, and because these shallow topsoils are easily degraded during construction, there is often little topsoil material available for amendment to final graded surfaces. Therefore, revegetation of these low nutrient, droughty DG substrates often involves application of organic and nutrient amendments.

We initially viewed regeneration of soil physical structure as a top priority on these difficult sites, thinking that this would ameliorate the hard-setting characteristics of DG, thereby enhancing plant growth and facilitating regeneration of a erosion resistant plant cover. Literature review in the initial phase of the project, however, suggested that poor soil physical characteristics can only be sustainably remediated by consistent plant growth on the site. This occurs because a vigorous plant community constantly pumps organic matter into the soil from litter-fall and from root exudates. The organic carbon feeds the soil microbial community that generates and maintains the soil structure. Plant growth, then, is a prerequisite condition for sustained soil structural improvement.

This information prompted a revision of the research priorities of the project. The focus on soil physical characteristics and generation of water-stable aggregates was reprioritized to include an evaluation of the soil conditions required for support of sustained plant growth on these harsh, nutrient poor and droughty substrates. Vigorous plant growth is expected to generate secondary beneficial effects on the DG substrates, including deposition of erosion resistant mulch layers, addition of moisture retaining soil organic matter, regeneration of pools of plant available nutrients, as well as the generation of water-stable aggregates.

Evaluation of several previously established Caltrans study plots in northern California also suggested a change to a focus on soil nutrients. In these studies, the most commonly cited reason for the eventual failure of the revegetation community was concluded to be loss of soil fertility, rather than poor soil physical conditions. Leiser *et al.*, (1974) in their report "Revegetation of Disturbed Soils in the Lake Tahoe Basin" conclude that a "minimum" application of 250 lb/ac of 16-20-0 ammonium phosphate fertilizer contained insufficient N to support plant growth after the end of the first season (pg 20). We revisited many of the sites described in this study in spring of 1998. Of those positively identified, scattered plants or rows of willows still persisted, but large areas of unvegetated, exposed DG were observed and accumulations of erosion resistant plant litter were low. A related study by Nakano *et al.*, (1976) reported positive responses to fertilization at six out of eight sites around the Basin, supporting the need for nutrients on these degraded soils. Other Caltrans studies, including "Planting Techniques and Materials for California Roadsides" (Clary, 1983), as well as "Revegetation of Problem Soils on Road Slopes" (Parks and Nguyen, 1984), also conclude that low fertility, especially low N, reduces plant growth on low pH soils, on serpentine soils, and on DG soils in the lake Tahoe Basin. A California Tahoe Conservancy publication "A Report on Soil Erosion Control Needs and Projects in the Lake Tahoe Basin" (Van Vleck, 1987) states that vegetation is an effective erosion control because it is "self-repairing and has a virtually unlimited life expectancy" (pg 13). While this is true for most undisturbed natural soils and their associated plant communities, these previous studies indicate that the "life expectancy" of revegetated plant communities on degraded soils receiving only fertilizer inputs is evidently often very short.

We interpret these studies as indicating that soluble N amendments from the specified fertilizers, where applied, were insufficient to support plant growth for more than a few seasons, and that the soil nutrient reserves were inadequate for continued plant growth in subsequent years. Reapplication of fertilizers was often mentioned in these studies as being needed to maintain plant growth. The amendments appeared to be too small to reestablish other components of the plant-soil community, including accumulations of plant litter and mulch, extensive root systems, and soil microbial communities. Each of these components requires N in amounts approximately equal to that in the above ground plant component, suggesting that larger nutrient amendments are required.

In the study described here, we present the argument that natural soils contain large pools of organically stabilized N that provide lower short-term (soluble) N availability but larger reserves of total N than are available from fertilizer applications.

The lower short-term N availability restricts weedy invasion while the large, organically stabilized reserve provides continued N release for multiple years. On degraded soils in which soil nutrients and organic matter have been depleted, organic amendments may be used to provide short and long-term N availability required for sustained revegetation.

Sustained revegetation of barren cut and fill slopes is an important component for reduction of non-point-source sediment and nutrient pollution. Preliminary data from a recent study indicates that 12 % of the N and 36 % of the P entering Lake Tahoe comes from direct runoff from overland flow, rather than from stream flow or atmospheric deposition (Reuter *et al.*, 1998). We assume that roadsides are significant contributors to this overland flow and that improved methods of revegetation on these difficult soil materials will directly reduce these sediment loads to adjacent watersheds.

In this report we review aspects of soil fertility and amendment that pertain to revegetation of degraded soils. The process of generation of water-stable aggregates, and the dependence on plant organic matter inputs is outlined in Chapter 2. Following this, and reflecting the change in research topic priority, is Chapter 3, a survey of the soil nitrogen contents that are correlated with the ability of a site to sustain a permanent plant community. Chapter 4 reports the results of a study measuring N release from several prospective amendment materials that could potentially be used on Caltrans revegetation projects. In Chapter 5, the results from a study on the effect of vertical placement in the profile are presented. Finally, in Chapter 6, the various studies are integrated and the implications for Caltrans revegetation projects are summarized.

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Chapter 2. Processes of water-stable aggregate generation and their formation on degraded soils.

ABSTRACT

Soil aggregation is the process by which small soil particles such as sand, silt and clay are bound together into larger units by natural forces and by substances derived from root and microbial exudates. Soil aggregates improve plant growth by improving plant water availability, gas diffusion, and microbial habitats and activity. Aggregates that are strong enough to be stable against water entry or rain-drop impact are especially important since aggregates must persist through normal soil wetting and drying cycles. The formation of water-stable aggregates in surface soils is thought to occur in a sequential process by different mechanisms for different size categories of aggregates. For this reason, the mineralogy and biological activity of the soil, as well as the type of human disturbance, has a strong influence on the formation and maintenance of aggregates.

This chapter addresses formation of water-stable aggregates in surface soils and then applies this information to aggregate formation on disturbed soils typical of revegetation projects. The first objective of this chapter is to describe the geometry and size relationships of water-stable aggregates, how they function within soils, and the mechanisms by which they are formed in natural soils. Next, aggregation in natural and agricultural soils will be contrasted with aggregation in drastically disturbed soils, including those that are badly eroded or chemically altered. Following this, the generation of aggregates by polymers, rather than natural process, will be reviewed.

INTRODUCTION

Soil aggregation is the process by which smaller soil particles are bound together into larger units by natural physical forces, by inorganic chemical bonding and by substances derived from root and microbial exudates (Glossary of Soil Science Terms; Anon., 1996). Different types of binding predominate the in various size classes of aggregates, culminating in large structures that can measure several millimeters to a few centimeters in the widest dimension. These aggregates are a common feature of well developed soils, and they help reduce erosion and increase gaseous diffusion, water movement and root growth. Soils without aggregate structure can develop a uniformly hard, impenetrable, structureless, or "massive", condition that can drastically reduce root penetration and infiltration. Artificial units with such a massive, structureless condition are called "clods" and result not from natural processes, but from shoveling, plowing, traffic compaction, or working of wet soil.

Natural soil aggregates range in size from < 2 μm up to about 10 mm (< 1/1000 to 3/8 inch) diameter (Burnes and Davies, 1986). They may be formed from either primary particles (individual sand, silt or clay particles) or from smaller aggregates which are united into larger aggregates by natural processes. Aggregates are split into two size groups based on empirical observations that larger aggregates (> 250 μm diameter, Emerson, 1967) are less resistant to tillage and mechanical disturbance compared to smaller, microaggregates (< 250 μm diameter).

The emphasis on "water-stable" aggregates, or those structures that are strong enough to persist through repeated soil wetting and drying cycles, is a result of the recognized benefits of aggregates in reducing soil erosion caused by water movement on the soil surface. Larger aggregates are less erodable than smaller ones because of their greater resistance to splash detachment and transport and because their inter-particle spaces create large soil pores that improve percolation and drainage.

As aggregates become larger, however, they also become weaker in internal strength. This results from both reduced mineral surface-to-mineral surface contact within the aggregate and also from the greater forces that are generated within larger aggregates. During rapid rewetting of air-dry aggregates, for example, air trapped within the aggregate by water films is compressed as strong matric forces continue to draw water into the aggregate. Sufficient air pressure may develop to explosively rupture and disintegrate the aggregate into smaller components ("slake"; Emerson, 1967; Kemper *et al.*, 1985). Evaluation of aggregates that are "water-stable" focuses on those structures that are large enough to resist erosion, and are also strong enough to last through rehydration processes that occur with normal soil wetting and drying cycles. In the following sections, the functions of aggregates will be discussed, followed by the mechanisms of their formation and maintenance.

FUNCTIONS OF WATER-STABLE AGGREGATES

Macroaggregates (> 250 μm)

The function of aggregates and the pores they create varies according to the size of the aggregate or void (Figure 1). Macroaggregates are defined as those aggregates measuring larger than 250 μm (0.01 inch) in diameter and ranging up to 10 millimeters (3/8 inch) in size. Macroaggregates provide several important functions for soils, including improved erosion resistance, more rapid infiltration and increased diffusion of soil air and moisture within the soil. Water stable aggregates reduce erosion because they form larger, sand sized aggregate particles from smaller clay and silt sized primary

Scale	Particles	Aggregates	Pore Function	Biota	Scale
10^{-0} (meter)	boulders	whole pedon		humans	10^{-0} (meter)
10^{-1}	stones	clods		moles	10^{-1}
10^{-2}	gravel	peds	drainage/ aeration		10^{-2}
10^{-3} (mm)	sand	macro-aggregates	macropores	invertebrates, plant roots	10^{-3} (mm)
10^{-4}		micro-aggregates			10^{-4}
10^{-5}	silt		$\psi < -0.03$MPa	mycorrhizal fungi	10^{-5}
10^{-6} (μm)	clay	domains	↑ plant available	saprophytic fungi, bacteria	10^{-6} (μm)
10^{-7}	colloids		water ↓		10^{-7}
10^{-8}	humic molecules	clay laminae	$\psi > -5.0$ MPa clay	viruses	10^{-8}
10^{-9} (nm)	organic molecules		interlayer water		10^{-9} (nm)
10^{-10} (Å)	atoms				10^{-10} (Å)

Figure 1. Scale and function in soil structure. (redrawn from Waters and Oades, 1991). (file: soilscale.doc)

particles. The greater the particle size, the less susceptible the unit is to splash detachment when impacted by raindrops whose mass may equal or exceed that of the aggregate. In addition, strong internal bonding within the aggregate volume compared to adjacent soil volumes a few millimeters away, creates a pattern of local areas of strength, or aggregation, and interspersed areas of weakness. This heterogeneity reduces the tendency of non-structured soils to puddle (form a dense, uniform slurry) when wet, and to hard-set or crust when dry.

The second function of macroaggregates is that they allow more rapid infiltration and percolation of water in the soil profile and greater rates of gas diffusion. This property is not so much a function of the aggregate particle size as it is a function of the pore size between adjacent aggregates. Pore spaces between these macroaggregates are 10 μm to > 30 μm in diameter (0.0004 to > 0.0012 inch) (Tisdall and Oades, 1982). These pores are large enough that the pull of gravity can draw water out of the pore, allowing gas diffusion and deeper percolation of moisture into the soil profile.

Microaggregates (< 250 μm)

The smaller pores within and between microaggregates regulate water retention in the soil. Pore sizes from about 30 μm down to about 0.2 μm are not emptied by gravity and retain water for plant growth (Tisdall and Oades, 1982). Calculated pore sizes (Hanks and Ashcroft, 1986) corresponding to permanent wilting points for agricultural plants (generally set at -1.5 MPa, or 15 bar moisture tension) are as small as approximately 0.15 μm. Wildland plants, however, may be able to withdraw moisture from pores as small as 0.05 μm diameter (-5.0 MPa, 50 bar moisture tension). Soils without aggregation can settle and compact so that almost all pore diameters are less than 30 μm diameter. The soil then retains water throughout the profile, blocking gas diffusion and creating the potential for anaerobic conditions if oxygen demand exceeds the rate of oxygen diffusion into the soil volume. Root penetration is difficult in soils with pores this small, making the moisture unavailable for plant use.

Much of the microbial activity (40 - 60 % of the total microbial biomass) occurs in aggregates 2 - 20 μm in diameter, probably because of their moisture retention characteristics and because the protective shielding of small pores and clay coatings reduces predation (Jocteur Monrozier *et al.*, 1991). Microaggregates (and the interiors of macroaggregates) commonly contain pore size diameters in this range.

Because microaggregates are created in part by humic materials and organic residues, their construction also means that the primary mineral surfaces are coated with organic films, reducing direct exposure of the root or microbe to the bare mineral surface. The organic materials themselves create reserves of nutrients, both for N (Lowe, 1973) as well as P (Harrison, 1987) and other cations.

MECHANISM OF WATER-STABLE AGGREGATE GENERATION IN AGRONOMIC SOILS

Natural water stable aggregates are constructed by assembling primary particles (single grains of sand or silt) into microaggregates and then by binding microaggregates into macroaggregates. This sequential building process is known as a "hierarchy" of soil aggregate generation (Tisdall and Oades, 1982; Miller and Jastrow, 1990; Waters and Oades, 1991). In this organizational scheme, small sized aggregates are stabilized by different mechanisms than large aggregates. Interparticle binding is influenced by soil inorganic and organic chemistry, soil microbial activity, soil physical processes and anthropogenic management. Because large particles physically incorporate smaller ones, characteristics of the larger aggregates may include some of those of the smaller aggregates. In general, the process of generating aggregates is similar a variety of soil types.

In the following section, the mechanism of aggregate generation is described from small to large scales, as summarized from Tisdall (1996) and Waters and Oades (1991). For size comparisons to structures mentioned in this section, soil bacteria are approximately 1 μm in size, soil decomposer fungi are about 1 or 2 μm in diameter and endomycorrhizal hyphae may be up to 10 μm in diameter. Clays are < 2 μm, silts are 2 to 50 μm and sands are 50 to 1000 mm (1 mm) in diameter. A human hair or a fine grass root is about 75 μm in diameter, mycorrhizal spores are commonly 60 to 200 μm in diameter, while earthworms may measure 1000 to 5000 μm (1 to 5 mm) in diameter.

<u>1. Clay, oxide and humic dominated microaggregates (< 2 μm).</u>

Microaggregates measuring < 2 μm are dominated by the clay mineralogy and iron or aluminum oxides of the soil. Clay domains (flexible sheets or blocky plates of relatively homogeneous types of clay minerals) are bound together, or aggregated, by surface iron and aluminum oxides or by humic materials and microbial residues. The contact surface area between adjacent clay platelets influences the stability of the clay domains. Pure calcium montmorillonite clays, for example, can have about 80 % of the surface area of individual lamellae in contact with each other, and so are much more cohesive than a low charge kaolinite mineral with less than 10 % surface area contact in an open, crystal face-to-crystal-end (card house) structure (Emerson *et al.*, 1986). Polyvalent cations, especially aluminum (Al^{3+}) and calcium (Ca^{2+}) increase binding of clay platelets by bridging between the two negative charges on the clay surfaces with a positive, polyvalent cation. This promotes a more rigid microstructure, although organic films such as humic materials on the surfaces may occasionally decrease this type of structure (Quirk and Murray, 1991). Soils with very high iron oxide contents (very red soils) may have a well developed microaggregate structure even with low clay contents.

<u>2. Microbial residue dominated microaggregates (2 - 20 μm).</u>

Aggregates of this size may be formed by pressure from growing roots that compress and mold the clay materials into a face-to-face orientation, by the binding action of plant and microbial mucilage, and by compression of local areas by drying as water is withdrawn into roots and mycorrhizal hyphae by plant transpiration (Dormaar and Foster, 1991; Dorioz and Robert, 1987). Once formed, water stable aggregates in the 2 - 20 μm range are very stable. Because of their small size and large particle to particle contact area, they are more resistant to physical disruption than are larger particles. These aggregates contain local clusters, or flocs, of clays that are bound by inorganic precipitates (iron and aluminum oxides) and by organic residues. Inorganic types of precipitates are more common in weathered soils. The microbial polysaccharides are produced as soil microorganisms grow and produce sticky slimes around their cells, either for nutrient adsorption, for defense, or in response to anaerobic conditions. Microbial polysaccharides are especially important in maintaining the stability of aggregates in this size class. About half of the microbial biomass in the soil is associated with microaggregates of this size (Jocteur Monrozier *et al.*, 1991).

3. Plant debris dominated microaggregates (20 - 250 μm).

Microaggregates in this size fraction (usually greater than 90 μm) are characterized by encrustation around fragments of plant debris. The age of this plant debris is not known, but because it is actively decomposing it is assumed to have been produced within the last few seasons of plant growth. Although the fragments are small, internal plant cell structures (tracheids, cell walls) are still visible. Aggregates of this size are more resilient to physical disturbance than are the macroaggregates, and are relatively unaltered by tillage in agricultural systems. Because of their interaction with plant cell fragments, microaggregates in this size class still require continuous input of plant materials.

As the plant material in the 20 - 250 μm size class decomposes, the aggregates frequently show internal void spaces. Although the recently added plant tissue fragments disappear, the accumulated microbial residues continue to hold the aggregates together. These organic residues have been radiocarbon dated and range from "modern" to about one thousand years old (Anderson and Paul, 1984; from Tisdall 1996)).

The 2 - 20 and 20 - 250 μm sized aggregates are most easily developed by amendment with organic residues. However, it is not merely the amendment with organics, but the decomposition of the organics by microbes (and subsequent mucilage production) that generates and stabilizes the aggregate structures (Burns and Davies, 1986).

4. Fine root and VAM hyphae dominated macroaggregates (> 250 μm)

Macroaggregates are stabilized assemblages of smaller aggregates and primary particles into aggregates greater than 250 μm up to 10,000 μm (10 mm) in diameter (1/10 inch to 3/8 inch). Roots and mycorrhizal hyphae are important structural components of this size of aggregate. In agricultural systems, fine grass roots (0.2 to 1 mm in diameter) and extraradical hyphal length were most strongly correlated with aggregate size (Miller and Jastrow, 1990). Grass roots are thought to aggregate the soil microstructure by compression from radial expansion of the growing root, by shear and orientation of the clay domains, by enmeshment of clay minerals in root hairs and hyphae, and by shrinkage of the soil microvolume with transpiration (Goss, 1987).

Soil management or disturbance that reduces fine root or mycorrhizal hyphal density also has a strong influence on water stable aggregates of this size class. Fine roots and hyphae are rapidly degraded by soil decomposers, and must be constantly renewed by additional plant and fungal growth. Water stable aggregates in this size class are easily degraded by disturbance such as tillage and loss of plant or microbial activity.

An alternative classification of soil aggregates based on the persistence or duration of the bonding mechanism gives approximately the same aggregate size groups (Tisdall and Oades, 1982). Microaggregates formed with humic and oxide bonding were viewed as being "persistent" with time and with tillage and were primarily found in the < 2 μm size category. The organic residues (mainly microbial polysaccharides) in the larger microaggregates (up to 250 μm) were labeled "transient." Roots and fungal hyphae that stabilized macroaggregates (> 250 μm) were termed "temporary". Continuous plant and microbial inputs are needed to maintain the larger aggregates size classes, while the smaller aggregates persist for years with little or no additional input.

WATER-STABLE AGGREGATES ON DEGRADED SOILS

Few studies exist on aggregate stability of wildland soils and fewer still on aggregate stability of severely degraded soils. Extrapolation from the literature for agricultural soils as cited in the previous section suggests that aggregate generation processes would be low on degraded sites mainly because of the low levels of soil organic matter in disturbed soils. This results both from the low levels of humic compounds that stabilize the < 2 μm sized microaggregates as well as the low levels of microbial residues that stabilize 2 to 20 μm sized aggregates. The harsh growing conditions on many degraded sites restrict plant growth, reducing the inputs from fine roots and mycorrhizal hyphae that are needed for macroaggregate formation in the > 250 μm size class.

In some special cases, the high concentration of iron oxides in soils with very high iron content (very red to maroon colored materials) may create microaggregates in spite of low organic matter contents. While these soils are well structured, the lack of clay size particles and low organic matter may make them droughty. Lack of clay may also reduce formation of larger aggregates sizes. Increased macroaggregate generation in these soils as well as others requires a continuous supply of microbial and plant carbon.

Degraded soils are often very low in organic matter content and often require inputs of organic materials. The quality of the amendment influences soil structural development since all organic inputs do not promote aggregate formation equally. For example, applications of peat (up to 20 kg m^{-2}) did not increase percent of stable aggregates while application of all rates of urban refuse (6.5 to 26 kg m^{-2}) did increase stable aggregates in a degraded soil (Diaz, *et al.*, 1994). Because the peat was resistant to microbial decomposition, aggregate generation may not have occurred in the microaggregate size category. Both long term as well as short term field amendments of peat to soils from the Rothamsted Experimental Station in England actually decreased aggregate stability (Ekwue, 1990). This probably results from the lack of soil microbial activity that is normally associated with organic inputs (usually plant materials) to soils (Browning and Milan, 1941; Miller and Kemper, 1962; Tisdall *et al.*, 1978), since organic matter added to a sterile soil shows little increase in aggregate stability (Martin and Waksman, 1940; Peele, 1940). The critical condition seems to be that the microbes grow and generate their polysaccharide materials in-place, within the soil matrix. This was shown through increased generation of water stable aggregates by addition of an 0.5 % glucose solution (an easily degraded sugar) compared to addition of microbially produced gums to the soil (Swift, 1991). The effect was maximum at one week and declined by half by 12 weeks, so continual amendments (as occurs with gradual litter decomposition) are also important. The use of non-composed yard (green) waste materials may provide this type of energy source for in-situ generation of water stable aggregates because microbial degradation occurs within the soil rather than in a compost pile.

Soils in Mediterranean climates such as in California often have poor aggregate stability (Singer, 1991). These soils commonly have low organic matter contents as a result of the hot, dry summers. Singer and Le Bissonnais (1998) characterize soils that are poorly aggregated and prone to crusting and increased overland flows as having < 20 % clay, < 3 % organic carbon, and < 2 % citrate-bicarbonate-dithionate extractable iron plus aluminum. These conditions are often typical of the subsoil materials that are exposed on disturbed sites following removal of organic matter and accumulated topsoil.

The lack of aggregate structure in degraded soils leads to close packing of individual soil particles and the development of surface crusting. The mechanisms involved in the crusting process are outlined in a detailed study of surface morphology on a weakly aggregated, granite-derived alfisol (Moss, 1991 a,b,c). Surface crusts were formed when silt sized particles (10 - 50 μm) became concentrated on the soil surface by preferential splash detachment and removal of clays and fine sands. This uniform sized silt fraction developed a rigid, close-packed, 0.5 mm surface layer that sealed the soil surface. The dense, silt-rich layer retained its structure against rain-drop impact because it became dilatant, meaning that the volume formed by the close-packed silts had to expand before particles would disperse. In this condition, the close packed silt particles remained tightly packed because the small pore size between the silt particles limited hydraulic flow into the inter-particle voids. Because particles were held together by the thin water films between them, the energy from raindrop impacts compacted underlying soils up to 5 mm deep by hydraulic transfer. Soils with coarse particles measuring sand size or greater did not pack as closely as the silt sized particles because of their more rounded shape and less dense packing geometry. These particles became grouped together during rainfall and maintained areas of open pore spaces into the soil, allowing infiltration of water. The author cited presence of larger particle sizes and interception of raindrop impact by plant or mulch covers as critical methods to resist this rain-impact derived soil crust, recommending a mulch cover with a plant leaf or litter fragment at a spacing of less than the average raindrop diameter (Moss, 1991 a,b,c).

SYNTHETIC GENERATION OF WATER-STABLE AGGREGATES

Studies of the mechanisms of crusting and hard-setting such as by Moss (1991) partially explain how synthetic generation of water stable aggregates by polymer applications can be beneficial. Surface crusting was identified as being caused by the close packing of silt sized particles 15 - 50 μm in diameter but not from particles measuring between 1 and 5 mm (Moss, 1991b). Polymers can be used to synthetically bind smaller particles together into larger ones to achieve this goal. Examples of successful synthetic generation of water stable aggregates include infiltration rates on furrow irrigated soils that have been doubled in the Imperial valley (Wallace *et al.*, 1986). Emergence of wildland grasses was increased as crusting was reduced, using rates from 10 to 40 kg polymer /ha (Rubio *et al.*, 1992), although plants continued to have water stress problems (Rubio *et al.*, 1989).

Benefits from use of polymers in field situations on degraded soils may be reduced by other factors, however. For example, the most effective way to apply polymers is to fully saturate the soil horizon with a dilute solution of the polymer, as in furrow irrigation (Wallace, 1993). Wildland sites will rarely be flooded for application of the polymer. A curing (drying) period also increases the effectiveness of the application (Letey, 1994;

Nadler *et al.*, 1992), but application of dry granules did not increase aggregates (Cook and Nelson, 1986). Drying of the soil may not occur on wildland sites treated just before seasonal rains begin.

Polymer generated aggregation commonly only penetrates a few (1 - 5) centimeters (Mitchell, 1986; Lentz and Sojka, 1994), and so is not expected to generate aggregates throughout the soil profile as occurs with natural aggregate formation. While a surface aggregate structure will improve erosion resistance, the lack of subsurface structure will reduce deep percolation and may allow saturation and liquefaction of surface soil layers during heavy precipitation. Penetration of the profile was increased (to 20 cm depth) when it was applied with sodium or calcium chloride salts, an uncommon practice for wildland plantings.

Polymers are best used on soils with pre-existing aggregate structure. Polymers assemble microaggregates into larger units, but in soils where there is no microaggregate structure, the polymers will merely stabilize the existing, dense, non-structured soil condition (Lentz and Sojka, 1994). Treating soils with little or no structure is recognized as giving little benefit to the soil (Shaviv *et al.*, 1987; Wallace and Wallace, 1993).

Once established, synthetic aggregates may last for several seasons if there is no further disturbance of the soil surface. Decomposition rates have been estimated at approximately 10 % per year (Barvenik, 1994). Because the decomposition of the acrylamide monomer in polyacrylamide (PAM) materials occurs within days, the gradual decomposition of PAM polymers does not result in accumulations of the toxic monomer (Barvenik, 1994; Grula *et al.*, 1994).

In recognition of the hierarchical mechanism of soil aggregate generation, polymer application should be viewed as a transient soil surface treatment. Long term generation of persistent water stable aggregates must still be facilitated by through plant litter inputs, root and mycorrhizal hyphal growth and microbial decomposition processes.

CONCLUSIONS

Water stable aggregates improve plant growth on dispersed, degraded soils by improving water movement, water retention, microbial micro-habitats and resistance to splash detachment. Water stable aggregates are generated in a systematic process of humic and oxide binding of clays, cohesion of clays and silts by microbial polysaccharides, either around microbial colonies or around plant debris residues, and finally, by stabilization of macroaggregate sized structures by plant roots and VAM hyphae. Synthetic polymers can provide cohesion of smaller, existing particles into larger aggregates, but the resulting polymer generated water stable aggregates will not have the same characteristics of natural macroaggregates. Polymers can provide temporary improvement and stabilization of existing microstructure for periods that are beneficial in establishing plantings, although degraded soils often have little of the baseline microaggregate development in the first place.

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Chapter 3. Soil Nitrogen Pools Associated with Revegetation of Disturbed Sites in the Lake Tahoe Area

ABSTRACT

Thin, poorly developed soils in the high elevation, summer-dry environment of the Lake Tahoe, California area are easily disturbed by anthropogenic impacts. Subsoils and parent materials exposed by vegetation removal and topsoil erosion, or by burial during construction activities, are difficult to revegetate and continue to erode for decades after disturbance. The resulting sediment loads contribute to decreased water quality in local watersheds and to the loss of clarity in Lake Tahoe. We hypothesize that soil disturbance has resulted in depletion of soil nitrogen (N) reserves and that remaining substrates are unable to provide adequate N for revegetation. In order to evaluate the relationship between soil N and plant cover on degraded soils, sites in the Lake Tahoe area were selected that had been previously disturbed, but that currently support plant communities with plant cover ranging from nearly zero to greater than 60 %. Results indicate that extractable ammonium and nitrate data correlated poorly with percent vegetative cover, while the correlations of anaerobically mineralizable N and total N were stronger and account for nearly 50 % of the variability in plant cover. Sites with plant cover greater than 40 % were associated with total soil N levels of over 1200 kg N/ha and anaerobic mineralizable N levels of about 26 kg N/ha. In spite of high concentrations of N in the surface soils, a large fraction of the N in the 0 - 50 cm profile occurred below 30 cm, when measured on a landscape basis.

INTRODUCTION

Drastically disturbed soils are those from which the topsoil and biological materials have been completely removed, buried beyond the reach of plant roots or radically altered as a result of construction, logging, or mining activity (Box, 1978). These sites typically must undergo primary succession and soil regeneration before they can support plant cover similar to adjacent vegetated areas. Drastic soil disturbance reduces plant growth by several negative impacts, the most common of which is by reduced soil nitrogen levels (Reeder and Sabey, 1987; pg 162; Munshower, 1994, pg 79; Bradshaw and Chadwick, 1980, pg 65; Van Kekerix and Kay, 1986, pg 56, 88).

Role of nitrogen in wildland plant-soil communities

Adequate levels of plant available nitrogen (N) are critical for regeneration of plant-soil communities because N is required for many different community components and functions. Most obviously, N is required for shoot and root biomass production, and it is utilized in the greatest amount of all potentially limiting nutrients (excluding water) for generation of plant tissues. In addition to its direct contribution to plant biomass production, N indirectly facilitates a number of other beneficial soil processes that are important during revegetation of barren sites. Nitrogen contained in plant litter and accumulated mulch or duff reduces soil evaporative losses and increases surface erosion protection. Increased N levels are also shown to stimulate decomposition of litter residues (Gill and Lavender, 1982), preventing the buildup of thatch that often constrains nutrient cycling on revegetated mined lands (Reeder and Sabey, 1987). Adequate N facilitates development of an extensive root system allows more complete acquisition of P (Power, 1983) and of available moisture, tapping water even from the saprolitic rock matrix (Arkley, 1981; Jones and Graham, 1993). Soil microbes also benefit from improved plant available N as a result of increased carbon flow for roots and root exudates.

The integrated effects of these N influenced components and processes results in a strong control by soil N on successional processes (Tilman, 1986; McLendon and Redente, 1992). For these reasons and others, plant available N is viewed as a potential keystone nutrient for revegetation of many degraded sites. (In some arid climates, in which nitrate is retained in the profile rather than being leached, growth limitations may be determined by phytoavailabile P rather than N (West, 1991).

Nitrogen limitations in wildland communities

Nitrogen is often limiting to plant growth on disturbed sites because of a combination of large plant and microbial demand for the nutrient and a small supply from the degraded soil (Bradshaw and Chadwick, 1980). Nitrogen is not weathered from most geological substrates as are all other plant nutrients (but see Holloway *et al*, 1998). The accumulated N in soils is a result of biological fixation and microbial cycling. Drastically disturbed soils, by definition, are very low in organic matter content and microbial activity and, therefore, often have low N contents, low N fixation rates and poorly functioning or disrupted N cycling patterns (Reeder and Sabey, 1987). Insufficient regeneration of soil nutrient cycles is cited as a primary reason for the failure, 20 years after establishment, of many revegetation projects on mine tails in the UK (Haigh, 1993).

Nitrogen limitations on roadside rights-of-way are also commonly recognized in California. Plant growth on a variety of "problem" (difficult to revegetate) soils is often adequate for one or two years after fertilizer application, followed by a steady decline in plant cover (Clary, 1983; Parks and Nguyen, 1984). In these studies, low N availability was often cited as a reason for the observed plant growth decline. The soil N levels in cut and fill slopes from a granitic area of northern California were about 30 % or less of the values in adjacent, vegetated soils that were not disturbed (Claassen and Zasoski, 1998).

Nitrogen deficiency symptoms are not usually observed immediately on disturbed sites because the lack of soil N reserves is masked by plant uptake of soluble but short-lived N fertilizers. Deficiency symptoms gradually appear several years after establishment because the amended N is leached out of the profile or incorporated into plants, litter or microbial tissue (Reeder and Sàbey, 1987). As the plant available N declines and plant growth slows, the canopy opens and soil is again exposed. Plant litter decomposes or washes away and the site returns to the barren, pretreatment condition. Surface erosion of accumulated plant litter and duff has an especially adverse effect. For example, in the Oregon Cascades, a study of *Ceanothus* shrubs suggests that the main input pathway for plant-fixed N into the soil is through litter-fall and decomposition, not directly from roots and nodules (Zavitoski and Newton, 1968). By removing N-rich duff material from the soil surface, erosion can slow or stop the accumulation of organics and nutrients that are a fundamental process of soil formation and primary succession.

Nitrogen contents of established plant-soil communities

The amount of N needed to restore or revegetate the plant/soil community following disturbance can be estimated by comparison to other grass or shrub communities. A number of studies have reported the N in various community components that are important for N cycling and erosion resistance. These biologically active components include plant shoots and roots, surface litter and microbial biomass.

A variety of grassland communities in the western U.S., for example, contained an average of 280 kg N/ha for N in the biologically active pools (Reeder and Sabey, 1987), and an annual grassland in the foothills of northern California contained 270 kg N/ha (Jackson *et al.*, 1988). An *Atriplex* shrub community in the Great Basin contained 421 kg N/ha (Gist *et al.*, 1978). The first plant communities (*Salix* spp.) that were not dominated by N-fixing plants during colonization of sandy china clay waste in the UK approximately 40 years after mining were associated with accumulations of 313 kg N/ha in plant shoot, litter and root materials (Marrs *et al.*, 1981).

These are relatively large N contents compared to the 71 kg N/ha (80 lb/ac) that are provided by common revegetation project fertilizer amendment rates of 560 kg/ha (500 lb/ac) of 16-20-0 ammonium phosphate fertilizer (Kay, 1974). Repeated applications of these soluble fertilizers are often required to provide N to maintain revegetation stands on degraded lands in the UK (Broomfield *et al*, 1982) and in the western US (Elkins *et al.*, 1986).

Another characteristic of chemical fertilizers such as ammonium phosphate is that the N is very soluble and is rapidly available for plant uptake or leaching. Short term N availability and soil solution N concentrations are known to alter the species composition and diversity of the community (Wedin and Tilman, 1995; McLendon and Redente, 1992). Higher plant available N levels can spur growth of weedy invasives (Kay, 1974), while lower N levels can restrain growth of invasive annuals and keep their size more similar to native perennials, as shown for *Bromus hordeacous* and *Elymus glaucus* on decomposed granite (Claassen and Marler, 1998).

The application of supplemental N to degraded, nutrient poor soils, then, has multiple constraints. Low N availability is required for controlling weed growth but total N loading rates must be high enough for regeneration of all of the various biologically active components of the plant/soil community (plant and microbial biomass, plant litter). Loading rates must be sufficient to establish plant cover, thus providing erosion protection, as well as to sustain growth until sufficient plant litter is produced to regenerate the nutrient cycling system. An important additional beneficial characteristic for long term sustainability of the plant/soil system is the presence of a reserve capacity of nutrients within the soil that is large enough to regenerate the plant cover following fire, grazing or severe drought.

Undisturbed soils appear to have this set of characteristics as a result of a large accumulation of soil organic matter combined with a slow rate of N mineralization (release of N by decomposition). For example, a fertile, grazed but untilled soil under a blue oak (*Quercus douglassii*) and annual grass plant community from the foothills of northern California accumulated 2920 kg total N/ha (0-30 cm), but had only 57 kg mineralizable (plant available) N/ha (0-20 cm depth only) and 2.3 kg extractable N/ha (Jackson *et al.*, 1988). A grazed but otherwise undisturbed annual grassland located several hundred kilometers to the south of the Tahoe area at the San Joaquin Experimental Range had an estimated 3200 kg total N/ha (0 - 30 cm) with only 90 kg mineralizable N/ha and less than 1 kg extractable N/ha (Woodbines and Duncan, 1980). An annual grassland in the northern California foothills had 5000 kg total N/ha in the 0 - 37 cm profile (Dahlgren and Singer, 1994). Dry coniferous forests in the volcanic soils of south-central Oregon, in contrast, have a total N content estimated at only 1769 kg N/ha (Youngberg and Dyrness, 1964).

Nitrogen contents of drastically disturbed plant-soil communities

Soil N levels on previously disturbed sites that have revegetated to diverse, sustainable plant communities typically have lower N levels than those of the relatively undisturbed soils just cited. Because they have not accumulated large amounts of N though centuries of biological activity, disturbed but currently revegetated sites suggest a threshold amount of soil N that may be the minimum required for regeneration of a plant community on these low nutrient substrates. In the United Kingdom, for example, the transition from pioneer communities dominated by N-fixing species on china clay waste to the first perennial shrub and tree (*Salix sp.*) communities was associated with about 660 kg total soil N/ha (with 980 kg N/ha in the plants and soils combined). Nearly 1200 kg total soil N/ha accumulated in the soil before the sites were colonized by oak and birch species (Marrs, 1981).

In North American systems, soils developing on spoil banks of the Mesabi Iron Range mines in Minnesota accumulated 548 kg N/ha at 21 years (0-30 cm depth, assuming 50 % fine soil fraction) and 1090 kg N/ha at 51 years (Leisman, 1957). On a Minnesota taconite ore spoil, Noyd *et al.* (1996) measured plant cover of 73% after three years with an initial compost amendment containing 986 kg total N/ha. Smaller rates of compost amendments provided 493 kg N/ha and resulted in a plant cover of only 52 %. Olsen (1958) concluded that sustainable revegetation in a Lake Michigan sand dune system with no N-fixing species required 400 kg total N/ha, although this value was for the 0-10 cm depth only and will be higher for a standardized 0 - 30 cm profile.

In the disturbed sandstone, limestone and igneous till of Glacier Bay, Alaska, an estimated 218 kg total N/ha was measured for the alder successional stage (0 - 9 cm depth, 60-70 years after glaciation) and 533 kg total N/ha for the spruce stage (0 - 15 cm, 200-225 years after glaciation)(Chapin *et al.*, 1994). Earlier work in the same area produced an estimate of 1200 kg total soil N/ha in the top 45 cm of soil at the transition between alder and spruce communities (Crocker and Major, 1955). If these values are expressed on a standardized 0 - 30 cm soil profile, a target threshold value in the high hundreds to around a thousand kg total N/ha appears to be the “N capital” that "yields" sufficient internal N cycling to support a diverse, permanent plant community.

Bradshaw (1987, pg 64) uses a calculational approach to estimate a minimum threshold value of approximately 1600 kg total N/ha, using estimated plant production levels, annual nutrient requirements and decomposition rates. A similar type of calculated estimate can be made using mineralizable and total N rates. For example, Palmer (1990) reports that the mineralizable N level associated with establishment of a diverse plant community on colliery spoils is between 20 and 40 kg N/ha. Using an average N mineralization rate in soils of 2 % of the total N (mineralizable N typically varies between 1 - 3 % of total N per year, Keeney, 1982), a calculated estimate of the total N pool required is between 1000 to 2000 kg N/ha.

Objectives of this study

While these calculated examples are hypothetical, they suggest that sustainable plant/soil systems on wildland soils require sizable stabilized pools of organic N. These pools must be large enough that the mineralization rate that is characteristic of the climate and organic matter of the site can provide adequate available N for plant growth. We interpret the steady decline of plant cover on many disturbed sites to result because soil nutrient pools on these sites are not adequately "capitalized" during initial amendment.

As a first step in evaluating this viewpoint, we measured the correlation of soil N level and percent plant cover in disturbed (but non-toxic) soils in the high elevation, xeric (summer dry) environment of the Lake Tahoe, California area. Grass and shrub covered sites with a range of percent plant covers were selected in which the plant community and underlying soil had previously been disturbed, but which have been under vegetative cover for an average of nearly ten years (range 3 - 25 years). We envision that a well vegetated herbaceous and shrub community represents an achievable reference community (Parker and Pickett, 1997) for revegetation projects in this region within a reasonable period of time (less than a decade). Although N-fixing species are viewed as critical components of diverse, sustainable plant-soil systems, they were excluded from this survey because symbiotic N inputs can mask the soil's ambient fertility and N supplying capacity.

The objectives of this study, then, were 1) to determine whether plant cover is correlated with several operationally defined soil N pools in this environment, 2) to evaluate different measures of soil N pools for predicting vegetative cover, and 3) to compare the size of the N pools of these Tahoe area soils to literature values of soil N associated with sustainable plant communities on drastically disturbed soils.

These data are expected to guide amendment of drastically disturbed sites, especially those having little or no soil development and extremely low soil N levels. Such sites have been measured to have less than two hundred mg total N/kg soil (Claassen and Zasoski, 1998). These are lower N levels than occur on many revegetation or restoration projects, which often have soil total N levels in the high hundreds (Zink *et al.*, 1995) to over one thousand mg total N/kg (Chambers *et al.*, 1994).

MATERIALS AND METHODS

Site selection

Initial basin-wide survey

During the summer of 1995, 30 widely distributed, revegetated sites were selected within the Lake Tahoe basin and nearby areas (Figure 1). All sites had been subjected to some level of disturbance, including highway cut and fill slope construction, ski run construction, forest or logging roads, and grazed areas (Table 1). However, at all sites, at least three years had elapsed since disturbance, so that plant growth patterns would tend to reflect ambient nutrient levels and not transitory fertilizer inputs. Average time since disturbance was estimated at nearly ten years. Widespread logging activity in the late 1800's was also recognized as a potential source of residual effects on current soil and vegetative conditions.

Three soil parent materials were sampled (volcanic, granitic and mixed alluvium) from sites of varying elevation (1890 to 2200 m; 6200 to 7200 ft) and slope angle (2° to 50°). Revegetated and native plant communities were sampled, including sparsely vegetated sites, gaps in forests that supported native and perennial grasses, as well as undisturbed native shrub communities. Plant cover was used as an indicator of that site's inherent fertility and ability to regenerate and sustain a vegetative community. Vegetation types were restricted to grass and herbaceous communities that are plastically responsive to soil nutrients, and that rely on soil N pools and not on supplemental N from biological fixation or fertilization. Other site conditions that were avoided included shallow soil depth and extensive shading from tree canopies.

Once a plant community had been located that was suitable for sampling, a line transect was randomly oriented within a uniform area of approximately 1000 m^2. Plant cover percent was estimated by line intercept of the plant canopy. Soil samples were then collected at 5 m intervals from 0-10 and 20 - 30 cm depths. Duff and litter were also sampled when present.

Because many California soils are naturally air dried in the field during summer, all soils were oven dried in a 40 °C to constant weight. This step standardizes sample preparation and facilitates sample collection from periods and locations where analysis of fresh soil is impractical. Soils were sieved to < 2 mm for nutrient analysis and the fine

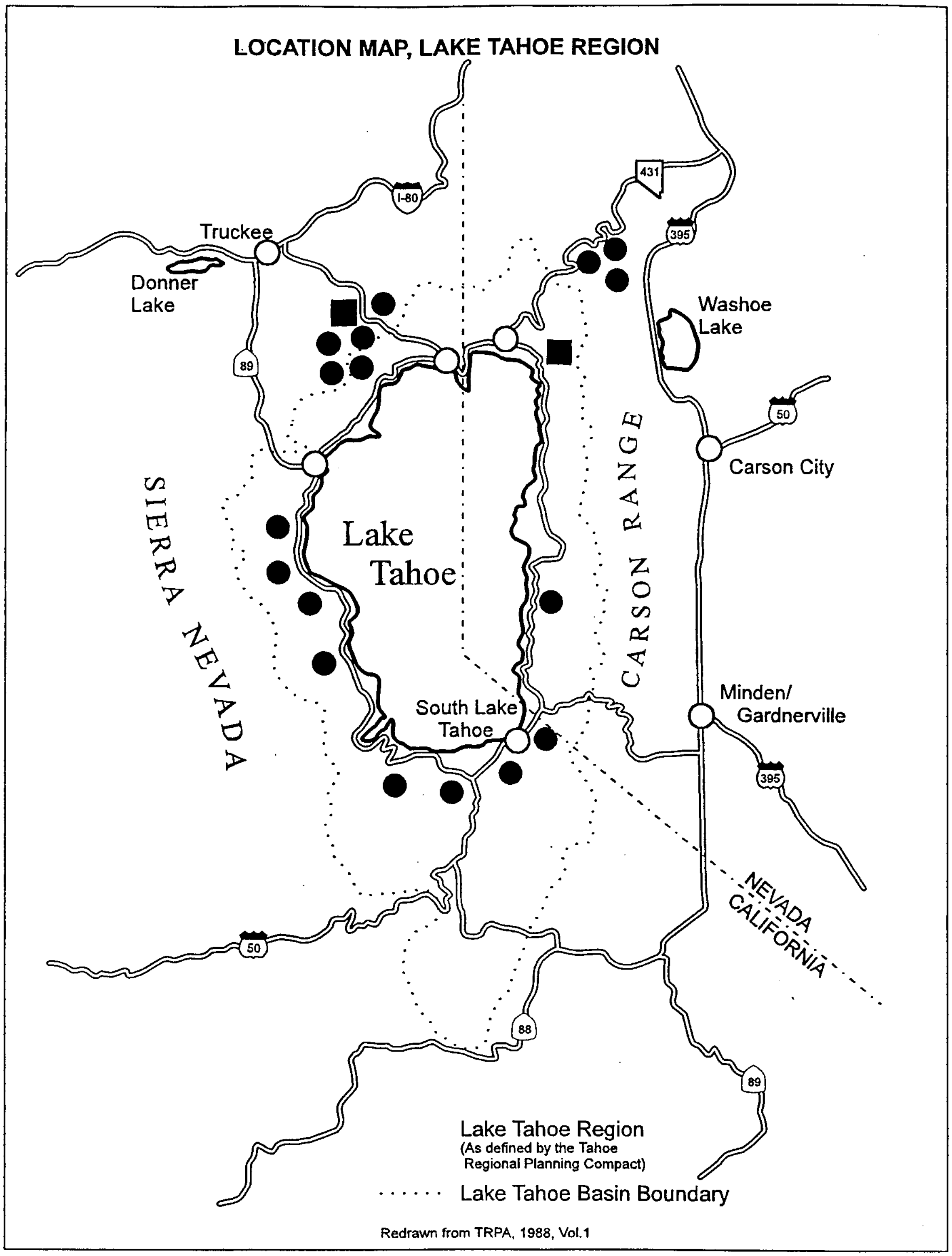

Figure 1. Map of Lake Tahoe Basin and initial basin-wide survey sampling locations (filled circles). Some locations provided multiple samples. The second year study sites are identified by filled squares.

Table 1. Characteristics of Tahoe area survey sites (site characteristics, number of sites)

Parent Material	#	Elevation (m)	#	Slope	#	Aspect	#	Disturbance Type	#
Volcanic	13	1900-2000	11	<10°	16	N (316-45°)	10	road sides	12
Granitic	7	2001-2100	3	11-20°	4	E (46-135°)	6	ski areas	10
Alluvial	10	2101-2200	8	21-30°	4	S (136-225°)	8	logging roads	6
		>2200	8	31-50°	6	W (226-315°)	6	grazed areas	2

soil fraction of the whole soil was calculated by weight (< 2 mm fraction / whole soil weight). To enumerate the size and distribution of the soil N pools on a field scale, the sample values were corrected for bulk density (0.83 for volcanic and 1.33 for granitic materials (Rogers, 1974) and fine soil fraction (average of 90 % < 2 mm for the granite and 40 % < 2 mm for the volcanic parent materials). Field soil concentration values were then prorated for the number of centimeters in the measured horizon and summed for a 30 or 50 cm profile.

Soil materials were analyzed for three operational soil N pools, including 1) extractable N, as an estimate of immediately available soil solution N content (2 M KCl, Keeney, 1982), 2) anaerobic mineralizable, N to estimate the N available for time periods of months (anaerobic, 40 °C, one week; Keeney, 1982), and 3) total N and total C by dry combustion (Dumas, 1886)/gas chromatography/thermal conductivity detection (Carlo Erba NA 1500).

Second year study

At the end of the first year basin wide survey, the strong influence of site characteristics on field soil N contents was recognized. In order to control environmental factors other than N, and to focus only on vegetation and soil N pool relationships, additional sites were selected that had fewer kinds of disturbance histories, that could be sampled more intensively than those in the basin wide survey, and that still demonstrated the effects of surface disturbance and topsoil removal that are common within the Tahoe basin. These sites were intended to provide a clearer picture of the soil N required for revegetation and also to validate the trends observed in the first year survey.

Sites matching these criteria were identified on contrasting parent materials (granitic and volcanic) at two ski area locations on the North Shore area of the Lake Tahoe Basin. Northstar-at-Tahoe is situated on the summit of Mt. Pluto, a volcanic formation which, along with several other volcanic peaks, defines the northern end of the Tahoe area. Diamond Peak at Ski Incline is situated on the Carson Range, a granitic spur range of the Sierra Nevada on the eastern boundary of the Tahoe Basin. Study plot areas on these sites were selected with similar slope angles (1 to 7 °), aspect (N to NW), elevation (2150 to 2375 m; 7100 to 7800 feet), and disturbance history (surface grading completed 4 to 10 years previously).

Prospective sites were evaluated using three 10 m line transects. Sites were then divided into three plant cover classes, including: 1) 0-10 %, 2) 11-40 % and 3) 41-100 % ground cover. These ranges are based upon erosion control effects of vegetative cover as suggested by Osborn (1954), as well as upon visual determination of the range of revegetating plant communities typical of these sites. Plant communities with > 40 % cover were identified that had both native (> 60 % native species) and non-native species compositions. Plots with native species included stands of *Elymus elymoides*, *Achnatherum* spp., and *Poa* spp. Plots with non-native species were predominantly covered by intermediate wheatgrass, crested wheatgrass, and Durar hard fescue. Reference communities were located which had experienced vegetative removal and surface disturbance, but which had still retained the soil material in place.

After plant cover was measured, soils were evaluated by sampling a total of 5 individual cores spaced at five 1 m intervals on the 10 m long transect. Each core was sampled at 5 different depths: 0-2, 2-10, 10-20, 20-30, and 30-50 cm, allowing a detailed estimate of soil C and N. At each site, a total of 75 samples were taken.

RESULTS

Initial basin wide survey

Data from the initial basin wide survey are graphed in Figure 2. Analysis of the survey indicates that percent plant cover is most strongly correlated to mineralizable N ($r^2 = 0.472$; $p < 0.000$) and total N ($r^2 = 0.466$; $p < 0.000$). Percent plant cover is much less well correlated with extractable ammonium ($r^2 = 0.069$; $p = 0.165$). Extractable nitrate has a slight negative relationship ($r^2 = 0.172$; $p = 0.532$).

Some of the residual variability in the mineralizable N and total N data could be accounted for by characteristic landscape positions. For example, sites with less plant growth than expected relative to the measured N levels (points left of the regression line) were typically from locations at which plants were continually impacted by traffic or that are physically unstable, such as over-steepened road cuts. Conversely, sites in foot-slope positions or low-lying areas often had greater plant growth than expected given the low soil N levels measured in the sample (points to the right of the regression line). Plants in these areas were potentially utilizing N from ephemeral overland flows or subsurface sources from outside of the sampled profile. These sources of variation prompted the selection of sites for the second year study that were more topographically similar and would give a clearer evaluation of soil N pool and vegetative cover relationships.

Second year study

Soil N pools on the more intensively sampled second year study showed the same trends as in the broader scale Tahoe area survey (Figure 3, 4). While extractable ammonium and nitrate showed significant differences between cover classes, they did not vary in proportion to vegetative cover. Both mineralizable N and total N, however, increased as greater vegetative cover increased on both the granitic and volcanic parent materials. Means for all cover classes were significantly different ($p < 0.05$).

The numerical values of the second year plot samples are listed in Table 2. For this table, the pooled > 40 % cover class data are split out between the native species reference sites (Nref), which did not have extensive soil degradation, the native species sites (N), and the non-native species sites (NN). The 10 - 40 and the < 10 % cover classes contained only non-native plant communities. Data were summed for both the 0 - 30 cm horizons or for 0 - 50 cm horizons. All data are expressed on a landscape basis following correction for coarse fragments and bulk density.

The N levels measured within the > 40 % vegetation cover class (native reference, native disturbed, non-native) do not vary in a consistent pattern with degree of disturbance, or native versus non-native species. The unusually high N contents of the Nref* site were attributed to its location in an area with deep, colluvial soil accumulations. This site was interpreted to be more N enriched than typical for a disturbed soil.

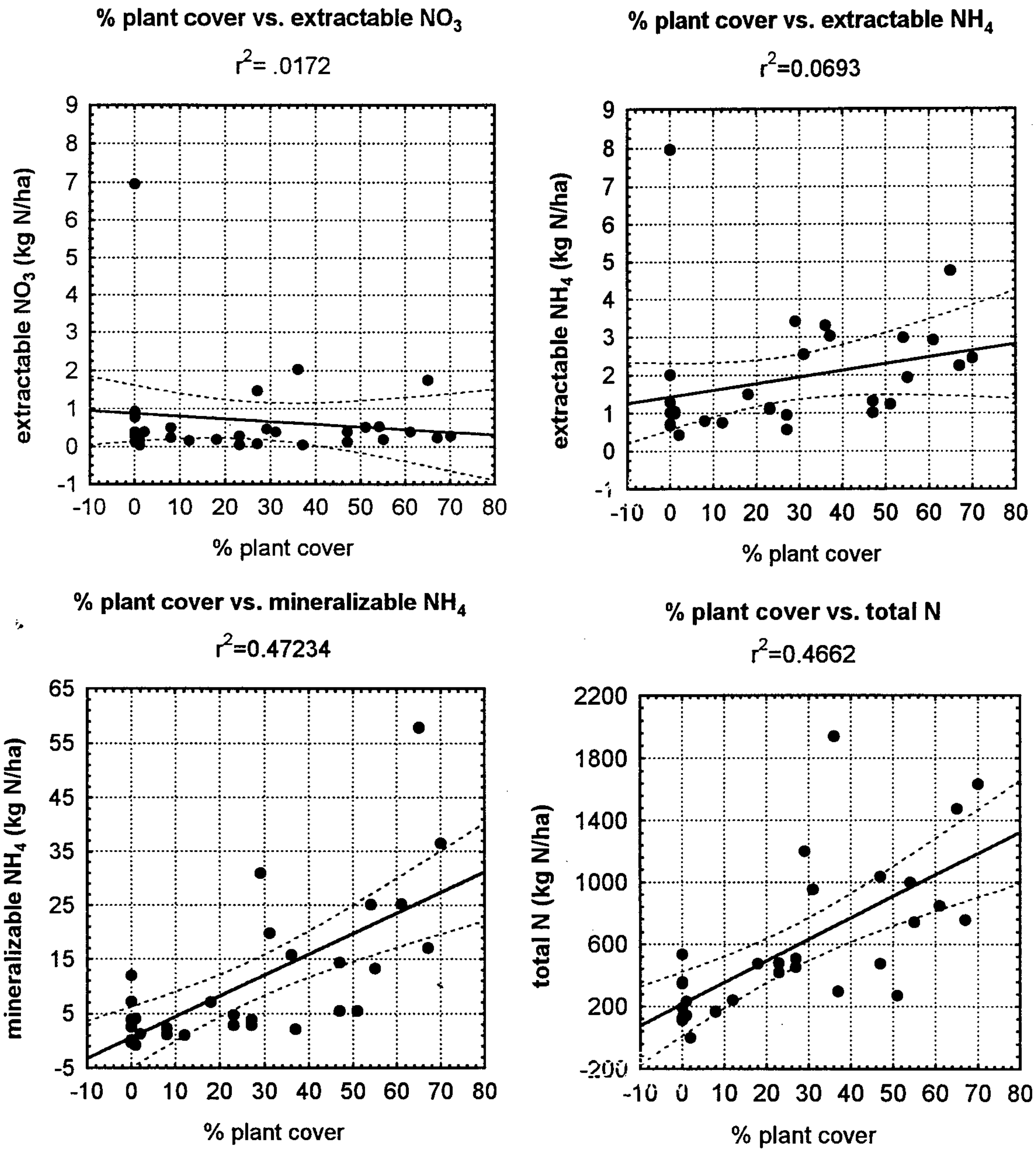

Figure 2. Correlation between percent plant cover and four operationally defined soil N pools, including extractable NO_3^+, extractable NH_4^+, mineralizable NH_4^+, and total N. Dashed lines indicate 95 % confidence intervals.

Table 2. Summary of soil N pools in the second year study for 0 - 30 or 0 - 50 cm depths, after correction for bulk density and coarse fragment contents. "Native" plant communities are defined as having > 60 % native species. Nref = native reference community with minimal soil disturbance; N = native community with disturbed soil; NN = nonnative community with disturbed soils. Nref* = a site with an unusually deep colluvial soil. All values in kg N/ha.

	extractable NO3					extractable NH4					mineralizable N					total N				
Granitic parent material																				
Pl type	Nref	N	NN	NN	NN	Nref	N	NN	NN	NN	Nref	N	NN	NN	NN	Nref*	N	NN	NN	NN
% cover	>40	>40	>40	10-40	0-10	>40	>40	>40	10-40	0-10	>40	>40	>40	10-40	0-10	>40	>40	>40	10-40	0-10
0-30 cm	1.8	2.8	1.7	1.1	3.9	4.7	1.9	2.0	1.6	4.5	27.7	16.3	19.4	11.5	2.8	3865.6	997.9	945.3	823.7	224.3
0-50 cm	2.1	3.0	2.1	1.1	6.7	6.9	2.6	3.1	2.2	6.7	32.0	18.8	27.9	17.3	4.3	5283.6	1335.6	1348.7	1237.2	407.6
Volcanic parent material																				
Pl type	Nref	N	NN	NN	NN	Nref	N	NN	NN	NN	Nref	N	NN	NN	NN	Nref	N	NN	NN	NN
% cover	>40	>40	>40	10-40	0-10	>40	>40	>40	10-40	0-10	>40	>40	>40	10-40	0-10	>40	>40	>40	10-40	0-10
0-30 cm	0.6	0.4	0.9	1.4	0.3	1.6	4.5	4.6	5.4	2.7	29.0	47.0	18.3	11.4	2.1	1236.9	1916.5	1047.1	759.6	300.2
0-50 cm	0.7	0.5	1.1	2.0	0.7	2.2	7.6	6.6	8.5	4.8	38.6	66.3	22.0	15.9	3.1	1551.3	2812.3	1330.5	1076.4	585.0

DISCUSSION

Nearly half of the variability in percent plant cover that was measured on revegetated sites in the Lake Tahoe area was related to soil nutrient pools of mineralizable N or total N. The remaining half of the plant cover variability is expected to be influenced by conditions that can also be ameliorated by, or co-vary with, improved N nutrition. These conditions include more extensive root distribution for better water acquisition, increased shoot biomass leading to greater litter and mulch accumulation, improved infiltration of precipitation resulting from improved soil organic matter content and structure, and increased microbial activity. The commonly used indicators of soil fertility, extractable ammonium and nitrate, had poorer correlation to plant cover.

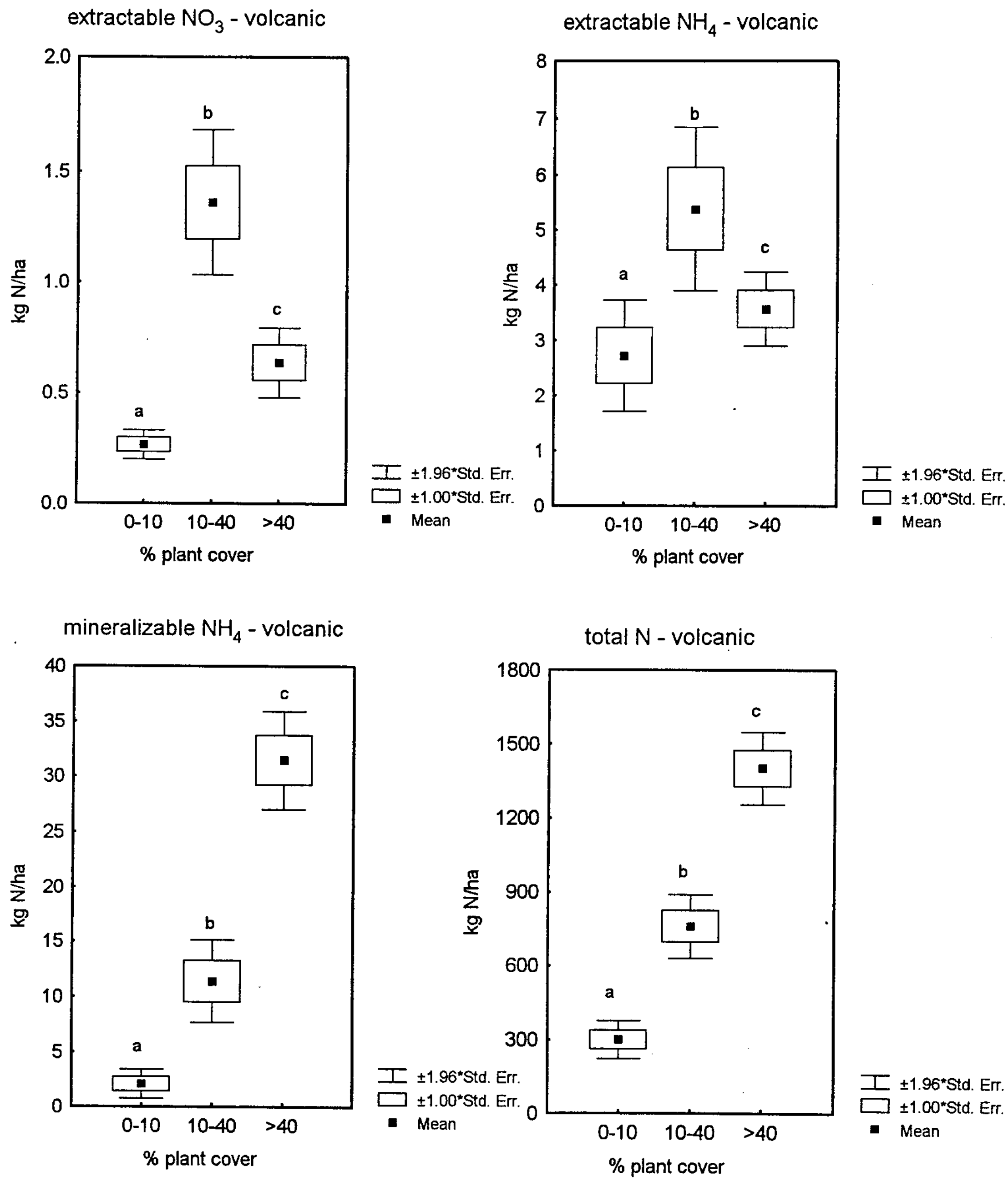

Figure 3. Soil N pools (extractable NO_3, extractable NH_4, mineralizable NH_4, and total N) from soils under three plant cover classes on volcanic substrates (0 - 30 cm depth).

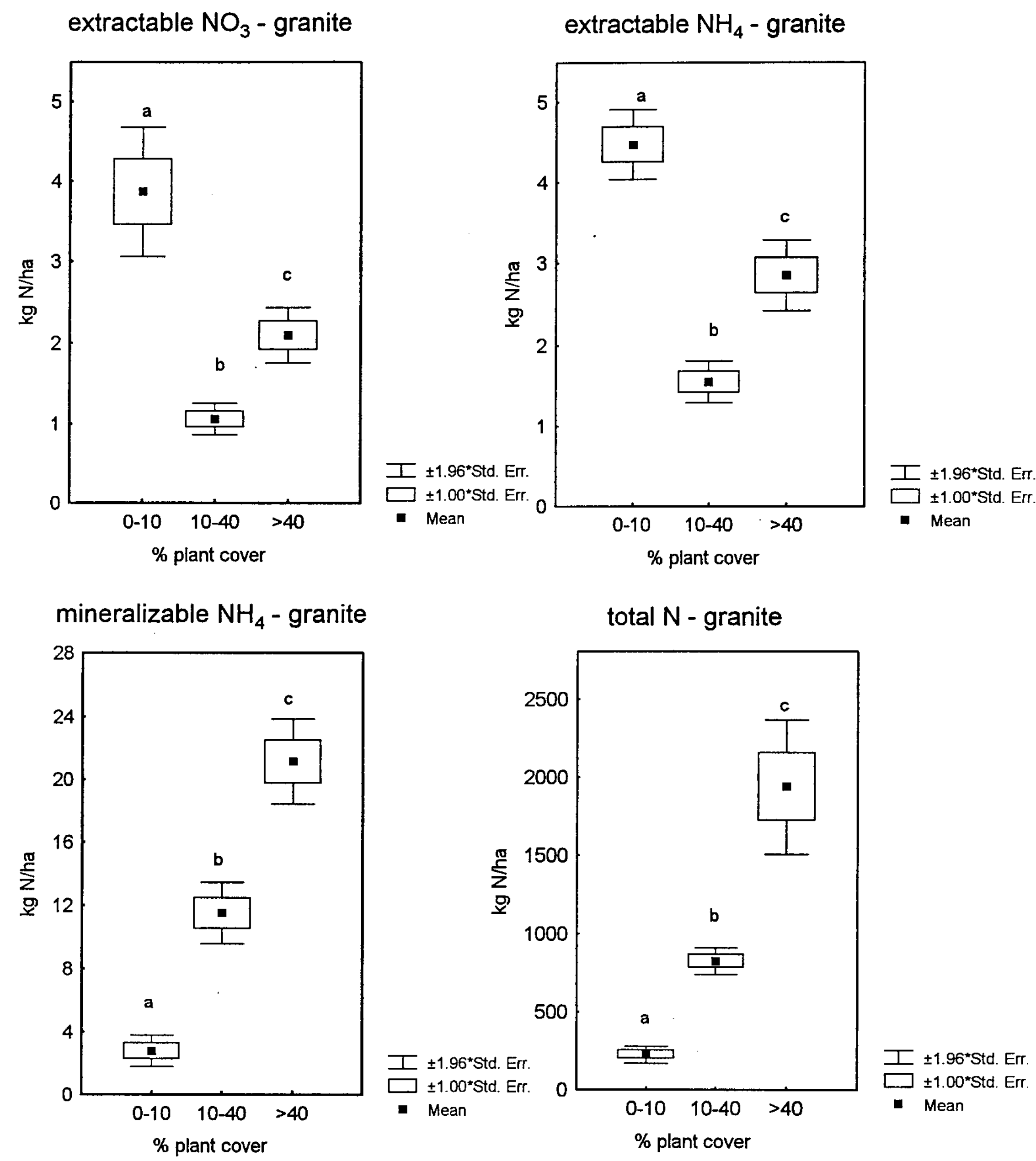

Figure 4. Soil N pools (extractable NO_3, extractable NH_4, mineralizable NH_4, and total N) from soils under three plant cover classes on granitic substrates (0 - 30 cm depth).

Concentrations of these extractable N forms are in dynamic balance between mineralization rates and plant uptake rates and, so, are highly variable within the soil and with time. Trends in the second year plots are similar to those observed in the first year survey, even though the two studies utilized different locations and sampling intensities. The more intensive sampling of the second year plots provides additional numerical for comparison of N pools between the different cover classes.

Mineralizable N on the second year study was about 2.1 % of the total N on the > 40 % cover samples (both parent material types combined), 1.4 % of the total N on the 10 - 40 % cover samples and 0.9 % on the < 10 % cover samples (percentages calculated from Table 2). The smaller size of the total N pool on the < 10 % cover sites, in combination with the lower mineralization percentage is expected to contribute to low plant available soil N levels on these sites.

The < 10 % cover classes (both parent materials) are also the only groups that have less mineralizable N than extractable N. Sites in higher vegetation classes have the opposite pattern, with an average of 4.5 times more mineralizable N than extractable N in the granite and 6.7 times more in the volcanic parent material samples. This solution N pool pattern of short term N supplies (extractable N) with little or no longer term N reserve (mineralizable or total N pools) has been observed in soils from other drastically disturbed sites. Soils with this characteristic are expected to have low potential for sustained revegetation from the perspective of soil N fertility.

Estimates of soil N contents are partly a function of the depth included in the soil N evaluation. Soil in the 30 - 50 cm horizon provided an additional 48 % total N compared to a more typical 0 - 30 cm horizon evaluation. An additional 41 % more mineralizable N was available when the 0 - 50 cm depth was summed compared to a 0 - 30 cm depth. Although roots are commonly observed to 50 cm depth and deeper, our soil N content data are expressed for a standardized 30 cm depth to allow comparison with other published literature values.

Another consideration when evaluating soil N on a landscape basis is the extent to which the fertility of the analyzed soil (< 2 mm fraction) is diluted by coarse rock material in the profile. When measured on a concentration basis, total and mineralizable N in the fine fraction of the volcanic soils was about 4.7 times greater than that of the granitic soils (data not shown). However, after correction for bulk density, fine soil fraction and soil horizon depth, the mineralizable N in the > 40 % vegetative cover plots did not significantly differ between the two parent material types ($p = 0.620$). Total N levels also did not significantly differ between parent materials ($p = 0.318$). Landscape level evaluation of N availability on wildland sites requires evaluation of soil depth, topographical position, coarse fragment content and disturbance history as well as the concentration of N in the fine soil fraction.

In this study, general threshold levels of total N that are adequate for plant cover of about 40 % are interpreted as being between 792 kg total N/ha (the average for the 10-40 % class) and 1228 kg total N/ha (the average for the > 40 % class without the colluvial, N-rich "Nref*" granite site). Mineralizable N thresholds for adequate plant cover are estimated to be between 11 (the average for the 10 - 40 % class) and 26 kg mineralizable N/ha (the average for all the > 40 % cover classes). These values should not be viewed as exact target values, since local climate, plant type and slope geometry will influence the interaction of plants and the underlying soils. Inclusion of N-fixing species in the planting mix is expected to lower the amount of N required from soil N pools in order to achieve a given level of vegetative cover. The actual rate of N-fixation on these high elevation, xeric soils, however, has not been widely studied and may be low on nutrient poor or droughty sites.

The total N can, in a general sense, be viewed as the "nitrogen capital" needed to produce the mineralizable N "yield". The actual N cycle in the field, however, is made up of a large number of internal N transformations between various kinds of organic matter, each with simultaneous and dynamic N immobilization and release rates. The concept of a constant N release rate from a single, large stabilized organic matter N source is, therefore, a very generalized model of the actual dynamic process.

We interpret these data to suggest that the various components of the plant-soil community will not be completely regenerated if soil N resources are below a general threshold level. With adequate soil N, however, the site is expected to support plant communities that are dense enough to retain and accumulate plant litter and duff and gradually rebuild a more fertile soil. With an improved soil resource, the plant community can then follow any of several successional paths, depending on plant recruitment, climate, disturbance and other environmental conditions (Parker and Pickett, 1997). With inadequate soil fertility, however, the site can essentially follow only one successional path - that of inadequate plant cover, soil erosion, loss of nutrients and a return to a barren condition. While exact threshold specifications are not a realistic objective, these data can be used to screen sites that have inadequate N fertility and can guide specification of amendments that can ameliorate this condition.

CONCLUSIONS

Total N and mineralizable N pools in the soil are more strongly correlated to percent plant cover than are extractable ammonium or nitrate pools. Nearly half of the vegetative cover data in this study was correlated with total and mineralizable N. Vegetative cover of > 40 % is associated with soil N levels (0 - 30 cm depth) of about 1228 kg total N/ha and 26 kg mineralizable N/ha (both soil types combined). While volcanic and granitic parent material soils had very different concentrations in the < 2 mm fraction, soil N levels in the two parent material types did not differ statistically when corrected for soil bulk density, the fine soil fraction, and soil horizon depth.

While these correlations do not prove that N is the single factor limiting plant growth on these sites, the relationship suggests that N is an important variable in revegetation following disturbance in the Lake Tahoe region and that sustainable revegetation communities in this area are characterized by large, stabilized total soil N pools with relatively low mineralization rates.

These threshold values can also be used to screen sites that have been surficially disturbed, but may or may not have lost their soil N reserves. The more drastically disturbed and nutrient poor sites can be identified for full soil amendment treatments, while sites with adequate ambient N fertility can be segregated for less intensive treatment, such as with only surface mulches and plant materials.

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Chapter 4. Nitrogen release rate from soil amendment materials

Introduction

The availability of soil nitrogen (N) has a strong influence on plant growth, competition and community development. When N availability is decreased by removal of organic N pools or is increased by amendment with soluble N fertilizers, community species composition is also modified (Wedin and Tilman, 1996; McLendon and Redente, 1992). In drastically disturbed soils, organic matter and N pools have often been removed during disturbance, leaving little or no ambient N fertility in the substrate. N availability for revegetation is provided primarily by nutrient release from chemical or organic amendment materials applied to the site. For this reason, the revegetation amendment can have a controlling influence on the composition of the revegetated plant community.

In the past, revegetation projects in California have commonly utilized soluble fertilizer materials. A typical amendment on a low fertility site without topsoil would include 560 kg/ha (500 lbs/ac) of ammonium phosphate sulfate (16-20-0) in combination with an erosion control mix of exotic annual grasses. The tendency of this fertilizer application rate to promote rapid annual grass growth to the detriment of native species was also recognized (Kay, 1974). When establishment of slower growing perennial species is a priority, control of soil N levels can be an important method for establishing desired plant composition on the revegetation site. Maintenance of a low soil solution N level can be used to restrict growth of invasive annuals so that they do not competitively displace slower growing perennials, as shown for *Bromus hordeacous* and *Elymus glaucus* on granite soils (Claassen and Marler, 1998).

An additional negative effect of the use of highly soluble fertilizer materials is that all of the N that is applied is rapidly available and is easily depleted (Bloomfield et al., 1982; Dancer et al., 1979; Palmer et al, 1986; Rauzi and Schuman, 1984). High initial application rates encourage rapid plant growth and nutrient uptake, while unincorporated soil solution N is easily leached from the profile. Without reapplication or N release from mineralized organic matter in the soil, available N levels rapidly drop to deficiency levels and plant growth on the site declines. This creates a commonly observed pattern on revegetation projects in severe sites in California in which plants thrive for several years but then steadily thin out and expose the bare soil to erosion (Parks and Nguyen, 1984; Clary, 1983). Proper amendment of drastically disturbed, low nutrient substrates, therefore, requires amendments that are large enough to support long term plant growth but which have low N release rates that correspond to uptake by perennial species and do not promote weedy invasion.

Given enough time, naturally revegetating mine tails and overburdens have shown a slow but steady accumulation of soil organic matter and soil N pools, even though the original substrates were severely nutrient depleted. After several decades, fertility is eventually adequate to facilitate colonization by a diverse, perennial plant community. Several studies have correlated the threshold of soil N in these reference areas that is found (either empirically or by nutrient cycling analysis) to adequately support such a diverse and long term vegetative cover (Dancer, 1977; Marrs et al., 1981; Roberts et al., 1981; Marrs and Bradshaw, 1993, Chapin et al., 1994; Palmer, 1990). Estimates of this threshold level are often much lower than found in well established ecosystems (Reeder and Sabey, 1986) and but still range from 700 to 1200 kg N/ha (Marrs et al., 1981). These are large N amounts compared to the 90 kg N/ha (80 lb/ac) provided by the generalized 500 lb/ac 16-20-0 application. The large pool of soil organic matter functions to buffer the N release rate (typically 1 - 3 % per year), and to retain reserve N for release in subsequent years. The extent to which revegetation amendments can provide suitable amounts of N and suitable rates of N release is expected to greatly influence the success of the revegetation project on low fertility soils.

Measurement of these low rates of N release on heterogeneous field soils is difficult. Seasonal variability alters release and uptake rates, and plant density and growth is difficult to control experimentally between plots. Areas of homogeneous soil materials that are large enough to use as replicate monitoring plots are difficult to find in disturbed wildlands sites. For these reasons, we chose to compare a range of potential revegetation amendment materials under uniform laboratory conditions using the Stanford and Smith (1972) aerobic incubation procedure. This method was selected because it spans a long enough period of time (months) so that short term effects of sample handling and dis-aggregation are reduced, and because it is an established procedure with a documented history of correlation to plant uptake and use on a wide variety of soils (Keeney, 1982). The method involves periodic leaching of N mineralized from the soil or amendment during incubation in a temperature controlled environment.

In theory, laboratory mineralization rates can be related to actual N release rates in field conditions, which usually have cooler temperatures. This is done by multiplying the degrees of soil temperature above a minimum temperature threshold, times the number of days incubation to give a value for an energy unit called the "degree day". The ratio of degree days in the field to degree days in the incubation chamber (maintained at 30 °C) should be proportional to the release rate in field conditions (assuming adequate moisture) compared to lab data, as shown with root growth in soil (Baret et al., 1992).

The objective of this study is to compare the N release rates from a wide variety of potential amendment sources, to check the incubation and leaching procedure for precision between duplicate experiments, and to compare release rates to those measured in a field situation.

Materials and Methods

Amendment selection

Selected amendment materials were obtained from producers as listed in Table 1. The materials represented a range of chemical and organically based materials, with slow to rapid N release rates. N contents are listed as represented on the bag, but the amendments were loaded into the columns based on the total N content of the material received. All amendments were loaded into the columns at the same rate, equivalent to 500 kg total N/ha.

Incubation procedure

Incubation chambers were constructed out of 5 cm x 20 cm PVC pipe with solid bottom plates. A vacuum lysimeter was installed in a 2 cm bed of quartz sand (250 to 500 µm particle size) at the bottom of each chamber. The top 15 cm of the chamber was filled with the revegetation substrate, mixed with the appropriate amount of amendment material. Substrates with fine particle size distributions were blended with an equal volume (50:50 ratio) with quartz sand to increase percolation and increase removal of the mineralized or released N materials. All chambers were incubated in a common insulated cabinet that is maintained at 30 °C with gentle air circulation. Humidity was maintained at near saturation with open pans of water within the cabinet.

Chambers were extracted at two week intervals initially, then four or eight week intervals later in the incubation. After extraction they were restored to a standard pore water content and returned to the incubation cabinet. Extraction involved connecting

Table 1. List of amendment materials and their treatment codes (in alphabetical order), with manufacturer, percent N and amendment type.

code	amendment	company	% N	type of amendment
AP	ammonium phosphate	Bandini Fertilizer Company, Los Angeles, CA	16 %	ammonium phosphate chemical fertilizer
BSM	BIOSOL MIX®	Rocky Mountain Bioproducts, Edwards, CO	6.5 %	fungal and bacterial biomass from pharmaceutical production
BS	BIOSOL®	Rocky Mountain Bioproducts, Edwards, CO	7 %	fungal biomass from pharmaceutical production
FFB	FERTIL-FIBERS™ NutriMulch	Quatro Environmental, Coronado, CA	6 %	seed meal based, composted poultry manure
G1	Gilton # 1	Gilton Resource Recovery, Modesto, CA	1.2 %	yard waste compost
G3	Gilton # 3	Gilton Resource Recovery, Modesto, CA	1.3 %	yard waste compost
G6	Gilton # 6	Gilton Resource Recovery, Modesto, CA	1.2 %	yard waste compost
GRO	GRO-POWER®	Gro-Power, Inc., Chino, CA	5 %	composted plant material with supplements
HP	HYDROPOST™	Organics International, Irvine, CA	1.65 %	compost mixture
MC	minus control			unamended substrate
OSM	OSMOCOTE®	Scotts-Sierra, Marysville, OH	18 %	resin prilled ammonium and nitrate chemical fertilizer
P38	POLYON PCU 38®	Pursell Technologies Inc. Sylacauga, AL	38 %	polyurethane encoated urea
P40	POLYON PCU 40®	Pursell Technologies Inc. Sylacauga, AL	40 %	polyurethane encoated urea
RTI	RTI/Nova Organics - IBDU	Reforestation Technol. International, Monterey, CA	7.7 %	composted biosolids / IBDU blend
RTM	RTI/Nova Organics - melamine	Reforestation Technol. International, Monterey, CA	8 %	composted biosolids / melamine blend
RTU	RTI/Nova Organics - ureaformaldehyde	Reforestation Technol. International, Monterey, CA	8 %	composted biosolids / urea-formaldehyde blend
RNG	RINGER	Ringer Corporation, Minneapolis, MN	5.0 %	plant and animal meal plus chemical supplements
SC	Sonoma Compost	Sonoma Compost Co., Petaluma, CA	1.5 %	yard waste compost
SUS	SUSTANE® Natural Organic	Natural Fertilizer of America, Cannon Falls, MN	5 %	composted poultry litter, feathermeal

the vacuum lysimeters in the bottoms of the PVC chambers to a vacuum manifold via flexible plastic tubing and sequentially extracting three leaching solutions through the soil-amendment mixture. The first two leaching solutions contained 0.01 M $CaCl_2$ to displace exchangeable N ions. The final leaching solution contained a minus-N nutrient solution to replace nutrient elements leached in the N removal procedure (Stanford and Smith, 1972). The purpose of this solution was to assure that microbial growth was not limited by nutrients other than N.

Extracts were pooled and tested for soluble ammonium and nitrate (Carlson, 1978, 1986), urea by urease digestion (Bremner, 1982), and total carbon and nitrogen by dry combustion (Dumas, 1831) and thermal conductivity detection of CO_2 and N_2 gases (Carlo Erba NA 1500). The accumulated available N released (ammonium, nitrate, plus urea) was graphed against number of days during incubation.

Substrate selection

Sand column study

During initial development of the experimental procedure, two sets of incubations were constructed using 150 mL volumes of sand. These 100 % sand columns were discontinued after release rates in the duplicate run failed to quantitatively match those of the first set. Differences in N release were attributed to a low ambient water content and diffusion rates in the coarse sand matrix, a relatively non-biological micro-environment that generated variable microbial activity and mineralization rates, and an excessively small substrate volume that required small, non-uniform amendment doses. For these reasons, the sample volume (originally 15 g substrate; Stanford and Smith, 1972) was increased again to over 400 g (318 cm^3) for the trials in the rest of this study, and the quartz sand (intended to be a neutral evaluation matrix) was replaced with low organic matter, low nutrient revegetation substrates collected from Caltrans project sites. These field substrates are assumed to provide better microbial microhabitats since they had a much wider particle size distribution and had a more typical supply of non-N nutrients.

US 50 substrates (Mill Creek Slide)

Spoil material from the Mill Creek slide on US 50 was used to construct a set of columns to evaluate revegetation potential of the slide face and the Kyburz spoil pile material. The ammonium release from this material was soon observed to be a fraction of that observed from the same amendment material when incubated in the Livingston materials (data summary in Appendix A). A slow release chemical formulation (Osmocote, with about half of the N released as nitrate and half as ammonium) showed only half of the reduction in N release (98 % down to 68 %). The lower release rate was hypothesized to result from fixation of ammonium in mineral interlayers, but not of the nitrate, which is not fixed in interlayer positions.

To evaluate these two possibilities, additional chambers were constructed with various sand:soil ratios in an effort to separate porosity and physical leaching restrictions from the potential for mineral interlayer ammonium fixation (data summary in Appendix B). These tests indicated that in spite of a very porous physical structure (allowing adequate flow of leaching solution), the US 50 material still retained large amounts of ammonium by interlayer ammonium fixation. For these reasons, the US 50 / Kyburz spoil pile material was eliminated as a standard reference substrate for evaluating N release from amendments.

Livingston subgrade material

One of two substrates used for the long term N release incubation experiments was collected from a subgrade construction project along State Highway 99 at Livingston, CA, Merced County in the San Joaquin valley. This site is on alluvial outwash materials associated with the Merced river that have been transported from the Yosemite Valley 100 km to the east in the Sierra Nevada. They are silts and fine sands from granitic parent materials with moderate drainage and low organic matter contents.

Emerald Bay substrate

The second substrate, collected for comparison of the trends and quantities of N released on the Livingston materials, was selected from the Caltrans right-of-way just north of Emerald Bay on the west shore of Lake Tahoe. This material was also derived from granitic parent material but was generated from residual, saprolitic material (weathered in place) as opposed to the sorted, alluvial material of the Livingston site. This coarser material was sieved to < 6.3 mm for use in the incubation columns.

Degree day calculations

The relationship of N release from the laboratory incubation to field release rates at the Livingston site was estimated by using a ratio of the number of degree days for the field soils compared to the number of degree days in the 30 °C incubation chamber. Field soil temperature data (15 cm depth under grass cover) were downloaded (www.ipm.ucdavis.edu/WEATHER/ phenoddretrieve.html) for the Modesto A CIMIS station # 71 located about 15 km (24 mi) to the north-northwest of Livingston. Base temperatures (threshold of biological activity) of 0, 4, or 10 °C were used to calculate accumulated degree days for comparison between the field and lab incubations.

Results and Discussion

In this report, results are organized into the following sections: 1) a comparison of total N release data on two different substrates, 2) total N release data compared between different amendment materials, 3) long term release rates evaluating sustained N yield, 4) a comparison of the release rates of unground versus ground amendment materials, 5) a review of each individual amendment material, and 6) the release rates of laboratory incubation versus field incubation rates. See Table 1 for key to amendment codes and the Amendment section for a discussion of individual amendment materials.

Comparison of total N release on two substrates.

Nitrogen amendment mineralization yields for the Livingston sands and the Emerald Bay granites are graphed on Figures 1 and 2. Plot traces are identified by position on the right axis.

Nitrogen release rates on the two different substrates were evaluated for statistical differences to estimate the ability of the leaching procedure to produce consistent N release rates between two different low fertility materials. Data were gathered at approximately 130 days incubation in the lab at 30 °C (Table 2). The actual data points used in calculations varied by seven days, since the incubation and leaching schedules were staggered by one week (Livingston data from 133 days and Emerald Bay data from 126 days). This time delay was necessary because of the required processing time needed for the large number of samples.

Of the eight materials tested, six had N release rates that did not differ significantly between the two substrates. Similar release rates were measured for a soluble chemical form (AP), for a slow release chemical form (OSM) and for four organic amendment blends (RBS, RBM, RTM, RTU).

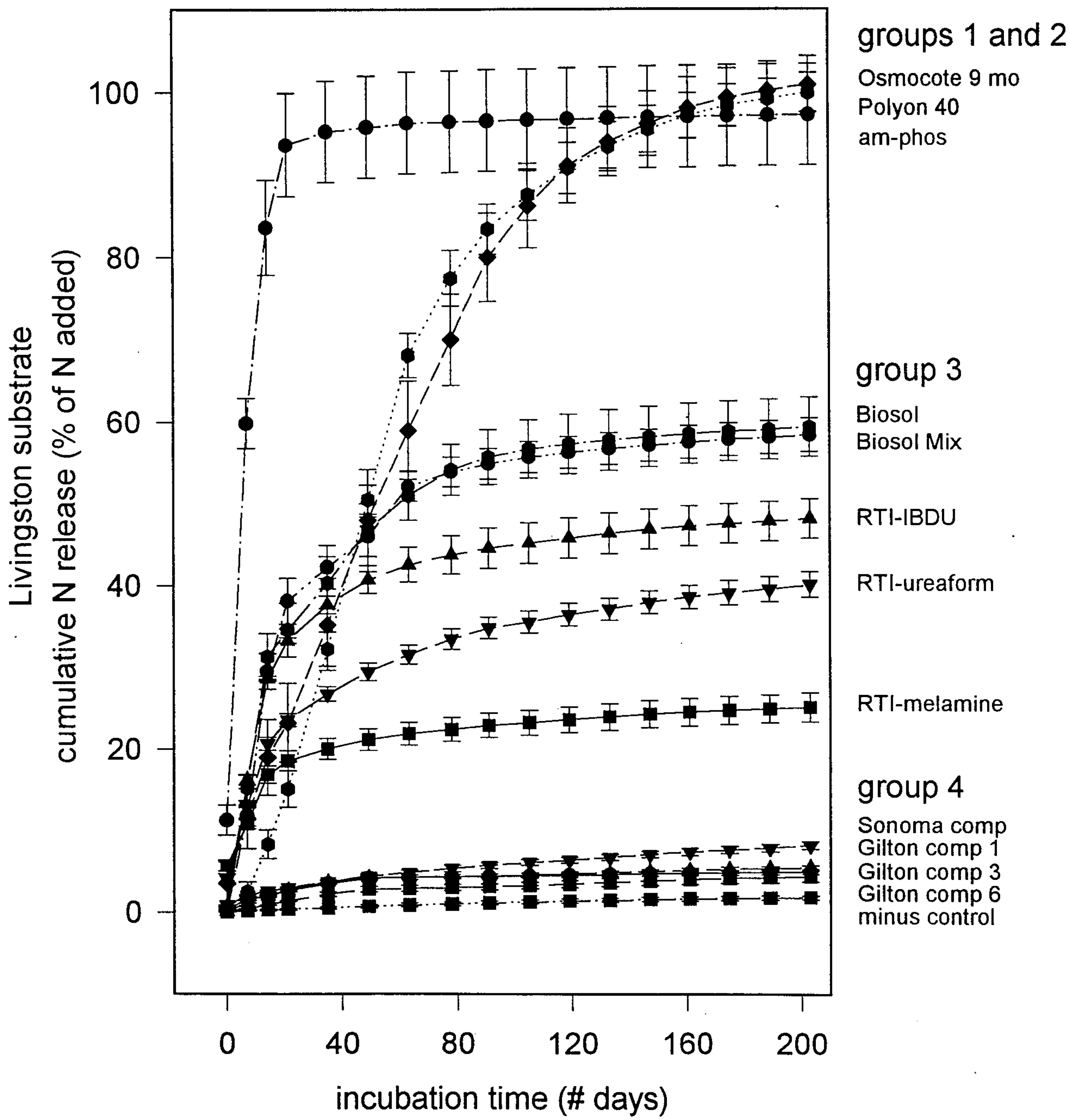

Figure 1. Cumulative N release by extraction from soil amendment materials on Livingston substrates (% of N added) during laboratory incubation at 30 °C. Group 1 amendments are chemical formulations; group 2 are slow release chemical formulations; group 3 are organic based blended materials and group 4 are unblended greenwaste composts.

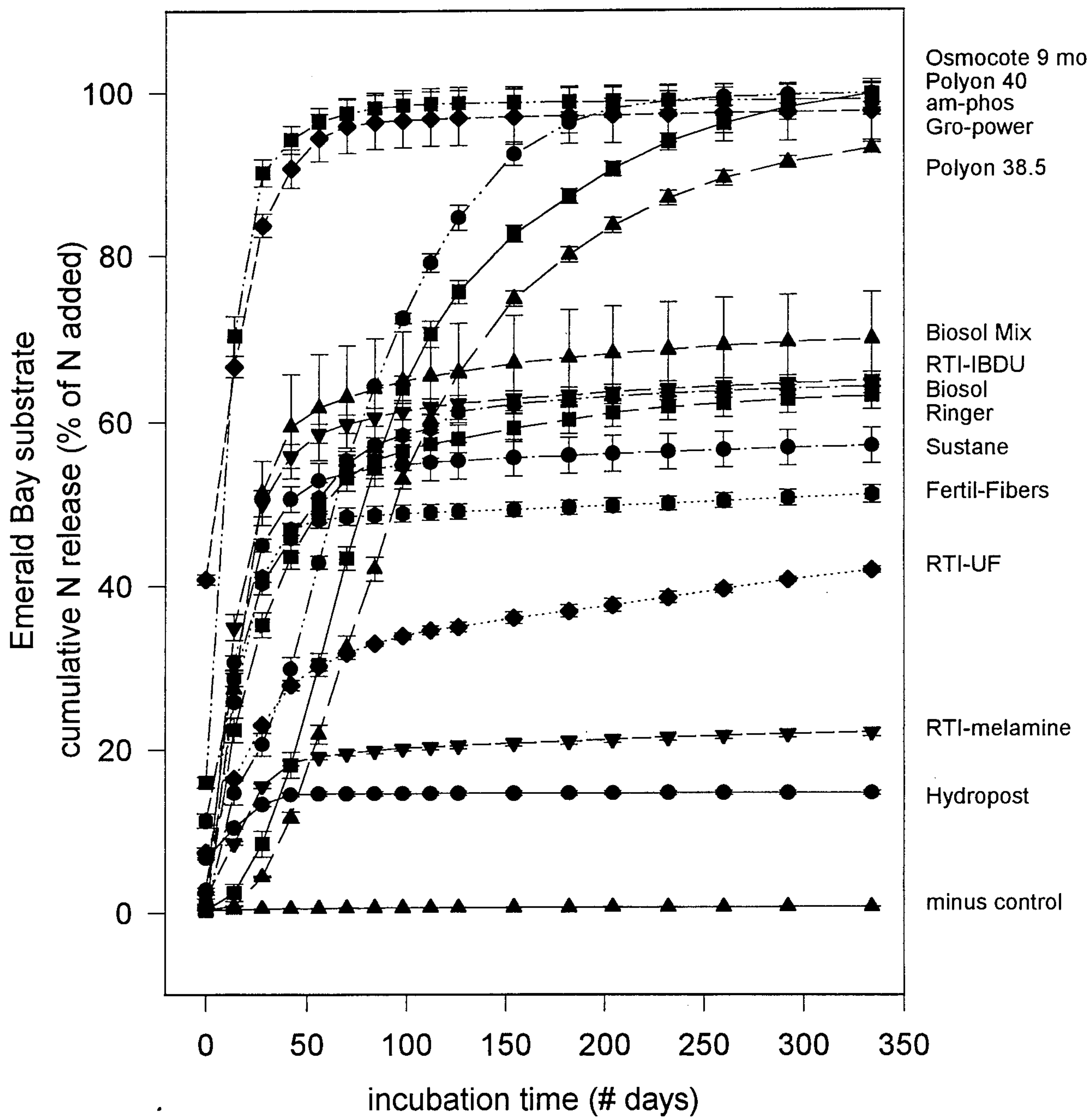

Figure 2. Cumulative N release by extraction from soil amendment materials on Emerald Bay substrates (% of N added) during laboratory incubation at 30 °C. All data points have standard error bars, some of which may be hidden by the plot symbol.

Table 2. Comparison of cumulative N release on two substrate materials after approximately 130 days incubation at 30 °C. All values are N released expressed as a percentage of the N loaded initially into the chamber. Values within each row followed by the same letters do not differ statistically ($p < 0.05$). Comparisons between rows (within each column) cannot be made from these data; see Tables 3 to 6 for comparisons between amendments.

	Substrate location	
Amendment	**Livingston**	**Emerald Bay**
ammonium phosphate (AP)	98.14 a	96.93 a
Polyon 40 (P40)	93.52 a	75.17 b
Osmocote (OSM)	94.09 a	89.23 a
Rocky Mtn Bioproducts Biosol (RBS)	57.81 a	57.63 a
Rocky Mtn Bioproducts Biosol Mix (RBM)	56.69 a	65.70 a
Reforest Tech - ureaformaldehyde (RTU)	37.22 a	34.80 a
Reforest Tech - IBDU (RTI)	46.35 a	60.96 b
Reforest Tech - melamine (RTM)	23.98 a	20.41 a

One slow release chemical formulation (P40) was significantly lower on the Emerald Bay material than the Livingston and one organic matter based blend (RTI) was significantly higher. Why these two materials showed different rates when other materials with similar release mechanisms (diffusion versus biological mineralization) did not show significant differences is not known. No single rationalization explains these findings, which are assumed to experimental error. We conclude that the two substrates are equivalent in their response to N release from potential revegetation amendments, and data from the two substrates are combined for the rest of this discussion.

<u>Comparison of cumulative total N release between various amendment materials.</u>

Nitrogen release curves from Figure 1 suggest a common pattern of rapid initial release rate followed by a period of slower release. Four general groups of amendment release rates are observed: 1) rapid release rates from chemical formulations (ammonium-phosphate), 2) controlled release chemical formulations (Osmocote, Polyon

40), 3) rapid initial release and slower long term release from organic materials and blends (the Biosol and Reforestation Technology products), and 4) little initial N release and slow subsequent release from straight compost materials (Sonoma and Gilton).

The Emerald Bay substrates (Figure 2) show the same general patterns after extended periods of leaching. Amendments with rapid and controlled release chemical formulations approach 100 % N release during this time period while the N release from the organic blends reaches 40 to 70% release. Analysis of the N in the residual amendment material is proceeding under a subsequent project involving compost utilization. Details of the N release curve of each product are reviewed individually by amendment material in the Discussion section of this report.

Statistical analysis of the N release data from the two substrate types are listed in Table 3 (for approximately 4 months incubation at 30 °C) and in Table 4 (for approximately 11 months incubation at 30 °C).

Comparison of the long term rate of N release between various materials after four or eleven months.

The laboratory (30 °C) incubation data indicate that N release rates are initially rapid but then decline to a slower rate (Figures 1 and 2). For this reason, we also analyzed the data taken from the second, slower phase of the incubation as an indicator of longer term N release such as would provide continued plant available N in the seasons following plant establishment. These release rates are expressed as an average % N released on a monthly basis after approximately 4 months incubation (Table 5) and after approximately 11 months incubation (Table 6).

After the first four months, about half of the organic based amendments continue to release statistically significant levels of N, including two Reforestation Technologies

Table 3. Cumulative N release from various amendments after approximately 130 days incubation at 30 °C, listed from greatest to lowest cumulative N release. Percent N release is calculated as a percentage of the loaded into the columns. Values in each column followed by the same letters do not statistically differ ($p < 0.05$).

Amendment	% N release	Substrate
ammonium phosphate (AP)	98.14 a	EB
Gro-power (GRO)	96.33 a	EB
Osmocote (OSM)	89.23 b	EB
Polyon 40 (P40)	75.17 c	EB
Polyon 38 (P38)	65.70 d	EB
Rocky Mtn Bioproducts Biosol Mix (RBM)	65.52 d	EB
Ringer (RNG)	61.97 d,e	EB
Reforest Tech - IBDU (RTI)	60.97 d,e	EB
Rocky Mtn Bioproducts Biosol (RBS)	57.63 e,f	EB
Sustane (SUS)	54.97 f	EB
Fertil-Fibers (FFB)	48.86 g	EB
Reforest Tech - ureaformaldehyde (RTU)	34.80 h	EB
Reforest Tech - melamine (RTM)	20.41 i	EB
Hydropost (HP)	14.56 i	EB
Sonoma Compost (SC)	6.69 j	LS
Gilton # 1 (G1)	4.80 j	LS
Gilton # 3 (G3)	4.61 j	LS
Gilton # 6 (G6)	3.62 j	LS
minus control (MC)	0.67 k	EB

Table 4. Cumulative N release from selected amendments on the Emerald Bay substrate after approximately 334 days (eleven months) incubation at 30 °C, listed from greatest to lowest cumulative N release. Percent N release is calculated as a percentage of the loaded into the columns. Values in each column followed by the same letters do not statistically differ ($p < 0.05$).

Amendment	% N release	Substrate
Osmocote (OSM)	99.84 a	EB
Polyon 40 (P40)	99.80 a	EB
ammonium phosphate (AP)	99.10 a	EB
Gro-power (GRO)	97.65 a	EB
Polyon 38 (P38)	93.13 b	EB
Rocky Mtn Bioproducts Biosol Mix (RBM)	69.94 c	EB
Ringer (RNG)	65.07 c,d	EB
Reforest Tech - IBDU (RTI)	64.30 c,d	EB
Rocky Mtn Bioproducts Biosol (RBS)	63.22 d,e	EB
Sustane (SUS)	57.11 e,f	EB
Fertil-Fibers (FFB)	51.21 f	EB
Reforest Tech - ureaformaldehyde (RTU)	41.99 g	EB
Reforest Tech - melamine (RTM)	22.19 h	EB
Hydropost (HP)	14.75 i	EB
minus control (MC)	0.82 j	EB

Table 5. Long term N release rate from various amendments at approximately 4 months incubation at 30 °C. Values listed are percent N released per month. Rates are the average for a 6 week period from 12 to 18 weeks, calculated as a percent of the total amount of N loaded into the columns. Values within the column followed by the same letters do not statistically differ ($p < 0.05$). *Because of their different N release mechanisms, the slow release chemical fertilizers were analyzed in a separate ANOVA procedure.

Amendment	% N release per month
Polyon 38 (P38)	15.8 a*
Osmocote (OSM)	14.3 a*
Polyon 40 (P40)	14.1 a*
Reforest Tech - IBDU (RTI)	2.73 b
Rocky Mtn Bioproducts Biosol (RBS)	1.77 c
Reforest Tech - ureaformaldehyde (RTU)	1.36 c,d
Rocky Mtn Bioproducts Biosol Mix (RBM)	1.33 c,d
Ringer (RNG)	1.13 d
Sonoma Compost (SC)	0.66 e
Sustane (SUS)	0.63 e
Reforest Tech - melamine (RTM)	0.41 e,f
ammonium phosphate (AP)	0.40 e,f
Gro-power (GRO)	0.35 e,f
Gilton Compost # 6 (G6)	0.34 e,f
Fertil-Fibers (FFB)	0.28 e,f
Gilton Compost # 1 (G1)	0.25 e,f
Hydropost (HP)	0.15 f
Gilton Compost # 3 (G3)	0.14 f
minus control (MC)	0.026 f

Table 6. Long term N release rate from selected amendments at approximately 11 months incubation at 30 °C. Values listed are percent N released per month. Rates are the average for a 74 day period from 260 to 334 days, calculated as a percent of the total amount of N loaded into the columns. Values within the column followed by the same letters do not statistically differ ($p < 0.10$).

Amendment	% N release per month
Polyon 38 (P38)	1.53 a
Polyon 40 (P40)	1.52 a
Reforest Tech - ureaformaldehyde (RTU)	0.986 b
Rocky Mtn Bioproducts Biosol (RBS)	0.401 c
Fertil-Fibers (FFB)	0.334 c
Rocky Mtn Bioproducts Biosol Mix (RBM)	0.304 c,d
Ringer (RNG)	0.299 c,d,e
Reforest Tech - IBDU (RTI)	0.211 c,d,e
Sustane (SUS)	0.207 c,d,e
Osmocote (OSM)	0.187 c,d,e
Reforest Tech - melamine (RTM)	0.174 c,d,e
Gro-power (GRO)	0.082 d,e
ammonium phosphate (AP)	0.030 e
minus control (MC)	0.024 e
Hydropost (HP)	0.014 e

products, Biosol and Biosol Mix, Ringer, Sonoma Compost and Sustane. The remaining materials have exhausted their releasable N and do not differ ($p < 0.05$) from the minus control. Within this group, the rate of release is probably increased by residues that are steadily degradable (thus releasing the N) as in the fungal mycelium of the Biosol products, the microbial biomass of the Sonoma Compost, or by the release of N from the fertilizer supplement, as with the Reforestation Technologies materials.

The sustained N release from the organic fractions of these amendments results from microbial mineralization of carbon for energy (McGill and Cole, 1985), and the subsequent release of N, depending on the ratio of the available C and available N in these materials. Characterization of the chemical makeup of the organic materials and their residue products can indicate the likely outcome of long term N release rates. The release pattern of the Gro-power, for example suggests that the main mechanism for N release is dissolution and hydrolysis of its urea fraction, while the mineralization curves of the organic blends suggest a slower, biologically mediated release of the organically bound N in the amendment residues.

Amendments that have high C contents (high available C:available N ratios) may retain (immobilize) N within the amendment for longer periods before it is released by mineralization. While this does not provide N for plant establishment, it does function to retain N for later release for plant maintenance and may be advantageous for continuity in N release as long as sufficient N is available in the initial period to support plant growth. Examples of this may be seen in the Hydropost material, which released a very low fraction of its N during these incubations. Because it is derived from shredded plant materials with a high C:N ratio, the N release may occur at a much later time, as may occur with the seed meal based Fertil-Fibers product. Analysis of the residues of these materials is occurring as part of a subsequent project on compost utilization.

The eleven month data evaluate the ability of the amendment to provide a sustained N release after an even longer period. By combining a chemical supplement with an organic base material, the Reforestation Technologies-ureaformaldehyde blend was able to sustain a significantly greater N release than the other organic matter based materials. While the slow release chemical formulations (Polyon 40 and 38) had higher monthly release rates, they had depleted the majority of their N content by this time, while the Reforestation Technologies material had released less than half of its total N. Continued release from this material will depend on the chemical composition of the remaining N residues. Substitution of organic based amendments with N derived from chemical sources must be done with respect to the other benefits that organics provide for soil remediation in addition to supplying supplemental N.

Comparison of N release from ground and unground amendment materials.

A manufacturing technique for reducing N release from a granule is to physically reduce the surface area and diffusion of N out of the granule (DeMent et al., 1961). To test if the granulated structure of the some of the amendments had an effect on the N release rate, selected samples were ground to pass a 1 mm sieve, imitating a moderate disruption force such as by passage through a hydroseed pump. The ground materials were then were incorporated into the standard leaching columns and leaching schedules (Livingston substrate). The differences between the release rates of the unground and ground amendments is presented in Table 7.

The only amendment to show statistically significant differences in release rates between ground and unground amendments was the RTI (IBDU) material. This product actually released less N in the ground than in the unground treatment, which is not the expected result from a finer particle size and a greater surface area. The grinding treatment does not result in increased N release, and, conversely, granulation does not appear to be a significant effect in slowing N release from these materials, at least as tested in this experiment. Further reduction of the amendment materials to a powder may have different results.

Table 7. Cumulative N release comparisons between unground (as received) and ground amendment materials after 84 days incubation at 30 °C. All values are N released expressed as a percentage of the N loaded initially into the chamber. Values in each row followed by the same letters do not statistically differ ($p < 0.05$).

Amendment	% N release unground	% N release ground
Rocky Mtn Bioproducts Biosol (RBS)	55.08 a	57.72 a
Rocky Mtn Bioproducts Biosol Mix (RBM)	63.81 a	56.63 a
Reforest Tech - IBDU (RTI)	57.24 a	53.63 b
Fertil-Fibers (FFB)	48.66 a	49.75 a
Sustane (SUS)	54.22 a	48.18 a
Reforest Tech – ureaformaldehyde (RTU)	32.90 a	33.02 a

Discussion: The Amendments

Ammonium phosphate 16-20-0 (AP)

The most rapid release rates are measured with ammonium phosphate (Bandini Fertilizer Company, Los Angeles, CA)(16 % ammonium-N). This very soluble chemical formulation is the standard 16-20-0 material that has historically been used for Caltrans roadside fertilization in the last several decades. The advantage of the material is that it is quickly released for plant uptake. For example, if applied in small amounts, it can be used for rapid correction of N deficiency, such as for a quick topdressing if an overly thick mulch immobilizes to much of the plant available N and plants become temporarily N limited. The significant drawback is that it is over 90 % released in the first three or four leaching events, and is available for uptake by fast growing species, or for leaching losses from the profile. The cumulative N release for this material is 98.1 % at 130 days of incubation (30 °C) and 99.1 % at 334 days. The N release rate at 4 months (30 °C) is 0.40 % per month and at 11 months it is 0.03 % per month.

The ammonium phosphate was used as a positive control in the leaching experiment, indicating the maximum release rate that could be expected from this set of amendments in these substrates. The N release curves on the two substrates show that the Emerald Bay granites had a slightly slower release curve than did the Livingston sands. This is interpreted to result from a two week leaching interval on the Emerald Bay set compared to a one week leaching interval on the Livingston set. The cumulative amount of N leached at the fourth leaching is about 94 % on both substrates, but the rate of the first two leachings is greater in the somewhat more porous Emerald Bay materials than the finer sized Livingston materials.

GRO-POWER (GRO)

GRO-POWER ® (Gro-power Inc., Chino, CA)is a urea-ammonium N blend with a plant compost base (5 % N, 4 % urea-N). The release rate is very rapid and is initially nearly all released as urea-N. Although this material is mostly composted plant material, the release rate of the added N is as fast as for ammonium phosphate. Although it is an organic blend, it should not be used as a slow release amendment, since the majority of the N is not organically bound except in the sense that urea is technically an organic chemical. The cumulative N release for this material is 96.3 % at 130 days of incubation (30 °C) and 97.6 % at 334 days. The N release rate at 4 months (30 °C) is 0.3 % per month and at 11 months it is 0.8 % per month.

OSMOCOTE 18-6-12; 9 month 70 °F formulation (OSM)

OSMOCOTE ® (Scotts-Sierra, Marysville, OH) is a resin prilled ammonium and nitrate source (18 % N). It is coated with a resin shell that moderates N dissolution and release. During soil handling, the resin coats had broken into several pieces, and may also rupture when used in hydroseed applications. The release rate in the lab incubation at 30 °C (86 ° F) was complete by about 200 days, as expected from the release rate indicated on the label (270 days at 21 ° C (70 ° F)). The cumulative N release for this material is 89.2 % at 130 days of incubation (30 °C) and 99.8 % at 334 days. The N release rate at 4 months (30 °C) is 14.3 % per month and at 11 months it is 0.2 % per month.

POLYON PCU 40 (P40)

POLYON PCU 40 N ® (Pursell Technologies, Inc., Sylacauga, AL) is a polymer encoated urea product (40 % N). The polyurethane coats of all prills were still intact when the columns were disassembled and would be expected to survive additional abrasion without rupturing and releasing the contents. N release rate in the Livingston material was 20 % faster than in the Emerald Bay material. The smaller pore size of the Livingston compared to the Emerald Bay material suggests that there was a greater pore water contact in the Livingston material and therefore greater diffusion from the prill. The majority of N release from this product appears to be between 30 and 100 days at 30 °C (900 to 3000 degree days). At field soil temperatures of about 10 ° C, this would translate to about 90 to 300 days, which is most of a year's growing season subsequent to amendment.

The released urea is hydrolyzed to ammonium by urease enzymes and, so, requires biological activity or enzymes adsorbed to soil surfaces. In some barren substrates, these may not be present and the hydrolysis may be reduced initially. Hydrolysis of urea creates a zone of alkalinity which, in unbuffered, low organic matter soils, may drive pH up. The cumulative N release for this material is 75.2 % at 130 days of incubation (30 °C) and 99.8 % at 334 days. The N release rate at 4 months (30 °C) is 14.1 % per month and at 11 months it is 1.5 % per month.

POLYON PCU 38.5 (P38)

Polyon PCU 38.5 N ® (Pursell Technologies, Inc., Sylacauga, AL) is a material similar to the P40, but with a thicker coat polyurethane coating and a slower release rate than P40 ($p = 0.0025$). This material will provide N later in the plant establishment cycle than the previous two. While the N cumulative release is not statistically different from the organic based products, the rate of release at the tenth extraction is very different and the material will release its N more rapidly than the organic based materials adjacent to it in Figure 2. Whether this is desirable depends on the actual release rates under field conditions and the rate of plant uptake rate during a given period. The cumulative N release for this material is 65.7 % at 130 days of incubation (30 °C) and 93.1 % at 334 days. The N release rate at 4 months (30 °C) is 15.8 % per month and at 11 months it is 1.5 % per month.

BIOSOL MIX (BSM)

Biosol Mix ® (Rocky Mountain Bioproducts, Edwards, CO) is a combination of fungal and bacterial residue byproducts from fermentation reactions (6.5 % N). It consists of a variety of N-containing compounds from cellular contents to cell wall structures and coatings. These compounds are similar to the biochemicals found in soil microbial biomass, and so are expected to mimic natural soil organic matter and decomposition and N release rates. However, the material is typically surface applied rather than being disseminated throughout the soil. The release shows an initial release of N followed by a plateau with a continuing N release rate of about 1 % per month (Table 3). This extended period of mineralization of N is expected to benefit establishment of the plant-soil community by providing a long term source of N for plant and microbe uptake. The cumulative N release for this material is 65.5 % at 130 days of incubation (30 °C) and 69.9 % at 334 days. The N release rate at 4 months (30 °C) is 1.3 % per month and at 11 months it is 0.3 % per month.

RINGER (RNG)

Ringer ® 5-10-5 (Ringer Corporation, Minneapolis, MN) is an organic based blend of agricultural by-products, including feather, blood, soybean and bone meals and chemical supplements (5 % N). The release rate of Ringer is similar to other organic based amendments, with an initial period of rapid release, followed by a steady plateau. The cumulative N release for this material is 62.0 % at 130 days of incubation (30 °C) and 65.1 % at 334 days. The N release rate at 4 months (30 °C) is 1.1 % per month and at 11 months it is 0.3 % per month.

RTI/Nova Organics - IBDU (RTI)

The RTI/Nova Organics ® - IBDU product (Reforestation Technologies International, Monterey, CA) is a blend of composted biosolids mixed with IBDU (isobutyledinediurea) (7.7 % N). The availability of the IBDU material in the blend is expected to be controlled by the dissolution of the fertilizer particles, and so the release is correlated with temperature and moisture (Tisdale et al, 1985). The released urea is hydrolyzed to ammonium by urease enzymes and, so, it also requires biological activity or enzymes adsorbed to soil surfaces. The mixture of the organic substrates with the chemical fertilizer is expected to facilitate the microbial activity needed to release the IBDU-N and to buffer the alkalinity that is produced by urea hydrolysis. The cumulative N release for this material is 61.0 % at 130 days of incubation (30 °C) and 64.3 % at 334 days. The N release rate at 4 months (30 °C) is 2.7 % per month, the highest of the organic material blends tested. At 11 months it is 0.2 % per month.

BIOSOL (BS)

Biosol ® (Rocky Mountain Bioproducts, Edwards, CO) is composed of fungal hyphal biomass residues from pharmaceutical manufacture (6.5 % N). The material is a blend of fungal cellular contents and cell wall structural compounds. These materials are similar to fungal residues the soil, a primary source of mineralizable N in natural soils. They are naturally resistant to rapid degradation, and are expected to provide a slow continuous N release pattern over time. The release rate of Biosol has a rapid initial phase, followed by a steady upward slope of N release. The cumulative N release for this material is 57.6 % at 130 days of incubation (30 °C) and 63.2 % at 334 days. The N release rate at 4 months (30 °C) is 1.77 % per month, the second highest of the organic material blends tested. At 11 months, it is 0.4 % per month.

SUSTANE (SUS)

Sustane ® (Sustane Corporation, Cannon Falls, MN) is a composted turkey litter and feather meal product (5 % N). The N release curve has a rapid initial increase, but the monthly release rate at 4 months was flatter than other organic materials. The ultimate release rate of the retained N is not known based on current chemical characterization methods. The cumulative N release for this material is 55.0 % at 130 days of incubation (30 °C) and 57.1 % at 334 days. The N release rate at 4 months (30 °C) is 0.63 % per month, in the moderately low range for organic material blends. At 11 months it is 0.2 % per month.

FERTIL-FIBERS (FFB)

Fertil-Fibers NutriMulch ® (Quattro Environmental Inc., Coronado, CA) is a seed meal based nutrient and fiber mulch containing composted poultry manure and humates (6 % N). The N release curve has a rapid initial increase, but the monthly release rate at 4 months was low. The release rate of the retained N is not known based on current chemical characterization methods and cannot be predicted for later times. If the plant derived fraction begins to mineralize, N release may again increase. The cumulative N release for this material is 48.9 % at 130 days of incubation (30 °C) and 51.2 % at 334 days. The N release rate at 4 months (30 °C) is 0.3 % per month, the lowest of the organic material blends. At 11 months it was 0.3 % per month.

RTI/Nova Organics - ureaformaldehyde (RTU)

The RTI/Nova Organics ® - ureaformaldehyde product (Reforestation Technologies International, Monterey, CA) is a blend of composted biosolids and ureaformaldehyde (8 % N). The urea material in the blend is polymerized into various chain-lengths of various solubility. The organic component will buffer the pH increase associated with hydrolysis and increase microbial activity in the amended soil. The cumulative N release for this material is 34.8 % at 130 days of incubation (30 °C) and 42.0 % at 334 days. The N release rate at 4 months (30 °C) is 1.36 % per month. This is the broadest contrast between a low initial release and a moderate long term release, which may be useful in establishment of low nutrient requiring native plants. At 11 months this material gave the highest release rate of the organic based materials at 0.99 % per month. A continued release of N is suggested by the continued, straight line of the N release curve from 100 to 334 days.

RTI/Nova Organics - melamine (RTM)

The RTI/Nova Organics ® - melamine (Reforestation Technologies International, Monterey, CA) is a blend of composted biosolids and melamine (8 % N). The melamine material in the blend has half of its N in heterocyclic ring positions and half in amine substituent groups. Melamine is degraded at a very slow rate in soils (Hauck and Stephenson, 1964) and is often found to be ineffective in boosting plant growth. These data indicate that it has a slow but measurable N release rate and may be useful for situations where a very long term N release is specified. The cumulative N release for this material is 20.4 % at 130 days of incubation (30 °C) and 22.2 % at 334 days. The N release rate at 4 months (30 °C) is 0.41 % per month and at 11 months it is 0.2 % per month.

HYDROPOST (HP)

Hydropost ® (Organics International, Irvine, CA) is a screened compost material (1.65 % N). It has the highest cumulative N release of the unblended compost materials, but has a much lower cumulative N release than the blended products. Because the material has a high plant material content, the bulk of the N release from this and the other composts may occur at a later time than measured in this study. This would potentially occur because the microbial biomass that is degrading the plant material runs out of carbon substrate and releases its retained N as the population declines. In this way, the N would be retained on site and would become available for plant uptake at a later time. The cumulative N release for this material is 14.6 % at 130 days incubation (30 °C) and 14.8 % at 334 days. The N release rate at 4 months (30 °C) is 0.15 % per month and at 11 months is 0.01 % per month.

Gilton composts (G1, G3, G6)

The Gilton green waste composts (Gilton Resource Recovery, Modesto, CA) (approximately 1.2 % N) were sampled several times to provide an estimate of the variability of this material from the Caltrans project at Livingston. G1 was collected on site and G3 and G6 were collected from the Gilton compost processing yards. The cumulative N release for these materials ranges from 3.6 to 4.8 % at 130 days incubation (30 °C) and the N release rates at 4 months (30 °C) are 0.14 to 0.34 % per month. The three samples do not differ significantly ($p < 0.05$) for either parameter.

Sonoma Compost (SC)

The Sonoma composts (Sonoma Compost, Petaluma, CA) (1.5 % N) were composite sampled from piles at the composting yard. The cumulative N release for this material averaged 6.7 % at 130 days incubation (30 °C) and the long term N release (measured at 4 months) was 0.66 %. This was the highest long term release of all the straight composts and was higher than some of the organic blend materials.

Calibration of lab incubation N release rates to field plots.

A field trial was constructed at the Livingston project site in the San Joaquin valley to evaluate N release rates in field conditions. Similar amendment materials were used as in the lab incubation experiment. PVC tubes (3 x 30 cm) were filled with 10 cm of amendment materials over 15 cm of unamended, N depleted substrate. At 6 and 12 weeks after installation in the field (ambient temperature and precipitation), three replicate columns for each amendment were retrieved and the top (amended) and bottom (unamended) soil portions were analyzed for extractable ammonium and nitrate, anaerobically mineralizable N and urea. Data are expressed in Table 8 in several columns: A) as N released at 6 weeks as a percent of the N loaded, B) as the percent of the 6 week released N in the nitrate form, C) as the percent of the 6 week released N that had moved (leached) to the bottom of the tube, D) as N released at 12 weeks as a percent of the N loaded or E) as a percent of the cumulative (total) N released from the same amendment as compared to the laboratory incubation (30 °C).

The Osmocote and ammonium phosphate produced rapid initial N release rates in the field trial similarly to the lab incubations (columns A and D; 6 and 12 weeks in the field). This rapid release of nutrients suggests that leaching may potentially remove N before plant growth and uptake begins. The three amendments with the highest movements of N from the surface (amended) section of the fertilizer tubes to the bottom (unamended) portion of the tube were ammonium phosphate, Gro-power and the IBDU blend (column C). This is largely attributable to the conversion of ammonium or urea to leachable nitrate (column B). Some of the organic based materials (Biosol, Biosol Mix, Fertil-Fibers) also had high rates of nitrate production, but the overall release rate was low enough to limit leaching movement. These materials were incorporated within the top 10 cm of the soil as opposed to being surface applied, and so will have greater decomposition rates and higher release rates than if they were unincorporated.

The major contrast in release pattern between the field and lab data was that the Osmocote material released much faster in the field experiment data than in the lab

Table 8. Cumulative N release from various amendments in field situations at the Livingston site, January 23 - April 24, 1998. A: cumulative N released as a percent of the loaded rate at 6 weeks; B: percent of N released in nitrate form at 6 weeks; C: percent of N released at 6 weeks that leached to 25 cm depth; D: cumulative N released as a percent of the loaded rate at 12 weeks; E: percent of the cumulative N release rate from the field plots compared to the cumulative N release rate at the same time in the lab incubation (30 °C) (field N release divided by lab N release, expressed as a percent).

	A	B	C	D	E
AMENDMENT	cumul N released (% of loaded) 6 weeks	% of N released in NO_3 pool at 6 weeks	% of N released leached to 25 cm 6 weeks	cumul N released (% of loaded) 12 wks	% of N released compared to lab incubation
Osmocote (OSM)	29.0	54.2	3.3	43.8	64.2
ammonium phosphate (AP)	27.7	99.2	68.3	35.4	36.1
Ringer (RNG)	15.4	46.5	3.8	25.9	42.7
Rocky Mtn Bioproducts Biosol (RBS)	16.8	84.1	10.2	24.7	44.7
Rocky Mtn Bioproducts Biosol Mix (RBM)	13.3	84.9	19.2	23.3	36.4
Fertil-Fibers (FFB)	12.9	64.9	5.3	20.6	42.2
Gro-power (GRO)	14.9	92.2	34.2	19.9	20.6
Reforest Tech - IBDU (RTI)	9.3	55.5	27.7	13.9	24.3
Sustane (SUS)	10.0	68.4	17.1	13.0	23.9
Polyon 40 (P40)	7.4	35.6	0.9	12.7	23.3
Reforest Tech - ureaformaldehyde (RTU)	5.4	52.1	19.0	9.8	29.8
Reforest Tech - melamine (RTM)	3.7	46.4	17.1	6.9	34.6
Polyon 38 (P38)	1.9	44.5	2.6	4.5	10.7
Hydropost (HP)	1.3	0.0	13.1	3.5	23.9
Sonoma compost (SC)	1.1	0.0	9.3	2.4	41.2
Gilton compost (G3)	0.9	0.0	0.0	1.9	42.0
minus control (MC)	0.4	0.0	---	0.4	---

incubation (column E) and was not at all similar to Polyon 40 as observed in the lab data. This effect is probably due to rupture of the prills during soil handling and processing, releasing the encapsulated ammonium and nitrate. Undisturbed prills are assumed to release N in a pattern similar to the lab incubation unless ruptured by other means in the field or during application.

Plant compost based materials (Hydropost, Sonoma compost, Gilton compost) all showed no nitrate production. This is interpreted to suggest that microbial immobilization of mineralized N during decomposition of the plant residues in the amendment consumed all available mineralized N. While this does not provide N for short term plant establishment, it suggests that a residual pool of microbial biomass N will be available for mineralization and release much later, when plant residues have been consumed. In the short term, these materials may be used to buffer N release and to adsorb excess N released from high N content amendments.

Degree day calculations

A ratio of degree days in the field to degree days in the lab incubation (30 °C) was calculated to prorate the more rapid N release rates from the lab incubations into the slower rates predicted for field conditions. Data from the Modesto A CIMIS weather station data for January 23 to April 24, 1998 (the length of the field trial) were used to calculate accumulated degree days, using three different temperature thresholds (base temperatures). Accumulated degree days for this period are estimated to be 1114 (0 °C base), 746 (4 °C base), and 195 (10 °C base). Using degree days calculated for the incubator of 2520 (0 °C base) , 2184 (4 °C base), and 1680 (10 °C base), the predicted ratio of field release rate to lab release rate can be estimated. These ratios predicted field N release rates that were 44.2 % (0 °C base), 34.2 % (4 °C base) and 11.6 % (10 °C base) of the lab rates.

A comparison of the cumulative N released in the Livingston plots compared to the lab incubation (30 °C) indicates that release rates varied from 10.7 % to 64.2 % (Table 8, column E). This broad range includes materials with very different release mechanisms. If only the organic based materials are considered, the range is reduced to 23.3 % to 44.7 %. The average of these values is 33. 9 % (± 8.9 std).

Degree day calculations using the 4 °C base give the closest prediction of the fraction of the N release rate predicted for field versus lab measurements (34.2 % versus 33.9%). In general, this suggests that during the winter and spring months, that field N release rate was approximately one third of the laboratory rates. Dry summer conditions are expected to further reduce the field N release rates relative to the lab release rates. Because so many other factors influence N release rate in the field, including temperature, moisture, leaching losses, incorporation method, diffusion gradients, microbial activity and plant uptake, these methods relating lab incubation N release rates to field release rates should at this point be used only as a first approximation.

Conclusions

The suite of lab procedures and chemical analyses developed in this project is able to evaluate N release rate from a range of amendment materials in a reproducible manner on the substrates tested, and at a rate approximately three times faster than under winter field conditions in the central valley of California. The procedure is consistent between two soils of similar parent material, but different textures. The procedure allows measurement of N release rates over long periods of time with only initial artifacts generated by handling, sieving or drying.

The methods indicate that amendments can be segregated into four major groups of N releasing materials: 1) rapid delivery of N (soluble ammonium phosphate and Gro-power), 2) the slower release pattern from chemical based fertilizers (Polyon or Osmocote), 3) the blended, organic based products with rapid initial releases of one- to two-thirds of their N content followed by a slower release rate (Biosol products, Fertil-Fibers, Reforestation Technology products, Ringer, Sustane), and 4) the slow release rate of the plant compost materials with little initial N release.

Depending on the objectives for the plant community (rapid versus slow growth; erosion control versus perennial plant establishment), various amendments can be used to provide appropriate amounts and release rates of N to the revegetation project. Other soil remediation characteristics will also need to be evaluated in the field, including pH, physical structure, water release characteristics, mulch protection, biological inoculation, and non-N nutrients. The addition of organic substrates will improve all of these characteristics, as well as increasing microbial activity, a major factor in generation of water-stable aggregates, as reviewed in an earlier chapter.

A general relationship was observed between the lab incubation (30 °C) and the data from the field site at Livingston, CA. Field release rates were approximately one third of the rates measured in the lab. Other cooler or drier sites would be expected to have slower release rates. Because of the overall consistency and representation of field N characteristics, the lab incubation procedure can be used as a screening and evaluation tool to compare different amendment materials, or combinations of materials, with greater convenience, speed and experimental control than by using only field plots. The most appropriate materials should still be compared under field conditions to evaluate the effect of other non-N variables that also influence plant growth and establishment.

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Appendix A. N release on substrates from the US 50 slide and from the Kyburz spoil pile.

N release on the US 50 (Mill Creek) slide material and from the Kyburz spoil pile was observed to be a fraction of the rates measured on substrates from the Livingston material. Table A1 summarizes the cumulative percent N release (second and third columns). These two values are expressed as relative % N release (fourth column).

Average percent relative yield ((US 50 / Livingston) x 100) of the urea or nitrate containing materials is 76.0 % (±12.8 std) and the average of the organic based materials and ammonium phosphate is 34.27 % (±7.0 std). The difference is attributed to fixation of ammonium (released from dissolution or mineralization) into interlayer positions in clays and mica minerals.

Table A1. Comparison of cumulative N release on the US 50 slide substrate as a percent of the cumulative N released on the Livingston substrate (Data from Table 2).

Amendment US50 slide face: (-f), Kyburz spoil pile: (-k)	**cumul % N release US50**	**cumul % N release Livingston**	**relative N release (US50/Liv) %**
Polyon 40 (p40-k)	67.57	75.17	89.89
Osmocote (osm-k)	65.70	89.23	73.63
Gro-power (gro-k)	62.11	96.33	64.47
Osmocote (osm-f)	54.31		
ammonium phosphate (ap-k)	38.75	98.14	39.48
Rocky Mtn Bioproducts Biosol Mix (rbm-k)	21.82	65.52	33.30
Ringer (rng-k)	19.96	61.97	32.21
Rocky Mtn Bioproducts Biosol (rbs-k)	18.88	57.63	32.76
Rocky Mtn Bioproducts Biosol (rbs-f)	17.14		
Reforestation Tech - ureaform (rtu-k)	16.71	34.80	48.02
Fertil-Fibers (ffb-k)	16.61	48.86	34.00
Sustane (sus-k)	13.33	54.97	24.25
Fertil-Fibers (ffb-f)	10.51		
Native (east of slide face) (native)	8.51		
Reforestation Tech - melamine (rtm-k)	6.15	20.41	30.13
Arizona compost (az-f)	6.15		
Reforestation Tech -melamine (rtm-f)	3.95		
Sonoma Compost (sonoma-k)	2.20		
minus control (mc-f)	0.31		

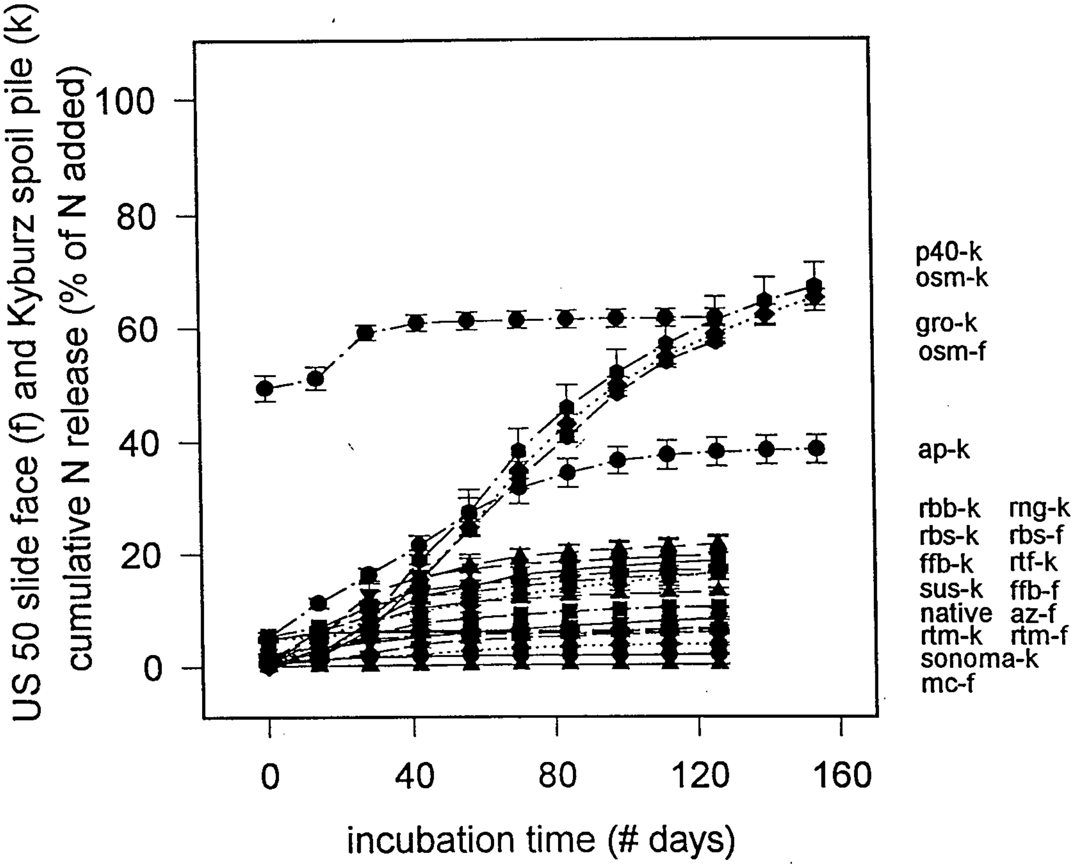

Fig A1. Cumulative N release as a percentage of that loaded into the incubation column. Substrates are collected from the lower third of the slide face (-f) or from the Kyburz spoil pile (-k).

Appendix B. N release on substrates from the US 50 slide and from the Kyburz spoil pile as influenced by mixture with various volumetric fractions of non-adsorbing quartz sand.

In an attempt to identify the cause of the reduced N release in the Kyburz material, the effect of poor soil porosity and poor extraction efficiency was evaluated. To increase the ability of the extracting solutions to wash out retained N, various materials were blended with 50 or 67 % non-adsorbing quartz sand (250 to 500 µm) and were compared to release rate in 100 % quartz sand. Most dramatic was the decrease in N release from the 100 % quartz sand plus ammonium phosphate treatment (100 QS + AP). This treatment yielded 95.57 % release in three extractions and was reduced to 27.46 % N release by the addition of 33 % by volume of the Kyburz spoil pile material.

Appendix B. N release on substrates and quartz sand mixtures from the Kyburz spoil pile (US 50 slide), Livingston and Emerald Bay materials. Quartz sand (zero N) was added to each substrate to test N release rate from ammonium phosphate and an organic soil amendment (Biosol). Sand addition increases percolation and removal of N (through incubation column leaching) but does not remove the effect of the substrate material.

amendment type	substrate type	% substrate	% quartz sand	cumul % N released
ammonium phosphate 16-20-0				
	Kyburz spoil pile	50	50	15.45
	Kyburz spoil pile	33	67	27.46
	Livingston silts,sands	100	0	69.59
	Livingston silts,sands	50	50	83.06
	Emerald Bay granite	100	0	77.09
	Emerald Bay granite	50	50	85.75
	quartz sand only	0	100	95.57
Rocky Mountain Bioproducts Biosol				
	Kyburz spoil pile	50	50	3.83
	Kyburz spoil pile	33	67	10.03
	Livingston silts,sands	100	0	18.63
	Livingston silts,sands	50	50	24.70
	Emerald Bay granite	100	0	19.84
	Emerald Bay granite	50	50	21.89
	quartz sand only	0	100	24.13
minus control (no N)	Emerald Bay granites	100	0	0.87

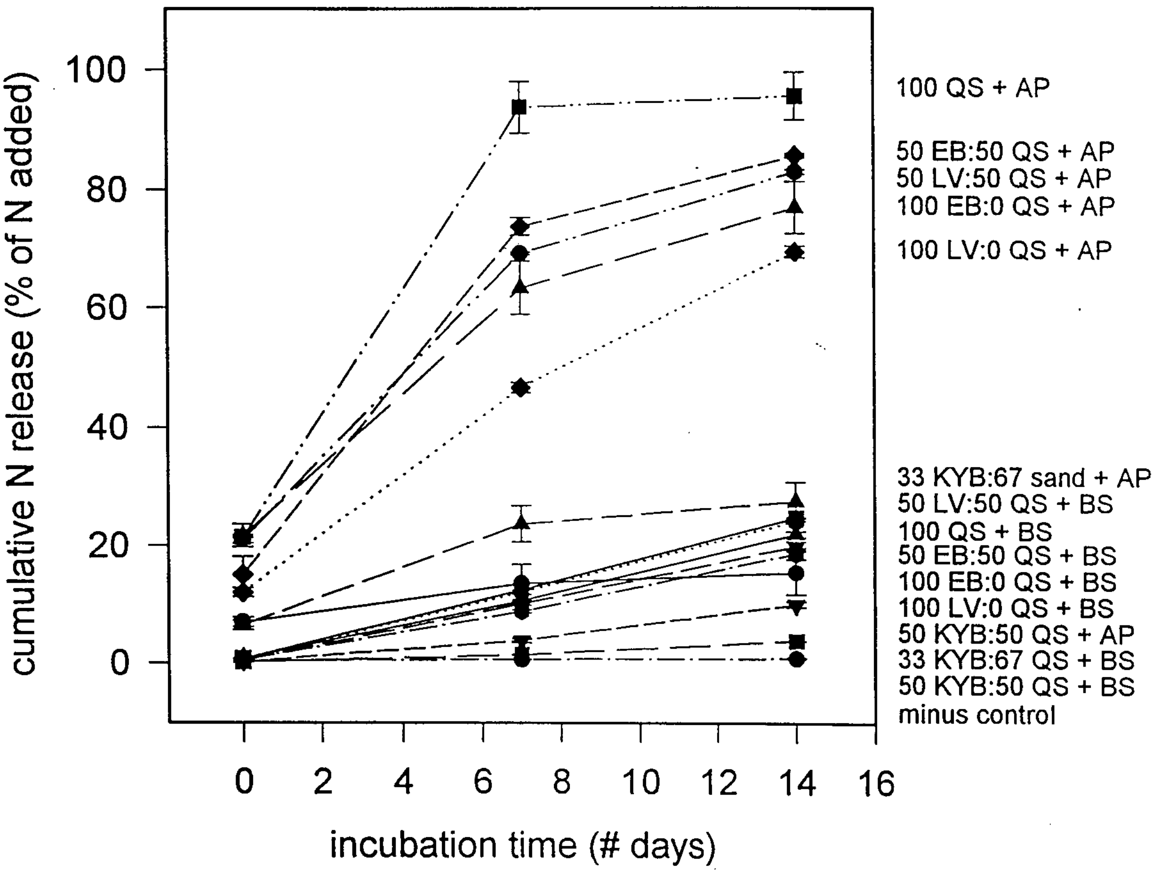

Figure B1. Cumulative % N release from two soil amendments (ammonium phosphate and Biosol) from three substrates (Kyburz spoil pile, Livingston sands, and Emerald Bay granite) with various proportions of quartz sand added.

Chapter 5. The Effect of Nitrogen Placement Depth on Two Perennial Grass Species in Decomposed Granite

ABSTRACT

The effects of stratified, vertical nitrogen (N) placement in a nutrient-poor decomposed granite material were evaluated through measurement of shoot and root biomass and root distribution of two cool season perennial grass species, *Elymus glaucus* and *Elytrigia intermedia*. The study addressed three questions: 1) does inclusion of a nutrient-rich organic layer at a shallow (0 - 10 cm) versus deep placement (20 - 30 cm) in a low-fertility granitic soil enhance growth of a cool season perennial grass; 2) does a concentrated amount of that nutrient addition have a greater influence on plant growth than that same amount distributed in a greater soil volume (at a lower concentration) and 3) does a native versus a non-native cool season perennial grass species respond differently to any of these treatments? After 120 days growth, additions of the same mass of an organic soil amendment (6 % N) at three different profile positions (0 - 10 cm, 20 - 30 cm or 0 - 30 cm) resulted in significantly increased plant growth ($p < 0.01$) in all treatments compared to the control. The 0 - 10 cm (top nitrogen, TN) treatment showed the greatest amount of total biomass with 6.38 g plant dry weight per pot, or 613% of the zero control. The 0 - 30 treatment (even nitrogen, EN) produced 3.82 g total biomass, or 367% of the control and the 20 - 30 cm (bottom nitrogen, BN) treatment produced 3.14 g total biomass, or 302% of the control. The difference between the total biomass of the TN and the EN and BN treatments was highly significant ($p < 0.01$) but the EN and BN treatments, while differing significantly ($p < 0.01$) from the control, did not differ significantly from each other. Native and non-native grass species biomass production did not significantly differ on between any of the

treatments. However, when root dry weights were analyzed by horizon, significant differences were observed between the two species in both the TN (0-10 cm layer) and BN (20-30 cm layer) treatments.

INTRODUCTION

Reestablishment of vegetative cover on disturbed sites can be extremely difficult (Brown and Chambers, 1989; Bradshaw 1992). This is especially true on high elevation granitic soils in the Sierra Nevada Mountains (Erman, 1997; Kay, 1988). When soils are disturbed, plants, mulch cover and nutrient-releasing organic matter are removed. These low cover-class sites (< 40% total cover) present a high potential for erosion, which adversely effects watersheds in several ways. Negative impacts of erosion include soluble nutrient movement through soil and water, accelerated eutrofication of watercourses and lakes, reduction of fisheries habitat, loss of the soil organic material that supports plant growth and microbial communities and increased maintenance costs of road sides and drains (Leonard *et al.*, 1979; Erman, 1997; Goldman, 1989; Megahan, 1986; Pacific Rivers Council, 1995a) as well as economic impacts to the community at large (Neimi and Whitelaw, 1995; Lee, 1987; Walker, 1994). Addition of nutrients, especially organic nitrogen, on disturbed, high-elevation granitic soils, can be critical for recapitalizing soil nutrient pools, nutrient cycles and microbial communities for enhancement of plant establishment (Reeder and Sabey; Li and Daniels, 1994; Bradshaw *et al.*, 1982).

Soil disturbance on these thin, poorly-developed soils usually results in one or more of three potential outcomes: 1) removal of topsoil and nutrients from the site, 2) mixing of topsoil with existing sub-surface layers or 3) burial of topsoil beneath nutrient-poor subsoil material. These types of disturbances can take place as a result of road building, ski run development, home site development, recreation or other activities common to high elevation areas.

A recent study indicates that there is often a large decrease in total nitrogen from surface to subsurface layers in these high elevation wildland soils (Claassen and Hogan, in prep). In the aforementioned study, sites were measured that contained N-rich layers buried deep (30 cm) in the soil profile, but that had little associated plant growth. This situation suggests that vertical placement of nutrients within the soil profile might impact biomass production and therefore influence revegetation outcome on disturbed sites. For example, a low N content amendment may be placed on the soil surface to encourage general plant growth, while an N-rich material may be placed at some deeper level to facilitate native plant establishment, root development and/or reduce weedy growth.

Several studies suggest that a certain level of nutrients must be present in the soil before an adequate plant cover can be established and maintained (Claassen and Hogan, Chapter 3, this report; Bradshaw, 1997; Bradshaw and Chadwick 1980; Reeder and Sabey; Li and Daniels, 1994). Landscape level studies such as these typically report nutrient levels averaged over an entire profile, with soil N levels reported as a sum of the 0 - 20 cm or 0 - 30 cm depth, for example. Wildland soils, however, tend to be strongly stratified with depth. Measurements of average concentrations may ignore the effect of nutrient position within the profile. Plants adapted to growth on these nutrient-stratified soils may be strongly influenced by differences in nutrient placement.

The purpose of this study is to determine whether the placement of nutrients at a specific depth within the soil profile results in an increase or decrease in the development and growth of two species of cool season grasses (a native, *Elymus glaucus* and a non-native, *Elytrigia intermedia*) commonly used for vegetative stabilization of disturbed lands in the Sierra Nevada Mountains of California and Nevada. (It should be noted that the term 'native' is here used to denote a species that is local or indigenous native to the Sierra Nevada mountains, since *Elytrigia intermedia* is native to Eurasia.)

MATERIALS AND METHODS

General Design

The design of this study was intended to mimic the three likely outcomes of soil disturbance as outlined above. The experiment was a 4 x 2 factorial, completely randomized design with 4 N placement treatments (TN: top nitrogen, EN: even nitrogen, BN: bottom nitrogen, C: control, and 2 plant types: "n" (native) *Elymus glaucus*, a native perennial grass species and "nn" (non-native) *Elytrigia intermedia* a Eurasian non-native species with similar physiological characteristics to the *Elymus*. An extremely low nutrient ($\leq$ 200 kg total N/ha), decomposed granite saprolitic material was collected from a road cut on the west side of the Lake Tahoe Basin at approximately 2250 m (7380 ft). Soil was sieved to < 2 mm. Forty PVC soil tubes, (40 cm x 15.75 cm) were divided vertically into four 10 cm sections. Each tube received one of the four treatments. In all treatments, the bottom 10 cm section received no nutrient addition. This enabled roots from plants to grow into this section without being 'air-pruned' as they grew beyond the 20-30 cm treatment layer.

Soil N additions were based on published values of plant community N content (Marrs and Bradshaw, 1982; Reeder and Sabey, 1987; Palmer, 1990; Li and Daniels, 1994) and on an intensive revegetation nutrient study conducted in the Lake Tahoe Basin [Claassen and Hogan, in prep]. The equivalent of 252 kg of total N/ha was added to each amended pot either to the 0 - 10 cm layer (EN), the 20 - 30 cm layer or throughout the 0 - 30 cm profile. No amendments were added to the negative control. The nitrogen was amended in the form of a commercially available fungal mycelium-based fertilizer product (Biosol ©) with 6 % total N and mineralization rate of approximately 30% per season. In order to equalize non-nitrogen nutrient availability across all soils, supplemental amounts of K and P equivalent to that in the slow release fertilizer were added to all soil layers that did not receive the organic amendment addition.

Seeds were placed on the soil surface and covered with 0.25 cm of clean, quartz sand mulch. An overhead mist-type irrigation system was used to irrigate on an as-needed basis. Pots were over-planted with 20 seeds per pot and thinned to 10 seedlings per pot at 1 week after emergence. Plants were grown for 120 days and harvested. Shoot biomass was calculated on a dry weight basis (air dried at 40 °C). Pots were dismantled in 10 cm depth increments and sieved to collect root material. All soil was dried at 40 °C (Anderson and Ingram, 1993; Bates, 1993).

The measured parameters included shoot (above ground) biomass, root (below ground) biomass, total soil nitrogen and carbon (dry combustion, Carlo Erba NA 1500), KCl extractable soil NO_3 and NH_4 (Keeney and Nelson, 1982), and 7 day anaerobic mineralizable NH_4 (Keeney, 1982). Available and mineralizable N were measured by conductimetric auto-analyzer (Carlson, 1978). All root and soil parameters were measured by individual layers in each pot.

Soil nutrient parameters were analyzed statistically (ANOVA) at two levels: 1) between treatments and 2) between depth levels within each treatment. Mean separation was evaluated using Least Significant Difference (Statsoft, Inc., Tulsa, OK).

RESULTS

Soil Parameters

All measured soil parameter differences were highly significant ($p \leq 0.01$) with the exception of extractable NH_4 and total N which were significant at $p \leq 0.05$, and total carbon and C:N ratio which were not significantly different between treatment types (p = 0.098 and p = 0.368). Concentrations of residual nitrogen generally followed the pattern of application, i.e., the 0 - 10 cm values tended to be higher in the TN treatment, the 20 - 30 cm values tended to be higher in the BN treatment and so forth. A notable exception was that NO_3 was significantly less all layers of the native TN treatment compared to the non-native TN treatment.

Plant Parameters

Both above and below ground biomass was significantly different ($p \leq 0.01$) between treatments but not between plant type. Table 1 presents means and percentages of means for the three treatments and the control, using data from both species combined. The top nitrogen treatment shoot biomass was 588% of the control while the root biomass was 670% of the control. Total biomass for the TN treatment was 613% of the control. The root to shoot ratios were as follows: TN: 0.487, EN: 0.33, BN: 0.314 and C: 0.489.

Native vs. Non-native grass response

Total shoot biomass between the native and non-native grass species did not statistically differ. The composite of root biomass means also did not differ between plant types (Table 3). However, there were two significant differences in root growth by soil depth: 1) the *Elytrigia intermedia* (non-native) produced a greater amount of root

Table 1: Data matrix for plant biomass; data is presented as a ratio of the treatment listed in column heading as a % of the treatment in the row heading. Treatment codes are TN: top nitrogen; EN: even nitrogen; BN: bottom nitrogen, C: negative control.

	Dry weight	Shoot Biomass in %			
Treatment	**Mean**	**TN**	**EN**	**BN**	**C**
TN	4.2921	100	66.97	55.69	16.99
EN	2.8745	149.32	100	83.15	25.38
BN	2.3901	179.58	120.27	100	30.52
C	0.7294	588.44	394.09	327.68	100

	Dry weight	Root Biomass in %			
Treatment	**Mean**	**TN**	**EN**	**BN**	**C**
TN	2.0891	100	45.44	35.94	14.92
EN	0.94937	220.05	100	79.08	32.77
BN	0.75075	278.27	126.46	100	41.52
C	0.3117	670.23	304.58	240.87	100

	Dry weight	Total Biomass in %			
Treatment	**Mean**	**TN**	**EN**	**BN**	**C**
TN	6.3812	100.00	59.92	49.22	16.32
EN	3.82387	166.88	100.00	82.14	27.23
BN	3.14085	203.17	121.75	100.00	33.15
C	1.0411	612.93	367.29	301.69	100.00

biomass ($p = 0.012$) in the 0 - 10 cm (shallow) layer of the TN treatment compared to the *Elymus glaucus* (native) and the *Elymus* exhibited a significantly greater amount of root biomass ($p = 0.034$) in the 20 - 30 cm (deep) layer of the BN treatment over the *Elytrigia.*

The effect of different plant species (as indicated by using total biomass measurements) was not significant ($p = 0.727$). The 2 x 4 factorial experiment showed a non-significant interaction trend ($p = 0.069$) between plant type and treatment. This trend suggests a differential rooting pattern at two of the four measured depths.

Table 2: Data table for selected soil N pools. All values in mg N/kg soil. Treatment codes are TN: top nitrogen; EN: even nitrogen; BN: bottom nitrogen, C: negative control. Nitrogen pool tests are extractable (ext), mineralizable (min), and total.

NH_4 ext. native				
N treat	0-10 cm	10-20 cm	20-30 cm	30-40 cm
TN	0.51	0.15	0.12	0.06
EN	0.14	0.23	0.17	0.04
BN	0.06	0.03	0.79	0.30
C	0.04	0.13	0.02	0.70
NO_3 ext. native				
N treat	0-10 cm	10-20 cm	20-30 cm	30-40 cm
TN	0.83	0.83	0.40	0.31
EN	1.75	1.95	2.34	1.13
BN	1.85	1.05	3.79	1.58
C	0.43	0.49	0.51	0.72
NH_4 min native				
N treat	0-10 cm	10-20 cm	20-30 cm	30-40 cm
TN	4.24	2.79	1.93	2.28
EN	2.21	2.99	2.62	1.50
BN	1.37	1.48	4.20	2.03
C	1.98	2.01	2.00	2.28
N total native				
N treat	0-10 cm	10-20 cm	20-30 cm	30-40 cm
TN	131.26	123.34	100.92	99.28
EN	124.00	135.38	131.48	111.36
BN	98.12	106.32	153.46	112.52
C	101.08	106.22	105.46	101.88

NH_4 ext. non-native				
N treat	0-10 cm	10-20 cm	20-30 cm	30-40 cm
TN	0.58	0.18	0.04	0.02
EN	0.15	0.13	0.10	0.02
BN	0.65	0.00	0.18	0.17
C	0.02	0.03	0.01	0.01
NO_3 ext. non-native				
N treat	0-10 cm	10-20 cm	20-30 cm	30-40 cm
TN	1.32	1.01	0.69	0.61
EN	2.94	2.49	2.60	1.58
BN	1.69	1.65	4.32	2.38
C	0.35	0.82	0.54	0.71
NH_4 min non-native				
N treat	0-10 cm	10-20 cm	20-30 cm	30-40 cm
TN	5.02	1.71	1.25	1.14
EN	2.53	2.72	2.53	1.61
BN	1.17	1.00	2.80	1.91
C	1.56	1.73	2.14	2.03
N total non-native				
N treat	0-10 cm	10-20 cm	20-30 cm	30-40 cm
TN	153.20	113.36	106.36	98.80
EN	116.52	124.74	145.36	113.14
BN	94.86	101.78	145.36	127.14
C	98.90	109.78	108.74	105.64

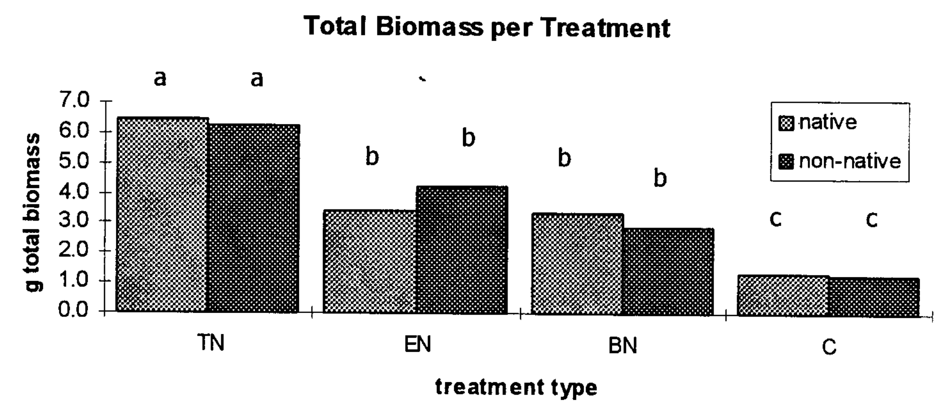

Figure 1. Total biomass (shoots plus roots) per treatment. Columns with the same letter did not differ significantly ($p \leq 0.05$).

Table 3: Plant biomass estimates for 3 treatments and control, both species combined. All values in kg ha^{-1}. Values within each column that are followed by the same letter do not differ significantly ($p \leq 0.05$).

Shoot Biomass		Root Biomass		Total Biomass	
Treatment	**kg biomass/ha**	**Treatment**	**kg biomass/ha**	**Treatment**	**kg biomass/ha**
TN	2353 a	TN	1145 a	TN	3498 a
EN	1576 b	EN	520 b	EN	2096 b
BN	1310 b	BN	412 b	BN	1722 b
C	400 c	C	171 c	C	571 c

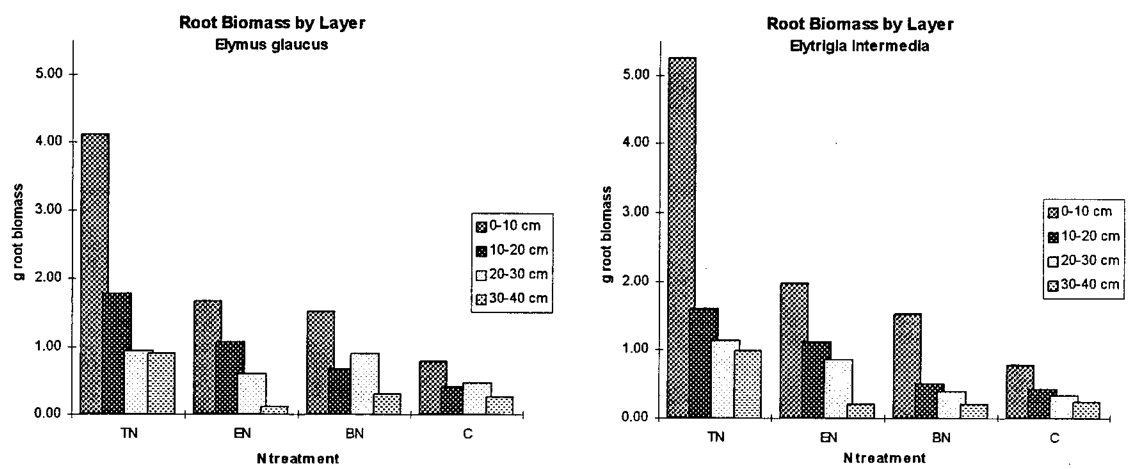

Figure 2: Comparison of plant type by N treatment at each soil depth. Root biomass of the *Elytrigia* was significantly greater in the 0 - 10 cm depth of the TN treatment than of the *Elymus*. Root biomass of the *Elymus* was significantly greater in the 20-30 cm depth of the BN treatment than of the *Elytrigia*. All other comparisons between plant types are non-significant ($p > 0.05$).

DISCUSSION

Results of this study indicate that organic nitrogen additions to any portion of the 0 - 30 cm soil profile will result in an increase in both root and shoot growth of perennial grasses compared to the zero control. Placement of organic amendments equivalent to 252 kg N ha^{-1} in the top portion of the profile produces a greater biomass increase compared to that same amount of N placed deeper in the profile. The same amount of N distributed evenly throughout the profile did not increase biomass production significantly compared to the BN treatment, although it did produce a growth increase over the control. These results imply that the placement of a soil amendment in the top 10 cm of the profile results in an increase in total plant biomass in the first growing season compared to an even or bottom N placement. Greater above ground biomass will produce greater ground cover, resulting in better soil surface protection. Greater below ground biomass implies a more extensive root distribution which provides structural stabilization to the soil. Both of these phenomena tend to reduce erosion on unconsolidated soils (Hudson, 1971; Gray and Leiser, 1982; Brady and Weil, 1996).

Other researchers have observed an increase in root biomass as a result of stratified N enrichment (Drew, Saker and Ashley; 1973; Drew and Saker, 1975), although these studies were done in solution culture. Our data suggest slightly different results than the two previous studies, perhaps because of the difference in the substrate medium. Since the present study was done in a soil medium, other inputs and variables were likely to be present. Additionally, the inclusion of an organic material in a depauperate soil may create additional effects, such as increased water holding capacity, increased microbial community (enhanced cycling of pre-existing nutrients) increased infiltration, and cation exchange capacity (Brady and Weil, 1996).

It is noteworthy that, although there was no significant difference in total biomass production between species type, the *Elymus glaucus* did produce significantly more root biomass in the 20 - 30 cm layer when that layer was N enriched. This result suggests that the native grass species may root more deeply in response to deeper placement of an organic amendment. This result agrees with observations by Claassen and Marler (1998) using the same soil material and native plant species in comparison to an invasive annual. The 20 - 30 cm layer of the *Elymus glaucus* soils also contained significantly less NO_3 ($p \leq 0.05$) than the *Elytrigia* soil. This phenomenon suggests an ecological strategy whereby the native species is more efficient at scavenging N deep within the profile than is the non-native. One of the arguments against native species is their slow establishment (Van Kekerix and Kay, 1986) and higher cost. However, if native species can subsist on less N or a more diverse distribution of N within the soil profile, better plant community persistence may result in low N soils when using native plantings compared to non-native species. The establishment and growth rate demonstrated in this study also suggests that not all native species are slower to establish, since, in these conditions, both species established and grew at approximately the same rate as demonstrated by the harvest biomass data.

Organic amendment placed in the top portion of the soil profile at the rates used in this study increased biomass production. Increased amendment loading must be done carefully, since excessive amendment may harm seedling growth. A preliminary scoping study using a much higher dose rate of organic amendment exhibited a significant rate of seedling mortality when that amendment was applied to the surface 10 cm. No mortality was observed when that same amount of amendment was placed either in the 20 - 30 cm layer or distributed evenly through the profile. This finding supports field observations that excessive organic amendment applications can have detrimental effects if planted soon after amendment. If the objective is to load the soil with large amounts of organics to recapitalize the degraded substrate, deeper placement may allow greater loading rates without damaging seedlings. Smaller amendments may be most effective when placed at the surface. The overall implication is that as loading rates are calculated for recapitalization of a depauperate soil, deeper mixing of large amounts of materials with high mineralization rates may accommodate the larger rates without reducing seedling establishment and growth.

When calculated on a landscape basis, the total biomass produced was equivalent to 3500 kg dry weight/ha for the TN treatment, 2096 for the EN treatment, 1722 for the BN treatment and 571 kg/ha for the control. This range of biomass production can have important management implications for community establishment. Greater above ground biomass is usually related to greater cover index (Wischmeier and Smith, 1978). Above ground biomass results in more soil surface cover, thereby reducing raindrop impact and related erosional effects (Hudson, 1971; Killham, 1994). An increase in root biomass results in an increase in physical soil stabilization as well as an increase in the microbial population through whose production of extracellular polysaccharides enhances soil structure. These plant inputs also favor the recreation of N cycles by providing substrates for soil microbes (Clark *et al.*, 1985; Paul and Clark, 1989).

Conclusions

The establishment and growth of perennial grass species can be a crucial step in succession on revegetation, erosion control and restoration projects. The amount and placement of a long term supply of nitrogen to those plants can have a crucial influence on the nutrient cycling regime and the ability of those species to compete and persist.

This study suggests that surface organic matter and N amendment placement in the top 10 cm of a degraded granitic soil can significantly increase above- and below-ground plant biomass in native and non-native grass species after one growing season (120 days) compared to deeper placement. Total biomass measurements indicate that these two species do not differentially take up N from the profile. However, when measured on a horizon-by-horizon basis, the non-native species produced significantly more roots in response to shallow organic amendment placement while the native species significantly increased root development in the deeper soil horizons in the bottom amendment treatments. The native species also reduced NO_3 concentrations to a lower level than the non-native species, lowering a potentially leachable form of nitrogen.

Further understanding of placement of and type of organic matter is crucial in our ability to sustainably stabilize disturbed soils in the Sierra Nevada and other similar low nutrient environments. This study confirms a strong influence of organic matter and N amendment placement on plant community establishment.

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Chapter 6. Conclusions, Recommendations, Implementation

Conclusions

This project initially focused on the hardsetting characteristics of decomposed granite (DG) materials. Our review of information on soil aggregate generation suggested, however, that surface application of soil stabilizer materials has only a short term effect on degraded soils. Long-term remediation of hard-setting, non-structured, degraded soil depends on establishing vigorous plant growth, which provides a protective mulch cover and organic matter inputs to the soil. Therefore, the priority of the project was shifted away from addressing only soil physical conditions, toward addressing the conditions required to support sustained plant growth on these nutrient poor, droughty, degraded soil materials. The conclusions presented here generally follow this same thought pattern, first addressing soil aggregate generation, then moving to plant growth requirements and especially soil nitrogen (N) content in soils. Details and references are contained in the body of this report.

Water-stable aggregates

Generation of water-stable aggregates is an important process for remediation of non-structured, degraded soils because aggregation assembles erosion-susceptible clay- and silt-sized primary particles into more erosion-resistant sand-sized particles. Water-stable aggregates are generated in a systematic, hierarchical process of assembly. The predominant method of cohesion is correlated with the average diameter of the aggregate unit. In smaller, microaggregates (< 250 μm), individual particles are bound together by iron and aluminum oxide coatings on clays, by root exudates and by polysaccharides generated by microorganisms during decomposition of plant materials. Larger macroaggregate structures (> 250 μm) are reinforced by fine roots and mycorrhizal hyphae.

Microaggregates are formed most efficiently when energy rich organic materials are dispersed throughout the soil matrix rather than when either synthetic or natural polymers are applied to the soil surface. Once formed, microaggregates persist for long periods of time (for several years) and are resistant to physical forces such as tillage. Macroaggregates, in contrast, are very sensitive to disruption (compaction, loss of plant inputs, physical disturbance) and must be maintained by continuous growth of plant roots and saprophytic and mycorrhizal fungi. Maintenance of a well structured soil, then, requires that a healthy, vigorous plant community exists on the site and provides a consistent source of organic material to be used as an energy source for the aggregation process.

Well developed water-stable aggregates have widely documented benefits for reduction of surface erosion, but they should also be regarded as beneficial for processes within the soil, such as improving water infiltration and percolation into the soil, improving aeration for unrestrained root growth and microbial activity, and for stabilizing organic matter inputs within the soil. These stabilized soil organic matter pools are important for providing nutrient and water retention, and for formation of slowly available reserves of plant nutrients, especially for soil N.

Synthetic polymers can provide a binding of soil particles at the soil surface, but do not create the range of aggregate sizes and functions that are formed by natural processes. Application of synthetic polymers to non-structured substrates merely stabilizes the substrate in the non-structured state.

Plant-soil community N requirements

Sustained plant growth on degraded soils is commonly observed to be limited by nutrients, especially by N. Inputs of N are needed to regenerate the various components of the plant-soil community including shoots, roots, litter and microbial biomass. Literature values from the western U.S. and measurements of Caltrans revegetation sites indicate that the total N contained in the plant-soil community often amounts to 200 to 300 kg N/ha. This amount of N is greater than is supplied by typical revegetation fertilizer application rates. Since degraded soils often have little or no inherent plant available N following loss of the topsoil, approximately this same amount of N must be provided in order to fully regenerate all the components of the new community. Insufficient amendment of N to these systems results in inadequate development of some or all of these plant-soil community components, leading to the often observed thinning of the plant stand, and erosion of the nutrient rich duff and plant litter layers.

This research provides a general quantification of the size of the soil N pools that are correlated to adequate plant cover in the Lake Tahoe area. Previously disturbed but revegetated sites with a percent plant cover > 40 % had an average of approximately 1200 kg total N/ha in the soil (0 - 30 cm depth), providing a large reserve of N. Slightly less than 2 % of this total N was released by mineralization tests, yielding approximately 26 kg N/ha for plant uptake. The N contents of the revegetated soils were more closely correlated to total and mineralizable N measurements than to extractable ammonium or nitrate values, which had little predictive value for percent cover on these sites.

N release rate from amendments

The types of amendment materials that may potentially be used on revegetation sites differ greatly in their N release rates. Results of these experiments suggest that amendments can be grouped into four general categories: 1) soluble chemical fertilizers, 2) slow-release chemical fertilizers, 3) organic materials or 4) unamended plant composts. The ammonium phosphate 16-20-0 formulation, as well as one of the organic based products, exhibited very rapid release rates. Rapid release rates make the N more available for leaching losses or plant uptake by fast growing plants, including weedy species. Depletion of the amended soil N is viewed as a common cause of the decline in plant cover on degraded sites, especially when fertilized only with rapidly soluble fertilizers.

In contrast, the remaining organic materials in the lab study showed extended duration of N release, and are expected to more closely match plant uptake and N incorporation rates. Blends of organically stabilized materials (biosolids composts, agricultural composts or industrial by-products) typically had an initial period of rapid N release followed by a much slower long-term release rate.

Because various organic amendments exhibit a range of N release patterns, different products can be matched to the revegetation N requirements on the site. Rapid establishment of erosion control cover, for example, would benefit from an amendment with a faster release rate. If the objective is to regenerate a slower growing perennial plant cover, an amendment with an extended period of N release would be more effective.

Release rates measured in the field during winter and spring conditions near Livingston, CA were about a third of those measured in the controlled laboratory experiments. Additional data on plant growth rates under site-specific conditions at other locations around the state are needed to improve specification of appropriate amendment materials and loading rates.

Effect of amendment placement on plant growth

Shallow placement (0 - 10 cm) of soil organic materials results in greater N uptake by plants than an even distribution of N through the profile (0 - 30 cm) or deep placement (20 - 30 cm). Placement depth can be used either to increase the efficiency of uptake of N from low yielding amendments or to reduce plant uptake of N from amendments with higher yield rates. Native perennials were observed to extract N to lower solution concentrations and at lower depths in the soil than the non-native perennials, suggesting a potential ecological difference between these two plant groups.

Recommendations

Soil N amendment

The method of providing the N needed to recapitalize the revegetation community can vary depending on the objectives for the site. If a site is intended to sustain vegetative cover indefinitely with little or no further input, then a large, stabilized N pool needs to be established to "capitalize" the N cycle of the plant-soil system. This means a large volume of slowly available N, probably in an organically stabilized form. Composted materials have pools of stabilized, organically complexed N that are released for several seasons and support plant growth through an extended establishment period. Yardwaste compost is a common, easily attainable source for organically stabilized N in large volumes. The compost application rate for a Caltrans project active during this study was 20,000 kg compost/ha (22,400 lb/ac).

Sites in the Lake Tahoe Basin that have revegetated for an average of ten years and have > 40 % cover contain soil organic matter N equivalent to 50,000 to 70,000 kg compost/ha (56,000 to 78,400 lb compost/ac). Because of the cost of application of these large volumes of amendments, lower applications rates may be used and combined with supplemental N sources such as fertilizers or organic soil amendments. The target levels of 200 to 300 kg/ha of available N are still required for development of the plant-soil community. Therefore, combinations of materials with appropriate N release should be selected carefully to provide this total amount of N release during the first 3 to 5 years of establishment. N release rates should be kept low enough that weedy vegetative growth is not encouraged. Because organic amendments provide benefits to degraded soils in addition to N supply, replacement of organic amendments with chemical fertilizers should be done cautiously.

Finally, note that this N target level is for the biologically active components only. It does not account for the inevitable removal of N from plant available forms into soil organic matter. The rate at which this occurs depends on the clay content, mineralogy, topography and microclimate at the site, and it continues until several thousand kg N/ha are incorporated into the soil. Sites in the Tahoe Basin that had greater than 40 % cover, for example, had over 1200 kg total N/ha. This inevitable buildup of soil N must be compensated for by other N inputs (N fixation, atmospheric deposition, organic inputs from surrounding communities) for many years after revegetation is initiated. Further field work is necessary to provide examples of the minimum levels of N incorporation into barren, degraded soils that still allows regeneration of a sustainable plant cover.

Soil aggregate regeneration

Soil aggregate generation by synthetic polymers should be used only as a temporary method to establish revegetation communities on soils with preexisting microaggregate structure. These would be materials with some previous soil development, but that have been disaggregated by handling or tillage. The focus of efforts to stabilize soil structure should be on promoting a thriving, long-term plant community on the site.

Implementation

Results of this study are currently being used for specification of revegetation amendments in the Tahoe area, including projects at Brockway summit (Highway 267), at Dollar Hill (Highway 28), for a cut slope revegetation project for the Incline Village General Improvement District, and for the Mill Creek slide along U.S. Highway 50 near Kyburz, CA. The methods and information are also being applied to revegetation projects for the Lahontan RWCQB at Leviathan Mine, for a California Department of Conservation, Office of Mine Reclamation mine closure project near Marshall, CA and for a USEPA Superfund at Sulphur Bank Mercury Mine near Clearlake, CA.

Results have been presented to national professional meetings (Soil Science Society of America, High Altitude Working Group, International Erosion Control Association), to Society of Ecological Restoration workshops, and to the Lahontan Regional Water Quality Control Board summer 1998 board meeting.

This study formed the background and justification for a cooperative research project between Caltrans and the Integrated Waste Management Board on utilization of compost and co-compost as primary erosion control materials. This subsequent grant continues to develop methods to quantify compost characteristics and to improve specifications for the use of these materials on roadside revegetation projects.

The results of this study have also created a change in Caltrans erosion control specifications. Most current specifications include compost as an organic amendment in erosion control amendments.

This report will be disseminated through normal state and federal distribution channels. It will also be distributed to all district Landscape Architecture and Environmental offices. Copies of the report will be made available for purchase from

Caltrans Publications Unit. Press releases will be sent to trade and professional journals to advertise the availability of this report.