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

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Abstract

Thin, poorly developed soils in the high elevation, summer-dry environment near Lake Tahoe, California are easily disturbed by anthropogenic impacts. Subsoils and parent materials that are exposed by vegetation removal and topsoil erosion or by burial during construction activities are difficult to revegetate and may 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. Field observations suggest that soil disturbance often results in depletion of soil nitrogen (N) reserves and that the remaining substrates may be unable to provide adequate N for revegetation. To quantify the levels of soil N that are associated with higher levels of percent plant cover on previously disturbed soils in the Lake Tahoe area, a basin-wide survey and a second paired site study were conducted. Results indicate that extractable ammonium and nitrate levels correlate poorly with percent vegetative cover, whereas the correlations of anaerobically mineralizable N and total N are stronger and account for nearly 50% of the variability in plant cover data. Sites with plant cover measuring greater than 40% are associated with total soil N levels of about 1,200 kg N/ha and anaerobic mineralizable N levels of about 26 kg N/ha. Despite high concentrations of N in the surface soils, a large fraction of the N in the 0- to 50-cm profile occurs below 30 cm, when measured on a landscape basis.

Key words: **decomposed granite, Lake Tahoe, native plants, nitrogen, revegetation, soil fertility, soil organic matter.**

Introduction

Drastically disturbed soils are those from which topsoil and vegetation have been completely removed, buried beyond the reach of plant roots, or radically altered as a result of construction, logging, mining activity, or natural disturbances such as landslide or flood erosion (Box 1978). The newly exposed subgrade material can be one to many meters beneath the original topsoil. Drastic soil disturbance reduces plant growth through several negative impacts, the most common of which is through the reduction of soil nitrogen (N) levels (Bradshaw & Chadwick 1980; Van Kekerix & Kay 1986; Reeder & Sabey 1987; Munshower 1994). For example, excavation and erosion of cut slopes during highway construction in northern California resulted in removal of topsoils containing total N concentrations greater than 650 mg N/kg soil and exposure of the underlying parent material (the substrate to be revegetated) containing less than 200 mg N/kg substrate (Claassen & Zasoski 1998). These are lower N levels than are reported in many revegetation or restoration studies, which often have total N levels in the high hundreds (Zink et al. 1995) to over 1,000 mg total N/kg (Chambers et al. 1994) in the residual soil materials. Our practical question is how to identify plant growth-limiting conditions on these drastically disturbed substrates and, specifically, how to provide adequate plant available N so that plant growth can commence rapidly, avoiding decades to centuries of soil development.

On drastically disturbed sites receiving conventional revegetation practices with soluble fertilizers, plant cover has often been observed to decline within a few years (Clary 1983; Parks & Nguyen 1984). Low N availability was often cited in these studies as a cause of this decline, as suggested by a strong plant growth response to supplemental N fertilization. However, the duration of the positive growth response to these chemical fertilizers was commonly observed to last only for a few years, followed by a steady decline in plant cover. Lack of long-term vegetative growth in these situations is thought to result from a depletion of plant-available N through leaching of inorganic N from these porous soil profiles, from low mineralization rates resulting from removal of soil organic matter during disturbance, or

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because of high rates of N sequestration into plant litter and soil microbial biomass (Bradshaw et al. 1982; Reeder & Sabey 1987). As N availability declines, reduced plant growth decreases the production of vegetative cover on the site, exposing the soil to increased surface erosion. Decreased input of nutrient-rich plant litter on the soil surface also disrupts a major link in N cycling from plants to soil decomposers and soil N pools. This path is the primary route of N incorporation into the soil from N-fixing shrubs in Oregon systems (Zavitkovski & Newton 1968) and is a critical component for sustained plant growth.

In contrast to the barren, continually raveling disturbed slopes, we observed that adjacent undisturbed sites with adequate soil nutrient pools supported sufficient plant cover and had adequate soil structure to remain uneroded, even at similar steep slope angles. We hypothesized that some approximate level of soil N is needed for adequate plant growth and that vegetative cover varies with soil N pool size. Analysis of soil N pools from a variety of sites was initiated to characterize the approximate pool sizes that are associated with adequate revegetation cover. Because N is held within the soil in a variety of chemical forms, we used several common operationally defined measures of soil N to estimate soil fertility and to evaluate which soil N pools may be correlated with plant cover on these disturbed wildlands sites. For this study, evaluation of soil N pools were emphasized, rather than evaluation of inputs from N fixers, because these symbionts are not common invaders of degraded sites in the Lake Tahoe area and because rates of N incorporation by N-fixing plant species are not well documented on harsh degraded sites.

These data are expected to guide the development of amendments for revegetation and reestablishment of N cycles on drastically disturbed sites, in particular those having little or no soil development and extremely low soil N levels. Although this study focused on soil N levels, we recognize that water, other nutrients, microclimate, soil microbial populations, and continued disturbances also strongly influence plant growth. Amendment of soil N to adequate levels is anticipated to reduce the predominance of N deficiency among the multiple conditions that may potentially limit plant growth on disturbed sites in the Tahoe Basin.

The specific objectives of this study, then, were to measure the correlation of percent plant cover with several operationally defined soil N pools in this environment and to compare the size of the N pools of these Tahoe area soils to literature values of soil N associated with sustainable plant communities from other sites with drastically disturbed soils.

Methods

Site Selection

Basin-wide Survey. During the summer of 1995, 30 widely distributed revegetated sites were selected within the Lake Tahoe Basin and nearby areas. Locations included sites at various elevations along the southeast, south, west, and north shores of Lake Tahoe. All sites had been subjected to some level of disturbance, including highway cut and fill slope construction, ski run grading, forest or logging road construction, or grazing (Table 1). Since disturbance, however, the sites had revegetated to some level of plant cover.

The site selection criterion was that at least three years had elapsed since the disturbance event, so that plant growth patterns would reflect ambient soil nutrient levels and not transitory fertilizer inputs. Other similar sites along roadcuts were observed to decline within two years after fertilizer inputs (Leiser et al. 1974), so the sites that were selected were viewed as producing biomass reflecting the ambient soil fertility of the site, not the effects of residual fertilizer materials, if applied. Average time since disturbance was estimated at nearly 10 years, with a range of 3 to 25 years. Because disturbance history was often not well known, successional time was not among the factors considered. Also, because the focus of the study was on soil N pool contents and their association with different levels

Table 1. Characteristics of Tahoe area basin-wide survey sites (type of site characteristic followed by percentage of total sites with that characteristic).

Parent Material	*%*	*Elevation (m)*	*%*	*Slope (degree)*	*%*	*Aspect*	*%*	*Disturbance Type*	*%*
Volcanic	44	1,900–2,000	36	<10	54	N (316–45°)	33	Road sides	40
Granitic	23	2,001–2,100	10	11–20	13	E (46–135°)	20	Ski areas	33
Alluvial	33	2,101–2,200	27	21–30	13	S (136–225°)	27	Logging roads	20
		>2200	27	31–50	20	W (226–315°)	20	Grazed areas	7

of plant cover, communities dominated by N-fixing plants were excluded from the survey.

Three types of soil parent materials were sampled (volcanic, granitic, and alluvial) from sites ranging between 1,890 and 2,200 m (6,200 and 7,200 ft) elevation. Slope angles ranged between 2 and 50 degrees above horizontal.

Plant cover was used as an empirical indicator of that site's inherent fertility and ability to sustain growth of a vegetative community. Typical vegetation cover was composed of grasses, *Elymus elymoides* (squirreltail), *Achnatherum* spp. (needlegrass), *Festuca trachyphylla* (hard fescue), *Elytrigia intermedia* (intermediate wheatgrass), and *Elytrigia pubescens* (pubescent wheatgrass); forbs, *Gnaphalium cansecens* (everlasting) and *Achillea millifolium* (yarrow); and shrubs, *Arctostaphylos nevadensis* (pinemat manzanita). Native and introduced grass species did not appear to segregate according to soil nutrient levels in the basin-wide survey sites, although this question was more specifically addressed in the paired site study.

Paired Site Study. To test correlation trends that were observed in the basin-wide survey, two additional sets of sites were evaluated using more intensive sampling. Paired sites were selected that were located on two ski areas on the North Shore area of the Lake Tahoe Basin. Northstar-at-Tahoe is situated near the summit of Mt. Pluto, a volcanic formation that, along with several other volcanic peaks, defines the northern end of the Lake Tahoe Basin. 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. The paired sites had contrasting parent materials (granitic and volcanic) but similar slope angles (1 to 7 degrees), aspect (N to NW), elevation (2,150 to 2,375 m [7,100 to 7,800 feet]), and disturbance history (surface grading was completed 4 to 10 years previously).

Plant Cover Measurement

For the basin-wide survey, suitable plant communities of approximately 1,000 m^2 or greater were located and a 20-m line transect was randomly oriented within the area. Percent plant cover was estimated by point intercept of the plant canopy along the transect (Elzinga et al. 1998).

For the paired site study, plant cover was evaluated using two 10-m line transects. Sites were categorized into one of three plant cover classes: less than 10%, 10% to 40%, and more than 40% plant cover. The cover ranges were based on erosion control effects of vegetative cover, as suggested by Osborn (1954), and on visual determination of the range of revegetating plant communities typical of these sites. Plant communities with less than 10% and 10% to 40% cover contained predominantly non-native species. Among plant communities with over 40% cover, sites were sampled in which native species contributed more than 60% of the cover, contrasting with other sites that contained predominantly non-native species compositions. Native species were predominantly *Elymus elymoides*, *Achnatherum* spp., and *Poa* spp. Non-native species were typically *F. trachyphylla*, *Elytrigia intermedia*, *Elytrigia pubescens*, and *Dactylis glomerata*.

Soil Sample Collection and Analysis

In the basin-wide survey, soil samples were collected from 0- to 10- and 20- to 30-cm depths from five locations at 5-m intervals along the plant transect. Soils were sampled from the top of the mineral soil horizon downward to the specified depth and were composited from several sides of the sample pit. Soils from the paired site study were evaluated by sampling a total of five individual cores spaced at five 2-m intervals along the 10-m transect. Each pit was sampled at five depths: 0 to 2, 2 to 10, 10 to 20, 20 to 30, and 30 to 50 cm, allowing a detailed analysis of soil N. At each site, 75 samples of soil were taken. 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). Soil N concentration values were then prorated for the number of centimeters in the measured horizon and summed for a 30- or 50-cm deep profile. All data were expressed on a landscape basis (kg N/ha) after correction for coarse fragments and bulk density.

Because many California soils are naturally air dried in the field during summer, all samples were dried at 40°C to a constant weight to standardize sample moisture and preparation. The use of a relatively low drying temperature minimizes loss of volatile forms of N (Anderson & Ingram 1993). After drying, soils were sieved to less than 2 mm for nutrient analysis and the fine soil fraction of the whole soil was calculated by weight ($<$2 mm fraction/whole soil weight).

Soil materials collected from both studies were analyzed for three operational soil N pools: (1) extractable ammonium and nitrate-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 somewhat longer periods (anaerobic, 40°C, 1 week; Keeney 1982); and (3) total N and total C by dry combustion (Dumas 1831)/gas chromatography/thermal conductivity detection (Carlo Erba NA 1500).

The anaerobic mineralizable N method is commonly used as a biological index of soil N availability, in which anaerobic microbes metabolize organic matter in the sample and release organically bound N into inorganic forms (Keeney 1982). Although developed for use with agricultural systems, it has been applied to wildlands soils as well (Shumway & Atkinson 1978; Powers 1980; Myrold 1986). Soluble ammonium and nitrate were measured by continuous flow conductometric analysis of KCl-extracted ammonium with reduction of nitrate to ammonium in a copper-coated zinc column (Carlson 1978, 1986).

Non-nitrogen soil nutrient tests included standard fertility assays for phosphorus (weak Bray and bicarbonate extracts), nutrient cations, sulfate-sulfur and cation exchange capacity (neutral ammonium acetate), pH and electrical conductivity (saturated paste), and micronutrient availability (diethylenetriamine pentoacetic acid; A & L Western Agricultural Laboratories, Inc., Modesto, CA, U.S.A., soil test suite S3C).

Statistical Analysis

Data were checked for normal distribution by the Kolmogorov-Smirnov two-sample test and were analyzed without transformation. Data from the basin-wide survey were evaluated by correlation, because soil N and plant cover data were interval values and neither variable was controlled by site selection (Afifi & Clark 1984). Non-N soil nutrient and chemical data were correlated with plant cover in the same way. Data from the paired site study were evaluated by analysis of variance, because sites with similar plant cover variable were grouped arbitrarily (<10%, 10% to 40%, and >40%). Means of N pools for each plant cover class were separated by least significant difference at the 0.05 level of significance (Statistica, StatSoft Inc., Tulsa, OK, U.S.A.).

Results

Basin-wide survey

Data from the initial basin-wide survey are graphed in Figure 1. These data indicate that percent plant cover is most strongly correlated with mineralizable N ($r^2 = 0.470$; $p < 0.000$) and total N ($r^2 = 0.464$; $p < 0.000$). Percent plant cover is less well correlated with extractable ammonium ($r^2 = 0.396$; $p = 0.000$). Even though the extractable ammonium data are numerically correlated with percent plant cover, this parameter is an insensitive indicator of vegetation trends, as shown by the very low slope of the regression line against vegetation cover. Extractable nitrate is poorly correlated with percent plant cover ($r^2 = 0.028$; $p = 0.385$). The first three N availability graphs are shown with the same vertical scale to contrast the slopes of the regression lines.

Results from correlation analysis of non-N nutrients with percent plant cover data are presented in Table 2. All macronutrients other than N (including P, K, Ca, Mg, and sulfate-S) have correlation values with percent plant cover that are less than 0.144, which was measured for weak Bray phosphorus extraction. Because the regression line for plant-available P remains above 15 μg extractable P/g soil for all levels of plant cover, available P is interpreted as being adequate for plant growth even at the poorly vegetated sites.

The highest coefficient of determination for the micronutrients and percent plant cover is measured for DTPA extractable iron ($r^2 = 0.199$). However, because the extracted levels for plant-available iron range from 15 to 30 μg Fe/g soil between low and high plant cover, which is in the medium to high range for agricultural plants, Fe levels are therefore interpreted as not limiting plant growth. DTPA extractable Zn is generally low in comparison with agricultural standards, but the correlation to differences in plant cover is poor ($r^2 = 0.144$).

Sand content decreases and silt content increases significantly between low and high plant cover, suggesting a role of soil texture in influencing plant cover, although the correlation is low ($r^2 = 0.104$ for sand and $r^2 = 0.147$ for silt). Content of clay, the primary source of water retention capacity, however, does not differ

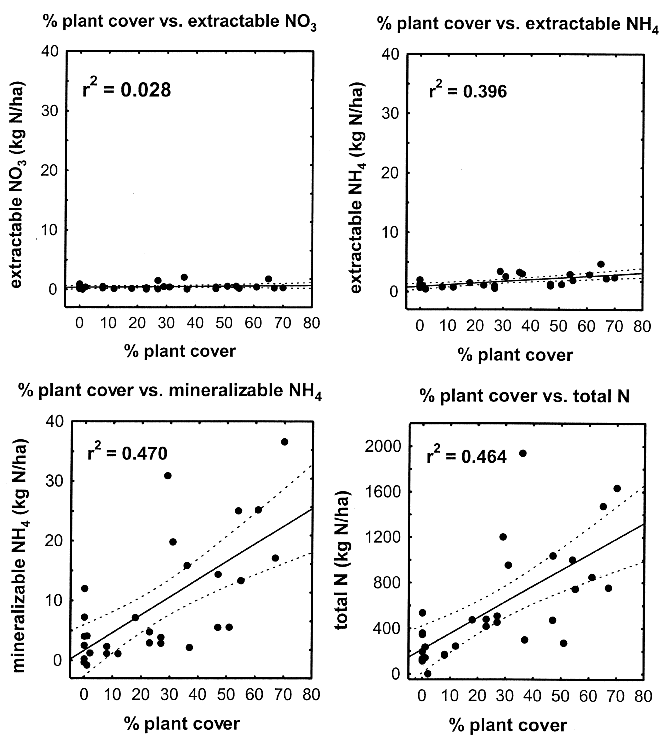

Figure 1. Correlation between percent plant cover and four operationally defined soil N pools, including extractable NO_3^-, extractable NH_4^+, anaerobically mineralizable NH_4^+, and total N.

with plant cover. Although the potential for other factors to influence plant growth is not discounted, no other measured parameters appear as strongly associated with plant cover as soil nitrogen. Therefore, while we recognize the need for all plant growth conditions to be sufficient for plant survival, we interpret these data to indicate that soil nitrogen content is well correlated with plant cover data and that these correlations are not overwhelmingly influenced by other plant nutrient conditions.

Paired Site Study

Soil N pools from the more intensively sampled paired site study (Figs. 2 and 3, Table 3) showed the same trends as in the broader scale basin-wide survey. Mineralizable N and total N both increase as vegetative cover increased in both the granitic and volcanic parent materials. Mean mineralizable N and total N are significantly different ($p < 0.05$) for all cover classes. Although extractable ammonium and nitrate also show significant differences between cover classes, they do not vary in proportion to vegetative cover and are not similar between the two parent material types.

The numerical values for the paired site samples are listed in Table 3 and are summed for both the 0- to 30-cm horizons and 0- to 50-cm horizons. Nitrogen contents in soils of sites supporting more than 40% plant cover of predominately native species do not differ significantly from soils supporting more than 40% cover of non-native species. The two plant community types are combined for subsequent analyses in Table 3.

Table 2. Summary of coefficient of determination (r^2) and slope significance data (p) for relationships between plant cover with non-nitrogen nutrients and soil characteristics from the basin-wide survey.

Soil Variable	r^2	p
Weak Bray P extract	0.144	0.046
Bicarbonate P extract	0.034	0.341
Extractable K	0.074	0.161
Extractable Mg	0.038	0.315
Extractable Ca	0.123	0.066
Extractable Na	0.005	0.704
Sulfate S	0.001	0.871
pH	0.009	0.617
Electrical conductivity	0.014	0.543
Cation exchange capacity	0.108	0.087
Extractable Zn	0.114	0.079
Extractable Mn	0.037	0.322
Extractable Fe	0.199	0.017
Extractable Cu	0.076	0.154
Extractable B	0.103	0.095
% sand	0.104	0.094
% silt	0.147	0.044
% clay	0.038	0.314

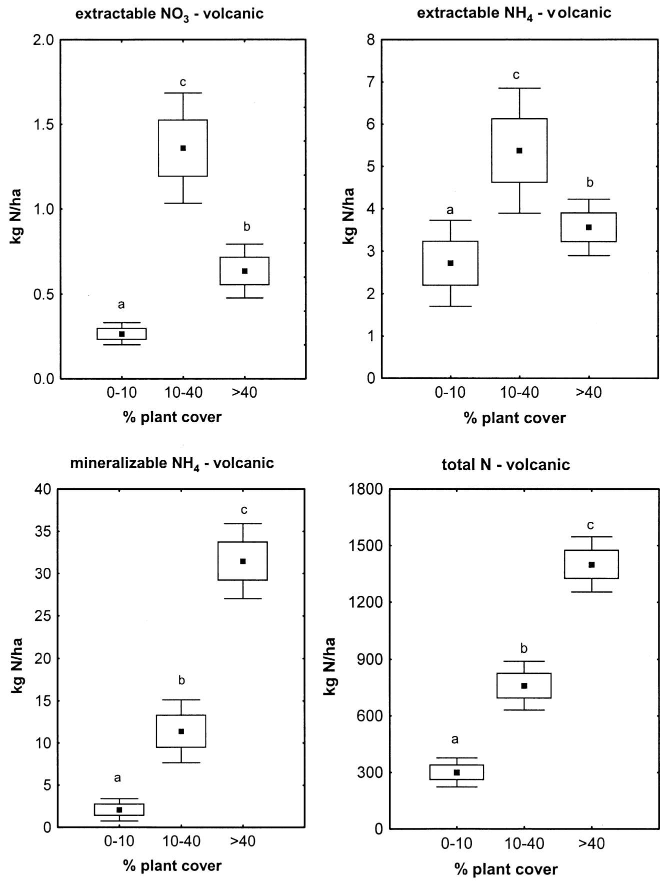

Figure 2. Soil N pools (extractable NO_3^-, extractable NH_4^+, anaerobically mineralizable NH_4^+, and total N) from soils under three plant cover classes on volcanic substrates (0- to 30-cm depth). Data points capped by similar letters do not statistically differ at the 0.05 level of significance. Box around mean indicates 1 standard error; brackets indicate 1.96 standard error.

Discussion

Comparison of N Levels Between Sites

Nearly half of the variability in percent plant cover measured on revegetated sites in the basin-wide survey in Lake Tahoe area is related to soil nutrient pools of mineralizable N or total N (Fig. 1). The commonly used indicators of soil fertility, extractable ammonium and nitrate, show a poorer relationship to plant cover. Correlation of plant cover with extractable N is probably low because this N pool is maintained at low levels by plant uptake at many different levels of plant cover or because of rapid leaching rates. Although the extractable ammonium correlations are numerically significant, they vary by less than 2 kg N/ha over the entire range of percent plant cover. These slight differences are difficult to distinguish during analysis of heterogeneous field samples.

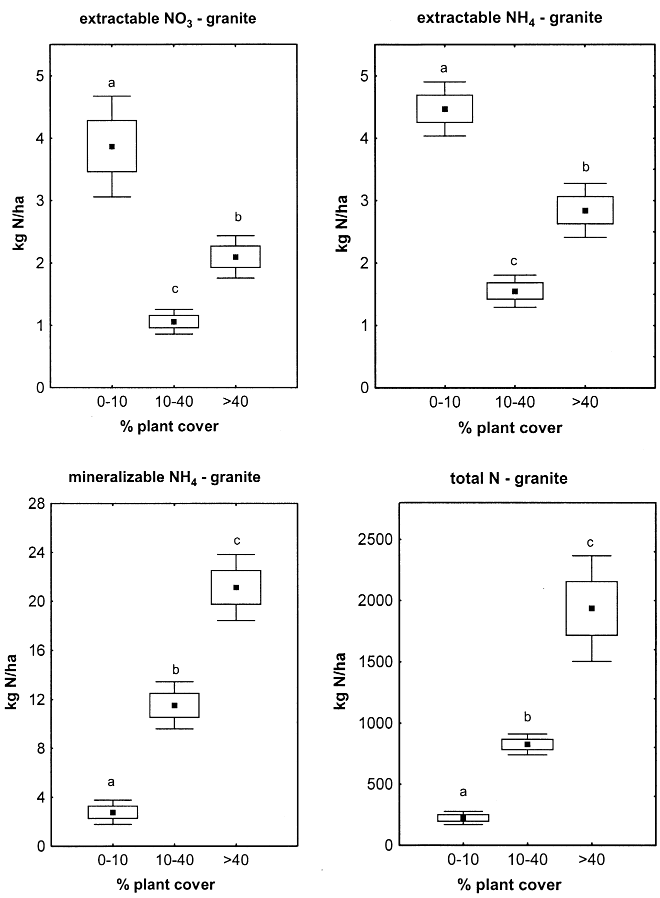

Figure 3. Soil N pools (extractable NO_3^-, extractable NH_4^+, anaerobically mineralizable NH_4^+, and total N) from soils under three plant cover classes on granitic substrates (0- to 30-cm depth). Data points capped by similar letters do not statistically differ at the 0.05 level of significance. Box around mean indicates 1 standard error; brackets indicate 1.96 standard error.

Slopes of the regression lines of mineralizable N and total N from the basin-wide survey are much steeper than for KCl extractable N because of greater differences between sites with low and high plant cover. They also show much greater variation about the regression line. Some of the distribution above and below the regression line can be interpreted on the basis of characteristic landscape positions of individual sample locations (data not shown). For example, sites with less plant growth than expected relative to the level of N measured in the soil (points left of the regression line) are typically from locations at which plant growth was frequently impacted by traffic or by physical movement of the substrate. Examples are sites with adequate soil fertility but frequent foot traffic or the nutrient rich but physically unstable band of residual topsoil at the top of over-steepened cut slopes. Conversely, sites in foot-slope positions or in 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 may have acquired N from overland flows during spring snowmelt and run-off or from subsurface N sources located beyond the sampled soil profile. Other sources of variation involve problems of sampling heterogeneous soils having both horizontal and vertical variation and uneven distribution of coarse fragments.

Plant cover and soil mineralizable and total N relationships in the paired site study are similar to relationships observed in the basin-wide survey, even though the two parts of the study examined different locations at different sampling methods. Plant cover increases as N contents increase, supporting the hypothesis that soil N is positively related to plant cover at these sites.

Table 3. Summary of soil N pools in the 0- to 30 or 0- to 50-cm depths after correction for bulk density and coarse fragment contents.

	Parent material					
	Granite			*Volcanic*		
	<10%	*10–40%*	*> 40%**	*<10%*	*10–40%*	*> 40%*
Extractable nitrate						
0–30 cm	3.9a	1.1c	2.1b	0.3a	1.4c	0.6b
0–50 cm	6.7a	1.1c	2.4b	0.7a	2.0c	0.8b
Extractable ammonium						
0–30 cm	4.5a	1.6c	2.9b	2.7a	5.4c	3.6b
0–50 cm	6.7a	2.2c	4.2b	4.8a	8.5c	5.5b
Mineralizable nitrogen						
0–30 cm	2.8a	11.5b	21.1c	2.1a	11.4b	31.4c
0–50 cm	4.3a	17.3b	26.2c	3.1a	15.9b	42.3c
Total nitrogen						
0–30 cm	224a	824b	1936c	330a	760b	1241c
0–50 cm	408a	1237b	2656c	585a	1076b	1898c

All values are expressed in kg N/ha for the soil profile to the indicated horizon depth. Values within each row for each parent material that are followed by similar letters do not differ significantly ($p < 0.05$). *Data include one colluvial soil.

The more intensive sampling density of the paired site study allowed us to characterize soil N and vegetative cover relationships more closely and to estimate the soil N that is associated with greater levels of plant cover. Part of the challenge of characterizing soil N pools involves viewing the soil resource on a landscape basis, including compensating for varying amounts of nutrient concentrations, coarse fragments, and rooting volumes. For example, N concentration in the fine soil fraction of the over 40% cover site on the volcanic soil is about 4.7 times greater in total and mineralizable N than the granitic soil (data not shown). However, after correction for landscape effects (bulk density and fine soil fraction), the total N in the 0- to 30-cm profiles of the over 40% vegetative cover plots does not significantly differ between the granitic and volcanic parent materials ($p = 0.318$). Mineralizable N levels also do not significantly differ between parent materials ($p = 0.620$). The rooting volume of these paired sites (contrasting parent material but similar elevation, slope angle, plant type, and disturbance history) appears to contain approximately equal soil N in these two nutrient pools.

The proportion of the total N pool that is mineralizable differs for the various plant cover classes. Mineralizable N is about 1.7% of total N in the over 40% sites (both parent materials combined). It declines to 1.4% of the total N on the 10% to 40% cover samples and is 0.9% on the less than 10% cover samples (calculated from Table 3). Not only is the absolute size of the total N pool smaller on the poorly vegetated site, but the percentage of the total N that was mineralized by this method is also smaller.

The less than 10% cover class (both parent materials combined) is the only group that has less mineralizable N than extractable N, by these operational analyses. Sites in higher vegetation classes have the opposite pattern, with an average of 6.5 times more mineralizable N than extractable N. The characteristic pattern of soils that have pools of short-term (extractable) N but little or no longer-term N reserve (mineralizable or total N pools) has been observed on other drastically disturbed sites (Noyd et al. 1996). Soils with this pattern of N pool distribution are expected to have low potential for sustained revegetation unless the required N is regenerated through repeated fertilization (Bloomfield et al. 1982), N fixation, or regeneration of the soil organic matter pools by accumulation or by amendment.

Estimates of soil N contents that are available for plant growth are partly a function of the depth included in the soil evaluation. Total N summed for the 0- to 50-cm depth was 48% greater than for the 0- to 30-cm profile. Mineralizable N is 41% higher for the 0- to 50-cm soil compared with mineralizable N for 0 to 30 cm. Because roots are commonly observed to 50-cm depth and deeper, the N available to the plant community is therefore larger than just that measured in the 0- to 30-cm profile. To allow comparison with other published literature values, however, our soil N content data are expressed for a standardized 30-cm depth. Although these data can be used as an index of adequate fertility at a site, analysis of the whole plant and soil system should account for the greater rooting depth and increased soil N resource.

Based on the paired site study data, soil total N levels on sites with higher cover percentages are estimated to range from 792 kg total N/ha (the average for the 10% to 40% class, both parent materials combined) to 1,228 kg total N/ha (the average for the >40% class). Mineralizable N thresholds for adequate plant cover are estimated to range from 11 (the average for the 10% to 40% classes) to 26 kg mineralizable N/ha (the average for the >40% cover classes). For interpretive purposes, one of the more than 40% cover sites on granite parent materials is omitted from this summary data set because it is located in a colluvial landscape position and is atypically deep compared with other soils in the region.

Comparison of Soil N Levels with Other Disturbed Soil Studies

Estimated total N and mineralizable N values in this study are similar to concentrations reported in other studies of diverse plant community established on drastically disturbed sites. 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 plants and soils combined). Nearly 1,200 kg total soil N/ha accumulated in the soil before the sites were colonized by oak and birch species (Marrs et al. 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- to 30-cm depth, assuming a 50% fine soil fraction) and 1,090 kg N/ha at 51 years (Leisman 1957). On a Minnesota taconite ore spoil, Noyd et al. (1996) measured plant cover of 73% after 3 years with an initial compost amendment containing 986 kg total N/ha. A smaller compost amendment rate provided 493 kg N/ha and resulted in a plant cover of only 59%. 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- to 10-cm depth only and would be higher for a standardized 0- to 30-cm profile.

In 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- to 9-cm depth, 60 to 70 years after glaciation) and 533 kg total N/ha for the spruce stage (0 to 15 cm, 200 to 225 years after glaciation) (Chapin et al. 1994). Earlier work in the same area produced an estimate of 1,200 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- to 30-cm soil profile, a target threshold value in the high hundreds to around 1,000 kg total N/ha appears to be the size of the total N pools that mineralizes sufficient plant-available N to support a diverse permanent plant community.

Studies on relatively undisturbed California soils report slightly larger soil N pools. A fertile, grazed, but untilled soil under a blue oak (*Quercus douglassii*) and annual grass (*Avena, Bromus*) plant community from the foothills of northern California accumulated 2,920 kg total N/ha (0 to 30 cm) but had only 57 kg mineralizable (plant available) N/ha (0 to 20 cm 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 at the San Joaquin Experimental Range had an estimated 3,200 kg total N/ha (0 to 30 cm) with 90 kg mineralizable N/ha and less than 1 kg extractable N/ha (Woodmansee & Duncan 1980).

This pattern of large total soil N and relatively small mineralizable soil N pools is interpreted as contributing to the long-term productivity of perennial plant communities by providing both a sizable reserve of organically stabilized N and a low annual percentage yield of mineralizable N from the organic N pool. Our interpretation of the commonly observed thinning of roadside vegetation within a few years after amendment with chemical fertilizers is that both the longevity and the absolute amount of plant-available N is insufficient to provide for establishment and maintenance of the plant and soil microbial community.

We recognize that reconstruction of plant-soil communities is an open-ended process that is influenced by a wide variety of external conditions and that, once established, the community remains in a state of dynamic flux (Aronson et al. 1995). For this reason, the soil N values measured in this study should not be viewed as exact target values, because local climate, slope geometry, plant type and recruitment, and subsequent disturbance will influence the interaction of plants with the underlying soils. Comparison with suitable reference communities (Parker & Pickett 1997) suggests that soil N levels sufficient to support vegetative cover are much larger than are often provided during fertilizer amendment to these types of degraded sites. Inclusion of N-fixing species in the planting mix is expected to lower the amount of N required from soil N pools to achieve a given level of vegetative cover. However, the actual rate of N-fixation on these low nutrient, high elevation, xeric soils is not currently well documented.

Conclusions

Total N and mineralizable N pools in the soil are more strongly correlated with percent plant cover than are extractable ammonium or nitrate pools. Nearly half of the variation in vegetative cover data in this study is correlated with trends in total and mineralizable N. Vegetative cover of more than 40% is associated with soil N levels (0- to 30-cm depth) of an estimated 1,228 kg total N/ha and 26 kg mineralizable N/ha (both parent material types combined). Although volcanic and granitic parent material soils had very different concentrations in the less than 2-mm fraction, landscape measures of soil N levels in the two parent material types do not differ significantly when corrected for soil bulk density, fine soil fraction, and soil horizon depth.

Although these correlations do not establish that N is the single factor limiting plant growth on these sites, the relationship suggests that soil N is an important variable in revegetation after disturbance and that large stabilized total soil N pools with relatively low mineralization rates are typical for soils supporting sustained vegetative cover. The values suggested by analysis of these Tahoe Basin sites or other appropriate local reference communities can be used to screen for less disturbed sites that may still retain their soil N reserves and can be successfully treated only with surface mulches and appropriate plant materials.

We anticipate that if barren disturbed sites are provided with adequate stabilized soil N, many will be able to support a sustainable plant cover that is dense enough to resist erosion and that can continue to rebuild the soil, allowing the site to develop along one of many potential successional paths. With inadequate soil fertility, however, the combination of insufficient plant cover and continued soil erosion may restrict the site to a regressive successional path of further nutrient loss and a return to a barren condition.

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