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ORIGINAL ARTICLE

Development and application of a soil organic matter-based soil quality index in mineralized terrane of the Western US

S. W. Blecker · L. L. Stillings · M. C. Amacher · J. A. Ippolito · N. M. DeCrappeo

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Abstract Soil quality indices provide a means of distilling large amounts of data into a single metric that evaluates the soil's ability to carry out key ecosystem functions. Primarily developed in agroecosytems, then forested ecosystems, an index using the relation between soil organic matter and other key soil properties in more semi-arid systems of the Western US impacted by different geologic mineralization was developed. Three different sites in two different mineralization types, acid sulfate and Cu/Mo porphyry in California and Nevada, were studied. Soil samples were collected from undisturbed soils in both mineralized and nearby unmineralized terrane as well as waste rock and tailings. Eight different microbial parameters (carbon substrate utilization, microbial biomass-C, mineralized-C, mineralized-N and enzyme activities of acid phosphatase, alkaline phosphatase, arylsulfatase, and fluorescein diacetate) along with a number of physicochemical parameters were measured. Multiple linear regression models between these parameters and both total organic carbon and total nitrogen were developed, using the ratio of predicted to measured values as the soil quality index. In most instances, pooling unmineralized and mineralized soil data within a given study site resulted in lower model correlations. Enzyme activity was a consistent explanatory variable in the models across the study sites. Though similar indicators were significant in models across different mineralization types, pooling data across sites inhibited model differentiation of undisturbed and disturbed sites. This procedure could be used to monitor recovery of disturbed systems in mineralized terrane and help link scientific and management disciplines.

Keywords Soil quality · Organic carbon · Total nitrogen · Soil enzymes

S. W. Blecker (✉) · L. L. Stillings
USGS, 1664 N. Virginia St., MS-176, Reno, NV 89557, USA
e-mail: steven.blecker@gmail.com

M. C. Amacher
US-Forest Service, 860 N 1200E, Logan, UT 84321, USA

J. A. Ippolito
USDA-ARS, 3793 N 3600E, Kimberly, ID 83341, USA

N. M. DeCrappeo
USGS, 3200 SW Jefferson Way, Corvallis, OR 97331, USA

Introduction

The myriad definitions of soil quality generally involve soil function, e.g., the ability of a soil to support vegetative diversity and biomass, or the ability of a soil to sustain itself through nutrient cycling (Doran and Parkin 1994; Karlen et al. 1997). Many studies have attempted to quantify soil quality, with respect to its functions, in order to evaluate the impact of natural and anthropogenic disturbances. In terrestrial ecosystems, indices initially developed for agroecosystems (Doran and Parkin 1994) have been increasingly applied to non-agricultural systems (Bastida et al. 2008). Though not without their limitations (Sojka and Upchurch 1999), soil quality determinations can improve our understanding of the controls behind ecosystem processes and allow for the distillation of information to help link scientific and management disciplines.

Soil quality indices (SQIs) are generally composed of a mixture of biological and sometimes physicochemical

parameters that attempt to reduce the complexity of a system into a metric of a soil's ability to carry out one or more functions (Papendick and Parr 1992; Halvorson et al. 1996). Effective SQIs should correlate well with soil or ecosystem processes, integrate those properties and processes, and be responsive to management practices (Doran and Parkin 1996; Dalal 1998; Nortcliff 2002) or anthropogenic disturbance. Studies utilizing simple ratios, such as the metabolic quotient, qCO_2 (quantity of mineralized substrate/unit of microbial biomass carbon/unit of time) and enzyme activity/total C, are generally too simplistic and often difficult to interpret (Gil-Sotres et al. 2005). However, these same indicators, when combined with other measures such as organic matter content, and microbial activity, form the core of many SQIs (Sikora and Stott 1996). One particular approach to SQIs involves the use of multiple linear regression (MLR) to predict soil total organic carbon (TOC) or total nitrogen (TN) based on significant soil biological and abiotic drivers and has been used to compare soil quality between disturbed and undisturbed reference soils (e.g. Trasar-Cepeda et al. 1998; Zornoza et al. 2007; Chaer et al. 2009). This method can be used as a means of monitoring changes to a system by comparing predicted versus measured values of either TOC or TN. Values greater or lower than the ratio established for undisturbed or reference sites can indicate the degree of disequilibrium caused by a disturbance to the system. This approach also shows the utility of multi-parametric approaches over single indicators, which can produce inconsistent results (Trasar-Cepeda et al. 1998; Gil-Sotres et al. 2005).

Commonly applied SQI biological indicators are associated with microbial activity and function (e.g., mineralization, respiration, microbial biomass, enzyme activity; Winding et al. 2005). Abiotic indicators can provide context to more clearly interpret the biological measures, but are less commonly included in SQIs. Cost, accessibility, ease of interpretation, and presence of existing data often dictate indicator selection. Thus, the parameters chosen for SQIs can be as varied as the studies themselves, reflecting the complexity of the soil and ecosystems within which they function.

In this study, a soil organic matter-based SQI was applied in undisturbed and mining disturbed areas in semi-arid ecosystems of the Western US, using sites of varying climate, vegetation, and trace metal chemistry to examine relations between TOC and TN and microbial/physico-chemical properties. Standardizing this procedure across diverse ecosystems (which is typically lacking; Gil-Sotres et al. 2005) could allow for more equivalent comparisons among systems of varying trace metals, climate and vegetation, and be used to monitor recovery of disturbed systems in mineralized terrane.

Materials and methods

Acid sulfate mineralization (Castle Peak and Masonic Mining District)

The Castle Peak study site was located east of Reno, NV (39.48°N, 119.7°W) at an average elevation of 1,350 m, with a mean annual precipitation (MAP) and a mean annual temperature (MAT) of 185 mm and 10.4 °C, respectively. The Masonic study site was located northeast of Bridgeport, CA (38.40°N, 119.1°W) at an average elevation of 2,125 m, with an MAP and MAT of 210 mm and 5.0° C, respectively. Both of these sites are located in the Mono Section of the Temperate Desert Division (Bailey et al. 1994). In both locations, epithermal alteration has resulted in acid sulfate gold mineralization, characterized by argillic alteration and abundant alunite. Soils developed within the mineralized areas are characterized by low pH and fertility and high Al (Schlesinger et al. 1989). The open woodland vegetation (*Pinus jeffreyi, Pinus ponderosa, Eriogonum robustum*) of the mineralized + undisturbed sites provided stark contrast to the adjacent sagebrush shrubland (*Artemesia* sp.) of the unmineralized + undisturbed sites that have developed on andesite. Waste rock and tailings were sampled at abandoned Hg and ferricrete mines within the Castle Peak site and precious-metal mines at the Masonic site (Blecker et al. 2010).

Cu/Mo porphyry mineralization (Battle Mountain Mining District)

The Battle Mountain study site was located southwest of Battle Mountain, NV (40.57°N, 117.1°W) at an average elevation of 1,380 m, with an MAP and MAT of 210 mm and 9.5 °C, respectively. The mineralized + undisturbed area at this site consisted of stockwork veinlets of quartz, chalcopyrite, and molybdenite surrounding a felsic porphyritic intrusion (Theodore et al. 1992). The surrounding unmineralized + undisturbed area was dominated by interbedded arenites, shale and greenstone of the Paleozoic Harmony Formation (Theodore et al. 1992). As the sagebrush communities (*Artemisia* sp.) on both the altered and unaltered rock did not differ visually, we utilized extensive mapping of mineralized terrane from Theodore et al. (1992) to determine appropriate sampling areas. Waste rock and tailings were sampled in areas of abandoned precious-metal mines (Blecker et al. 2010).

Study design/field sampling

At each of the three study sites, soil quality was evaluated for four different sample areas: (1) unmineralized + undisturbed by mining, (2) mineralized (geologically

enriched in metal-bearing elements) + undisturbed by mining, (3) waste rock (material removed and transported during mining operations), and (4) tailings (material removed and transported during mining operations further impacted by other physical and chemical activity such as crushing and leaching). Waste rock and tailings have also been subjected to other alterations such as change in soil structure and density, loss of organic matter and nutrients, and change in pH, which in concert can adversely impact above- and below-ground biota. Three random locations within each sample area were situated on a similar aspect (150°–210°), elevation, and slope within the same sub-watershed. At each of these locations, three 30 m transects (spaced 120° apart) were randomly established. One soil sample (0–15 cm in depth) was taken at a random position along each transect for a total of 9 samples (3 samples × 3 locations) per sample area, at each of the three study sites. The soil surface was cleared of any litter prior to soil sampling. Soil samples were stored at 4 °C in the field and passed through a 2-mm sieve upon return to the laboratory. A separate soil core sample (0–15 cm in depth) for measurements of bulk density and soil moisture was collected using a slide-hammer. Sites were sampled one time in the spring of 2008 near peak soil moisture/microbial activity.

Soil microbiological analyses

Soil quality indicator variables included:

- Analyses for C and N mineralization potential provide a general measure of microbial activity and the ability of the microbial community to generate plant-available N.
- Enzyme assays for the S-cycle (arylsulfatase activity) and P-cycle (acid and alkaline phosphatase activity) focus on specific nutrients, while fluorescein diacetate (FDA) is a more general indicator of enzyme activity that is hydrolyzed by a number of different enzymes (protease, lipase, and esterase; Green et al. 2006).
- C substrate utilization provides a qualitative measure of bacterial community activity and functional diversity using Biolog EcoPlates (Biolog Inc., Hayward, CA, USA) that contain various C sources, including polymers, carbohydrates, carboxylic acids, amino acids and amines/amides.
- Phospholipid fatty-acid (PLFA) provides an estimate of microbial community structure and biomass-C. Certain lipid "signatures" within the cell membranes of living microbes can be used to identify a portion of the microbial community: gram + and gram − bacteria, fungi, actinomycetes, and protozoa (Sinsabaugh et al. 1999).

Carbon and N mineralization potential was performed with a 10-d static incubation on 25 g of soil that was first brought to 60 % water-filled pore space. Five ml of 1 M NaOH was used to trap the CO_2 generated by the incubation, which was then determined by titration with 1 M HCl at the end of the incubation period (Robertson et al. 1999).

Enzyme assays for arylsulfatase and acid and alkaline phosphatase were carried out on air-dried samples following the method of Dick et al. (1996), which involved short-term incubation at controlled temperature and pH, followed by spectrophotometric analysis. The FDA assay was carried out on field moist samples utilizing a short-term incubation and subsequent spectrophotometric analysis (Green et al. 2006).

For C substrate utilization analysis, Biolog EcoPlates were inoculated with soil microbes following the method of Sinsabaugh et al. (1999). Spectrophotometric measurements were taken at 590 nm every 24 h on a microtiter plate reader over 5 days. Absorbance values are averaged from all substrate-containing cells (after being corrected with the blank cell values) to determine the average well color development (AWCD) for each plate. Data presented here are all from day 4 (96 h) to allow for maximum well response variance without exceeding the linear absorbance range (Garland 1996).

For PLFA analysis, extracted lipids from freeze-dried soil were re-suspended in a hexane and MTBE solution and analyzed on a gas chromatograph with a flame ionization detector (GC/FID; Hill et al. 2000). Microbial biomass-C was determined as the sum of the phospholipid fatty acids extracted from all microbes within a sample.

Soil chemical and physical analyses

- pH using a 2:1 de-ionized water:soil ratio; (Thomas 1996)
- Electrical conductivity on a saturated paste extract (Rhoades 1996)
- Organic and inorganic C using a LECO RC-412 C species analyzer (LECO Corp., St Joesph, MI, USA)
- Total N and S using a LECO TruSpec C/N/S analyzer (LECO Corp., St Joesph, MI, USA)
- Inorganic N was determined by 2 M KCl extraction and flow injection analysis (Robertson et al. 1999)
- Water-soluble P was determined via ICP-AES on a saturated paste extract
- Total metals were determined using a 4 acid dissolution and subsequent ICP-MS analysis (Briggs and Meier 2002)
- Diethylenetriaminepentaacetic acid (DTPA) extractable metals were determined following Amacher (1996), and represent an estimate of the bioavailable soil metal pool
- Particle size distribution using the hydrometer method (Elliott et al. 1999)

- Bulk density from soil cores (Elliott et al. 1999)
- Gravimetric moisture analysis by oven-drying soils for 72 h at 110 °C

Statistical analyses (measuring soil quality)

For each parameter, one-way analysis of variance and Tukey's HSD comparisons were used to determine the minimum significant difference between the unmineralized, mineralized, waste rock and tailings within a given site, at a significance level (α) of 0.05. Data were analyzed for normality and transformed as necessary for statistical analysis. While all data presented here are untransformed, the cited statistical differences are based upon the transformed data. Multiple linear regressions were used to develop models to predict TOC and TN. All possible regressions using all indicators were considered, with the best model chosen based on the following criteria: (1) a small number of parameters with a multiple correlation coefficient as close to unity as possible; (2) an acceptable p value for the correlation coefficient; (3) a Mallows' Cp statistic (Mallows 1973) close to the total number of parameters; (4) a variance inflation factor (VIF) <10 (Marquard 1970). A Mallows' Cp statistic with a value close to the parameter number indicates a small total mean squared error and smaller model bias, while lower VIF values indicate lower parameter multicolinearity. In addition, models were validated by ensuring the predicted error sum of squares (PRESS) statistic was relatively close but greater than the sum of squared errors (SSE). All statistical analyses were performed using JMP software v 8.0.1 (SAS Institute, Cary, NC, USA).

Soil quality index development

The approach for determining soil quality follows that of Trasar-Cepeda et al. (1998), who used the relation between microbial activity and key components of soil organic matter, TOC and TN, as indicators of soil quality. They used multiple linear regression (MLR) to model the biochemical variables that best correlated with TN, then compared predicted versus measured TN values. Our objective in choosing this technique was to develop a simple yet sensitive indicator of soil quality that allowed for the comparison of disturbed systems to undisturbed (reference) systems. The underlying assumption with this approach is that soil organic matter content (in the form of TOC or TN) and biological activity are in equilibrium in undisturbed systems (Trasar-Cepeda et al. 1998; Chaer et al. 2009). When compared to disturbed or stressed systems, the ratio of predicted/measured TOC or TN values will then be either lower or higher than the undisturbed system. Negative predicted values and thus negative ratio values can result from negative MLR variable coefficients.

Results and discussion

Acid sulfate mineralization (Castle Peak and Masonic Mining District)

Within the Castle Peak study area, TOC, TN and all of the microbial variables were significantly higher for the unmineralized (andesite) soils compared to the mineralized (acid sulfate) soils and tailings, while only half of the biochemical variables showed this trend within the Masonic area (Table 1). The waste rock had similar TOC and TN values compared to the andesite soils and lower values for acid phosphatase, mineralized-C, -N, and microbial biomass-C at Castle Peak, and was similar for all biochemical variables except for acid and alkaline phosphatase at Masonic (Table 1). Most biochemical variables were similar between the acid sulfate soils and tailings except for FDA and acid phosphatase, which was greater for the acid sulfate soils at Castle Peak, and FDA and TOC which was greater for the acid sulfate soils at Masonic (Table 1).

Soil pH values were near neutral for the andesite soils and waste rock at both study sites, and around 4 for the acid sulfate soils (Table 2). Soil pH for the tailings was near neutral at Castle Peak and averaged 5.7 at Masonic. Electrical conductivity, NO_3 and NH_4 showed the highest values within the acid sulfate soils at both sites. Water soluble-P was lowest in the acid sulfate soils and tailings. The only difference in DTPA-K occurred at Castle Peak, where the tailings were significantly lower. Total and DTPA-S levels were lowest in the andesite soils, and though total-S was similar between the acid sulfate soils and disturbed sites, the former had higher DTPA-extractable values.

Within both study areas, DTPA-Al was greater in the acid sulfate soils compared to all other soils, despite similar total-Al concentrations (Table 3). DTPA-Zn was similar across all soils at both study areas, despite significant differences in total-Zn levels. At Castle Peak, both waste rock and tailings had lower DTPA-Mn concentrations compared to the undisturbed soils, and tailings had greater, though highly variable DTPA-Na compared to the other soils. DTPA-Mn and -Na were higher for the andesite and acid sulfate soils compared to the waste rock and tailings at Masonic.

To summarize, acid sulfate mineralization is characterized by low pH and high concentrations of Al and SO_4, reflected by the lower pH and higher concentrations of DTPA-Al, DTPA-SO_4 in the acid sulfate soils. The acid sulfate soils had lower water soluble-P compared to the

Table 1 Microbial community indicator variables, TOC and TN for all study sites

Site	Ecoplate: AWCD	FDA (mg kg^{-1} h^{-1})	Aryl-sulfatase (mg kg^{-1} h^{-1})	Acid phosphatase (mg kg^{-1} h^{-1})	Alkaline phosphatase (mg kg^{-1} h^{-1})	Min-C (mg g^{-1})	Min-N (mg kg^{-1})	Microbial biomass-C (nmol g^{-1})	TOC (%)	TN (%)
Castle Peak										
Unmineralized	0.329 a (0.07)	57.7 a (7.3)	8.8 a (0.7)	325.3 a (15.4)	162.4 a (18.4)	315.7 a (26.1)	10.4 a (1.8)	30.9 a (5.5)	0.80 a (0.11)	0.062 a (0.007)
Mineralized	0.032 b (0.01)	17.4 b (2.7)	1.3 b (0.4)	104.5 b (66.4)	44.7 b (29.4)	54.4 c (5.1)	2.4 b (0.4)	8.9 b (2.1)	0.30 bc (0.08)	0.019 bc (0.003)
Waste rock	0.285 a (0.07)	40.2 a (10.3)	6.4 a (0.5)	96.5 b (54.6)	140.7 a (14.7)	169.2 b (41.0)	2.2 b (0.4)	10.0 b (2.7)	0.58 ab (0.13)	0.041 ab (0.003)
Tailings	0.115 b (0.02)	1.74 c (1.1)	0.21 b (0.21)	11.4 c (2.6)	0.0 b (0.0)	0.0 c (0.0)	0.48 b (0.48)	4.5 b (2.1)	0.08 c (0.01)	0.010 c (0.001)
Masonic										
Unmineralized	0.244 a (0.06)	48.2 a (3.3)	8.2 a (0.7)	245.5 a (24.3)	59.9 b (8.8)	139.7 a (8.9)	3.5 a (0.65)	18.0 ab (2.1)	0.60 a (0.05)	0.057 ab (0.004)
Mineralized	0.027 c (0.01)	28.9 b (4.9)	4.7 ab (0.3)	62.2 b (11.7)	21.3 b (5.2)	56.2 b (10.2)	0.50 b (0.61)	19.7 ab (2.9)	0.60 a (0.12)	0.039 bc (0.005)
Waste rock	0.125 ab (0.06)	46.8 a (2.1)	8.9 a (3.2)	85.3 b (16.7)	209.2 a (31.8)	149.0 a (12.6)	4.7 a (1.3)	26.6 a (7.4)	0.90 a (0.16)	0.075 a (0.014)
Tailings	0.027 c (0.01)	6.7 c (3.3)	0.92 b (0.92)	14.6 b (4.9)	5.6 b (1.5)	14.2 b (14.2)	−0.07 b (0.43)	6.2 b (1.5)	0.16 b (0.03)	0.013 c (0.005)
Battle Mountain										
Unmineralized	0.438 a (0.06)	75.9 a (4.9)	43.1 a (7.7)	160.6 a (26.9)	191.8 b (15.6)	429.3 a (31.6)	15.2 a (2.6)	32.6 a (3.8)	1.18 a (0.10)	0.091 a (0.006)
Mineralized	0.339 ab (0.05)	76.4 a (4.6)	44.3 a (4.7)	153.7 a (18.2)	257.8 a (18.4)	303.4 b (24.6)	12.5 a (1.9)	23.7 ab (2.5)	1.02 a (0.10)	0.071 a (0.005)
Waste rock	0.135 ab (0.01)	13.2 b (1.5)	10.2 a (2.3)	70.2 a (2.4)	11.6 c (1.8)	52.4 c (25.8)	1.9 ab (1.8)	7.9 bc (2.5)	0.79 a (0.28)	0.057 a (0.012)
Tailings	0.132 b (0.03)	0.0 c (0.0)	0.0 c (0.0)	2.7 b (2.2)	0.0 d (0.0)	8.6 c (8.6)	−1.8 b (1.1)	4.9 c (2.0)	0.06 b (0.02)	0.015 b (0.003)

Data are averaged within each design level. Data in parentheses are listed as ±one standard error of the mean. For each variable within a study site, numbers marked with different letters are significantly different from each other ($p < 0.05$)

Table 2 Soil pH and statistically significant explanatory variables (EC and macronutrients) from the MLR equations for all study sites

Site	pH	EC (dS m^{-1})	NO_3 (mg kg^{-1})	NH_4 (mg kg^{-1})	Water soluble-P (mg kg^{-1})	DTPA-K (mg kg^{-1})	Total-S (%)	DTPA-SO_4 (mg kg^{-1})
Castle Peak								
Unmineralized	6.6 b (0.18)	0.17 b (0.02)	1.29 a (0.65)	1.28 ab (0.43)	0.31 b (0.05)	64.9 a (21.3)	0.24 c (0.10)	11.2 b (1.8)
Mineralized	4.2 c (0.10)	1.21 a (0.41)	3.30 a (1.0)	4.03 a (1.1)	0.04 c (0.01)	37.6 a (9.2)	1.40 b (0.51)	1,247 a (504)
Waste Rock	7.7 a (0.28)	0.28 ab (0.05)	1.94 a (0.68)	0.90 ab (0.38)	0.66 a (0.04)	55.7 a (15.8)	3.6 ba (1.6)	16.7 ab (16.7)
Tailings	7.0 ab (0.54)	0.26 ab (0.21)	1.75 a (0.76)	0.14 b (0.13)	0.08 c (0.07)	5.8 b (3.2)	5.4 a (0.8)	33.2 ab (33.2)
Masonic								
Unmineralized	6.4 a (0.08)	0.07 b (0.008)	1.92 a (0.27)	0.03 b (0.02)	0.53 a (0.12)	34.1 a (4.1)	0.47 a (0.14)	0.74 b (0.10)
Mineralized	3.7 b (0.10)	0.92 a (0.50)	2.96 a (0.94)	6.54 a (2.7)	0.02 b (0.02)	87.0 a (32.8)	0.95 a (0.18)	449 a (254)
Waste Rock	7.0 a (1.2)	0.10 ab (0.04)	2.38 a (0.18)	0.52 ab (0.37)	0.49 a (0.14)	51.8 a (6.9)	0.71 a (0.46)	0.50 b (0.01)
Tailings	5.7 ab (2.0)	0.17 ab (0.05)	1.45 a (0.37)	1.78 ab (0.82)	0.06 b (0.06)	34.1 a (4.1)	0.93 a (0.18)	29.2 ab (28.7)
Battle Mountain								
Unmineralized	7.4 a (0.19)	0.33 a (0.06)	2.51 a (0.42)	0.35 b (0.13)	1.51 a (0.49)	239 a (59)	0.09 b (0.03)	16.1 b (7.3)
Mineralized	7.5 a (0.10)	0.24 a (0.02)	1.55 a (0.11)	0.37 b (0.19)	0.79 a (0.11)	88.0 ab (13.7)	0.04 b (0.01)	5.8 b (2.1)
Waste Rock	5.8 b (1.5)	0.49 a (0.24)	2.57 a (0.92)	1.86 ab (1.86)	0.34 a (0.34)	22.2 ab (22.2)	1.4 ab (1.3)	238 b (216)
Tailings	2.7 c (0.18)	0.33 a (0.33)	1.28 a (0.86)	4.49 a (1.94)	0.74 a (0.44)	0.37 b (0.13)	2.7 a (1.0)	4,492 a (1,888)

Data are averaged within each design level. Data in parentheses are listed as ± one standard error of the mean. For each variable within a study site numbers marked with different letters are significantly different from each other ($p < 0.05$)

Table 3 Statistically significant explanatory variables (micronutrients and metals) from the MLR equations for all study sites

Site	Total-Al (mg kg^{-1})	DTPA-Al (mg kg^{-1})	DTPA-Mn (mg kg^{-1})	DTPA-Na (mg kg^{-1})	Total-Zn (mg kg^{-1})	DTPA-Zn (mg kg^{-1})
Castle Peak						
Unmineralized	8.1 a (0.23)	0.03 b (0.007)	12.8 a (4.5)	17.8 b (2.3)	82.7 a (2.5)	0.29 a (0.06)
Mineralized	8.5 a (0.41)	75.0 a (22.4)	8.0 ab (4.8)	16.3 b (6.5)	52.7 b (4.7)	0.70 a (0.31)
Waste Rock	8.4 a (0.89)	0.02 b (0.006)	1.9 b (0.80)	10.8 b (7.3)	45.0 b (10.4)	0.37 a (0.12)
Tailings	8.1 a (0.23)	0.03 b (0.005)	0.36 b (0.17)	160.1 a (148.4)	13.5 c (0.5)	0.24 a (0.06)
Masonic						
Unmineralized	7.5 a (0.35)	0.04 b (0.01)	13.5 a (2.1)	23.5 a (6.2)	65.6 a (3.8)	0.53 a (0.04)
Mineralized	8.6 a (0.44)	109 a (29)	9.5 a (4.0)	31.7 a (23.4)	25.8 b (6.0)	0.82 a (0.20)
Waste Rock	8.0 a (0.73)	0.10 b (0.09)	2.9 a (1.4)	3.8 a (1.4)	67.7 a (12.7)	0.59 a (0.25)
Tailings	8.4 a (0.45)	48.6 ab (36)	3.0 a (1.2)	5.4 a (4.4)	47.0 ab (10.4)	1.0 a (0.21)
Battle Mountain						
Unmineralized	7.2 a (0.07)	0.05 b (0.02)	5.1 b (0.63)	40.2 a (11.8)	68.7 b (1.8)	0.60 b (0.12)
Mineralized	7.2 a (0.08)	0.03 b (0.003)	6.3 b (0.67)	26.9 ab (3.6)	247 ab (48.9)	1.3 b (0.23)
Waste Rock	7.2 a (0.49)	0.25 b (0.20)	9.0 ab (5.1)	27.2 ab (13.1)	923 a (806)	75.7 ab (72.4)
Tailings	6.3 a (1.0)	41.4 a (23.6)	31.4 a (24.4)	0.18 b (0.08)	573 ab (509)	183 a (154)

Data are averaged within each design level. Data in parentheses are listed as ± one standard error of the mean. For each variable within a study site, numbers marked with different letters are significantly different from each other ($p < 0.05$)

andesite soils, an observation also noted by Schlesinger et al. (1989) and DeLucia et al. (1989) in their studies of acid sulfate systems in western Nevada. Low pH, high metal content, and physical disturbance presumably combine to inhibit microbial activity in the tailings. Microbial activity in the waste rock generally equaled or exceeded that of the acid sulfate soils, suggesting that the inherent low fertility of the acid sulfate soils inhibits microbial activity to a greater extent than the disturbances associated with the waste rock.

Cu/Mo porphyry mineralization (Battle Mountain Mining District)

Only alkaline phosphatase and mineralized-C differed between the undisturbed mineralized and unmineralized soils (Table 1). Waste rock TOC and TN values were similar to those of the undisturbed sites and approximately an order of magnitude greater than the tailings. Microbial values for the undisturbed sites exceeded those of the tailings for all measures except AWCD and those for the waste rock except for FDA, acid and alkaline phosphatase and mineralized-C. Microbial values for the waste rock were greater than the tailings for all enzyme analyses, but similar for the other measures.

Soil pH ranged from near neutral for the undisturbed soils to strongly acidic in the tailings (Table 2). Macronutrient levels were similar between the unmineralized and mineralized soils. Relative to the undisturbed soils, the tailings had greater NH_4 and DTPA-SO_4, lower DTPA-K, and similar NO_3 and P concentrations. Waste rock values were generally in between those of the tailings and undisturbed soils.

Micronutrients and metals were similar between the unmineralized and mineralized soils, except that the latter had greater total Cu (Table 3). Relative to the undisturbed soils, the tailings typically had greater micronutrient and metal values, except for DTPA-Na, which was lower. Waste rock values were typically in between those of the undisturbed soils and tailings.

To summarize, compared to the undisturbed soils, the tailings were characterized by low microbial activity, low TOC and TN, low pH, high values of total and DTPA-S, high NH_4, and high DTPA-Al, -Fe, -Mn, and -Zn, (Tables 1, 2, 3), along with high bulk density, and high levels of As and Pb (Blecker et al. 2010). Because concentrations of inorganic N and water soluble-P were similar to the undisturbed sites (Table 2), it may be that the low pH and high metal contentrations likely contributed to the low microbial activity. The negative mineralized-N values for the tailings indicate that net N immobilization occurred over the course of the incubation.

Data for the waste rock were highly variable, as indicated by the large standard errors in Tables 1, 2 and 3. Generally, the levels of microbial activity, pH, S (Total and DTPA-extractable), and metals were between those of the undisturbed soils and tailings. The exception was DTPA-Zn, which was higher in the waste rock than the tailings. Compared to the undisturbed soils, lower levels of nutrients such as P and K, along with higher concentrations of Zn, may be driving the lower microbial activity in the waste rock.

Soil quality index

At each of the three study sites, we present MLR models for both TOC and TN to examine potential differences in the models. Two different groups of explanatory variables were considered: microbial indicators (biotic) alone (those indicators listed in Table 1) and microbial and abiotic indicators (all) together (those indicators in Tables 1, 2, 3). We used this approach to compare our results with previous studies, which typically utilize microbial indictors alone. At the same time, we wanted to explore the potential benefits of using a greater set of explanatory variables. In addition to these site level MLR models, we attempted to scale up this approach across an ecoregion (pooling undisturbed site data, both unmineralized and mineralized, from all study sites, which are located in the Mono and Lahontan basin sections of the intermountain semi-desert and desert province; Bailey et al. 1994).

Acid sulfate mineralization (Castle Peak Mining District)

Correlations, explanatory variables and model parameters for the Castle Peak MLR models are presented in Table 4. The MLR models were run with two different datasets, andesite soils and andesite + acid sulfate soils. These datasets were chosen to examine model variability between the andesite and acid sulfate soils and because the disturbed areas were located in andesite terrane. From the eight microbial indicators (Table 1), two indicators (mineralized-N and acid phosphatase) were used in the TOC models, and five indicators (mineralized-N, acid phosphatase, arylsulfatase, FDA and microbial biomass-C) were used in the TN models. For the abiotic indicators, DTPA-Zn, DTPA-Mn, and water soluble-P were significantly correlated with the TOC models, while total-S and DTPA-P were significantly correlated in the TN models, showing the potential importance of both macro- and micronutrients in this system.

Results for selected models from Table 4 are presented in Figs. 1 and 2. Applying models derived from the andesite soils to the acid sulfate soils produced SQI values significantly away from unity, which is not surprising given the differences in these ecosystems (Tables 1, 2, 3). In most cases the tailings were statistically different (both positively and negatively) from their undisturbed counterparts. In only one instance, in the TOC biotic model (model 2:U (biotic), Table 4), waste rock pile showed a significantly different SQI value compared to the andesite soil. Thus, considering Figs. 1 and 2, and the model parameters from Table 4 (model 2:U (biotic), Table 4), that model provides the most reasonable assessment of this system relative to mining disturbance.

Table 4 Best set of explanatory variables for TOC and TN as modeled by MLR for two different datasets within the Castle Peak (acid sulfate) study site: andesite soils and andesite + acid sulfate soils

Dependent variable	Model number[a] and name	Data set	Explanatory variables[b]	r^2	Cp[c]	VIF[d]	n
TOC	1:U (all)	Andesite	DTPA-Zn**; Mineralized-N	0.793	−1.8	8.1	9
	2:U (biotic)	Andesite	Mineralized-N***; Acid-P**	0.983	3.2	1.1	9
	3:U + M (all)	Andesite + acid sulfate	DTPA-Mn****; Water soluble-P****	0.853	1.7	1.2	17
	4:U + M (biotic)	Andesite + acid sulfate	Mineralized-N****	0.736	2.9	1.0	17
TN	5:U (all)	Andesite	Total-S****; DTPA-P**	0.925	3.4	1.5	9
	6:U (biotic)	Andesite	FDA*; Arylsulfatase; Mineralized-N	0.877	3.7	9.2	9
	7:U + M (all)	Andesite + acid sulfate	DTPA-S**; Water soluble-P**; FDA****	0.929	0.8	3.8	17
	8:U + M (biotic)	Andesite + acid sulfate	FDA**; Acid-P**; Microbial biomass-C**; Arylsulfatase*	0.974	3.7	6.0	17

M mineralized (acid sulfate), *U* unmineralized (andesite), *all* abiotic + microbial parameters, *biotic* microbial parameters, *n* total number of samples used in each model

[a] Model numbers correspond to the numbered regression equations listed below

[b] Values are significant at * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$; **** $p < 0.001$

[c] Mallows' Cp statistic

[d] Variance Inflation Factor

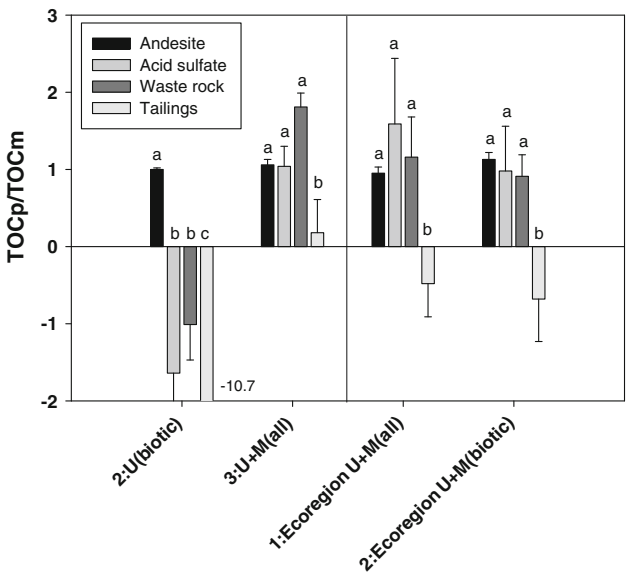

Fig. 1 Castle Peak (acid sulfate) SQI values [ratio of predicted TOC (TOCp) to measured TOC (TOCm)]. The *x* axis models correspond to selected TOC models in Tables 5 and 8 (ecoregion), where *U* unmineralized (andesite), *M* mineralized (acid sulfate), *all* abiotic + microbial, *biotic* microbial. *Different letters* represent significant differences between sampling levels ($p < 0.05$). *Negative values* indicate that the explanatory variables were present in concentrations below the range of the calibration dataset, resulting in a negative, predicted TOC value

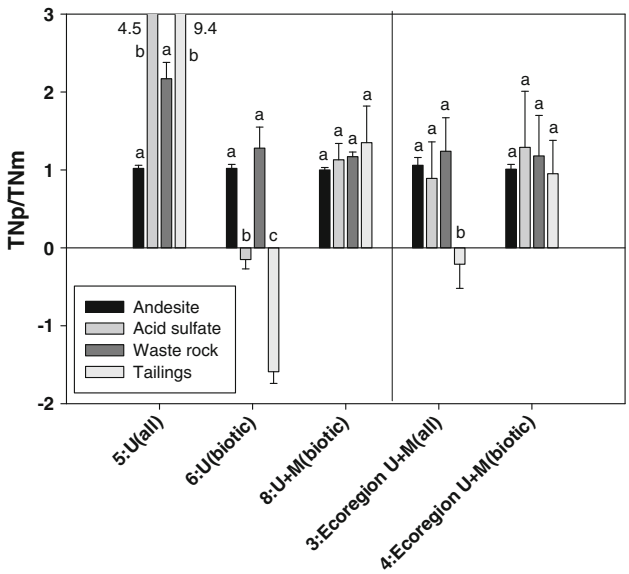

Fig. 2 Castle Peak (acid sulfate) SQI values [ratio of predicted TN (TNp) to measured TN (TNm)]. The *x* axis models correspond to selected TN models in Tables 5 and 8 (ecoregion), where *U* unmineralized (andesite), *M* mineralized (acid sulfate), *all* abiotic + microbial, *biotic* microbial. Values for those results extending beyond the *y* axis are listed on the graph. *Different letters* represent significant differences between sampling levels ($p < 0.05$)

Acid sulfate mineralization (Masonic Mining District)

Correlations, explanatory variables and model parameters for the Masonic MLR models are presented in Table 5. The MLR models were run with two different datasets, andesite soils and andesite soil + acid sulfate soils. The andesite-based models produced the highest correlations for TOC, while all the models produced relatively high correlations for the TN models ($r^2 > 0.90$). The TOC and TN models

Table 5 Best set of explanatory variables for TOC and TN as modeled by MLR for two different datasets within the Masonic (acid sulfate) study site: andesite soils and andesite + acid sulfate soils

Dependent variable	Model number[a] and name	Data set	Explanatory Variables[b]	r^2	Cp[c]	VIF[d]	n
TOC	1:U (all)	Andesite	Microbial biomass-C***; Alkaline-P***	0.882	−1.0	1.0	9
	2:U (biotic)	Andesite	Acid-P***; Mineralized-C***; Microbial biomass-C***	0.946	60	7.2	9
	3:U + M (all)	Andesite + acid sulfate	NO_3*; Microbial biomass-C***	0.629	3.9	1.1	17
	4:U + M (biotic)	Andesite + acid sulfate	Microbial biomass-C ****; Alkaline-P**	0.721	−1.9	1.0	17
TN	5:U (all)	Andesite	DTPA-Na*; Arylsulfatase***	0.908	0.7	1.2	9
	6:U (biotic)	Andesite	Alkaline-P***; FDA**; Mineralized-N*	0.941	5.3	1.3	9
	7:U + M (all)	Andesite + acid sulfate	Water soluble-P; FDA**, Arylsulfatase**; Acid-P	0.903	2.0	7.5	17
	8:U + M (biotic)	Andesite + acid sulfate	FDA****, Alkaline-P***; Mineralized-C**	0.935	6.9	5.2	17

M mineralized (acid sulfate), *U* unmineralized (andesite), *all* abiotic + microbial parameters, *biotic* microbial parameters, *n* total number of samples used in each model

[a] Model numbers correspond to the numbered regression equations listed below

[b] Values are significant at * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$; **** $p < 0.001$

[c] Mallows' Cp statistic

[d] Variance inflation factor

had three microbial indicators in common (acid and alkaline phosphatase activity, and mineralized-C). Microbial biomass-C was significant in all of the TOC models, and none of the TN models. Only NO_3 was a significant abiotic explanatory variable in any TOC model, while DTPA-Na and water soluble-P were significant explanatory variables in the TN models.

Results for selected models from Table 5 are presented in Figs. 3 and 4. Model results for both TOC and TN showed a somewhat similar pattern to those seen at Castle Peak, with andesite-only models providing the best separation between undisturbed and disturbed sites in terms of SQI values. SQI values between the andesite and acid sulfate soils (Figs. 3 and 4) showed a greater degree of similarity at Masonic compared to Castle Peak (Figs. 1 and 2), which may be due to the greater similarity in microbial and abiotic values from Table 1, 2 and 3 at the Masonic site. For TOC, only the andesite-based models, U ('all') and U ('biotic'), showed significant differences between both the waste rock and tailings compared to the undisturbed soil. For TN, the U ('biotic') and U + M ('biotic') models showed significant differences between the waste rock and undisturbed sites. As with the Castle Peak site, the 'biotic' models perform better than the 'all' models in terms of SQI values and model parameters. One explanation could involve the greater differences in microbial (Table 1) compared to abiotic (Tables 2, 3) between the andesite and acid sulfate soils or that key abiotic parameters such as pH, which likely impact soil organic matter content in these systems (Schlesinger et al. 1989), were not selected using this MRL approach.

Comparing the model variables between the Castle Peak and Masonic acid sulfate sites, the TOC models have completely different sets of explanatory variables between the two study sites. However, the TN models share similar abiotic (water soluble-P) and microbial variables (mineralized-N, FDA, arylsulfatase, and acid phosphatase). Thus, similarities between TN and microbial parameters indicate the potential utility of using these models at a larger scale (i.e. across these two sites).

Cu/Mo porphyry mineralization (Battle Mountain Mining District)

Correlations, explanatory variables and model parameters for the Battle Mountain Cu/Mo porphyry mineralization MLR models are presented in Table 6. The MLR models were run with three different datasets, unmineralized soils, mineralized (Cu/Mo porphyry) soils, and the combined data from both sets of undisturbed sites. For both TOC and TN models, the unmineralized and Cu/Mo porphyry data sets taken separately produced higher correlations than combining them, despite similarities in the microbial and abiotic indicators (Tables 1, 2, 3). Model correlations were similar comparing the 'all' models (1v2, 3v4, 7v8 and 9v10: Table 6) versus 'biotic' models within a given data set ($r^2 > 0.876$), except for the lower r^2 (0.768) in the case of model 8. For the TOC models, seven of the eight microbial indicators were significant explanatory variables in at least one model with the exception of AWCD. For the TN models, six of the eight microbial indicators were significant explanatory variables in at least one model with the exception of FDA and mineralized-C. Electrical conductivity and NO_3 were significant abiotic explanatory variables for TOC and TN models. Electrical conductivity values were generally low (i.e. < 0.5 dS/m; Table 2), and

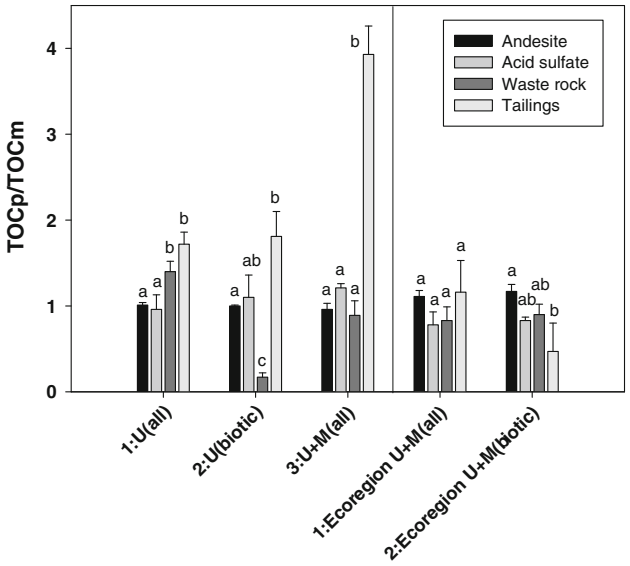

Fig. 3 Masonic (acid sulfate) SQI values [ratio of predicted TOC (TOCp) to measured TOC (TOCm)]. The *x* axis models correspond to selected TOC models in Tables 6 and 8 (ecoregion), where *U* unmineralized (andesite), *M* mineralized (acid sulfate), *all* abiotic + microbial, *biotic* microbial. *Different letters* represent significant differences between sampling levels ($p < 0.05$)

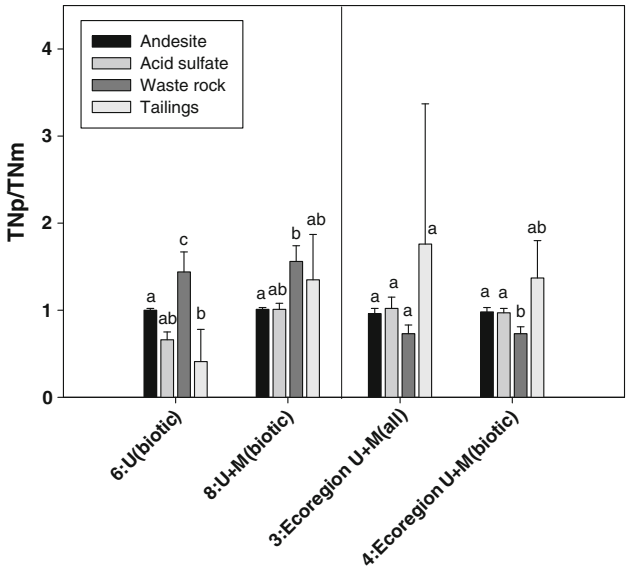

Fig. 4 Masonic (acid sulfate) SQI values [ratio of predicted TN (TNp) to measured TN (TNm)]. The *x* axis models correspond to selected TN models in Tables 6 and 8 (ecoregion), where *U* unmineralized (andesite), *M* mineralized (acid sulfate), *all* abiotic + microbial, *biotic* microbial. *Different letters* represent significant differences between sampling levels ($p < 0.05$)

positively correlated with TOC and TN. Thus it is possible that higher EC levels relate to greater nutrient content in the form of higher soluble salt concentrations. In addition, P and SO_4 were significant for TOC models and NH_4, Mn and Zn for TN models, suggesting the potential importance of these nutrients in this sagebrush ecosystem. Micronutrients, in particular, have received limited study in sagebrush ecosystems but have been found to play an important role (Aanderud et al. 2008).

Results for selected models from Table 6 are presented in Figs. 5 and 6. Model results for both TOC and TN were quite varied. In all TOC and TN models, the SQI values were statistically similar and near unity for both undisturbed soils, the unmineralized and Cu/Mo porphyry soils. The TOC 'biotic' models, regardless of the dataset, produced a similar trend of significantly lower SQI values for the waste rock and tailings compared to their undisturbed counterparts. The 'all' models produced mixed results, tending toward greater SQI values for the waste rock and tailings relative to the undisturbed sites for both TOC and TN models. For the TN models, 8:U ('biotic') was the only model to produce SQI values that were significantly different between the waste rock and tailings and undisturbed soils. Overall, the TOC-based models were more consistent in differentiating undisturbed from waste rock and tailings based on SQI values. The best models based on Figs. 5 and 6 and the parameters listed in Table 6 are 2:U ('biotic') and 3:M ('all') for TOC and 8:U ('biotic') for TN.

SQI development within an ecoregion

To examine the utility of scaling up this approach across a larger area (e.g. ecoregion), we combined datasets among all three sites (Table 7). For TOC models, FDA and microbial biomass are common explanatory variables for both this ecoregion approach and each of the individual sites. For TN models, FDA and arylsulfatase are significant explanatory variables for the ecoregion model and many of the acid sulfate system models, but only a couple of the Battle Mountain models. In most instances, r^2 values are lower for the ecoregion models compared with the individual site models. The ecoregion TOC and TN models introduce two new abiotic explanatory variables (DTPA-Al, DTPA-K), while DTPA-Na and water soluble-P appeared in previous models.

Results of the ecoregion TOC microbial models are varied across the study sites (Figs. 1, 3, and 5). Five of the six TOC models (all except ecoregion model 1, Fig. 3) differentiated the tailings from the undisturbed soils, but only the models at the Cu/Mo porphyry site differentiated both the waste rock and tailings from the undisturbed soil based on the SQI values. Results of the ecoregion TN models are shown in Figs. 2, 4, and 6. Three of the six TN models (ecoregion model 3, Fig. 2; ecoregion models 3 and 4, Fig. 6) differentiated the tailings from the undisturbed soils; one of the six TN models (ecoregion model 4, Fig. 4) differentiated the waste rock. Only one model (ecoregion

Table 6 Best set of explanatory variables for TOC and TN as modeled by MLR for three different datasets within the Battle Mountain (Cu/Mo porphyry) study site: unmineralized soils, Cu/Mo porphyry soils, unmineralized + Cu/Mo porphyry soils

Dependent variable	Model number[a] and name	Data set	Explanatory variables[b]	r^2	Cp[c]	VIF[d]	n
TOC	1:U (all)	Unmineralized	EC***; DTPA-P**; DTPA-SO4*	0.910	1.4	3.2	9
	2:U (biotic)	Unmineralized	Alkaline-P***; Mineralized-C**; Microbial biomass-C*	0.927	1.0	1.3	9
	3:M (all)	Cu/Mo porphyry	NO_3***; DTPA-P***	0.907	0.4	1.1	9
	4:M (biotic)	Cu/Mo porphyry	Acid-P***; Mineralized-N***	0.876	−4.2	1.2	9
	5:U + M (all)	Unmineralized + Cu/Mo porphyry	NO_3****; FDA*; DTPA-P**	0.818	1.0	1.4	18
	6:U + M (biotic)	Unmineralized + Cu/Mo porphyry	Arylsulfatase***; Acid-P**; Mineralized-N**	0.602	1.9	1.3	18
TN	7:U (all)	Unmineralized	EC****; Mineralized-N**	0.900	4.4	1.1	9
	8:U (biotic)	Unmineralized	Alkaline-P**; Microbial biomass-C*; Arylsulfatase*;	0.768	5.7	1.1	9
	9:M (all)	Cu/Mo porphyry	DTPA-Mn****; Arylsulfatase*; NH_4***	0.982	6.6	2.6	9
	10:M (biotic)	Cu/Mo porphyry	Acid-P****; Mineralized-N**	0.914	6.3	1.2	9
	11:U + M (all)	Unmineralized + Cu/Mo porphyry	NO_3***; Total-Zn**; Mineralized-N*	0.737	1.1	1.3	18
	12:U + M (biotic)	Unmineralized + Cu/Mo porphyry	Mineralized-N***; AWCD**	0.398	1.2	1.3	18

M mineralized (Cu/Mo porphyry), *U* unmineralized, *all* abiotic + microbial parameters, *biotic* microbial parameters, *n* total number of samples used in each model

[a] Model numbers correspond to the numbered regression equations listed below

[b] Values are significant at * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$; **** $p < 0.001$

[c] Mallows' Cp statistic

[d] Variance inflation factor

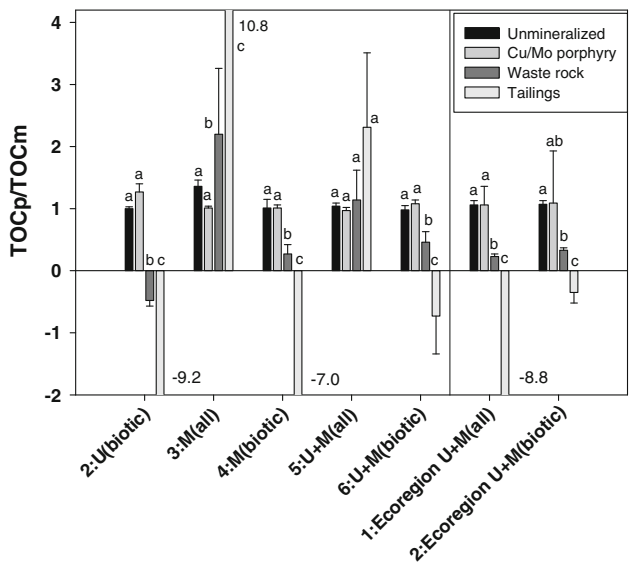

Fig. 5 Battle Mountain (Cu/Mo porphyry) SQI values [ratio of predicted TOC (TOCp) to measured TOC (TOCm)].The *x* axis models correspond to selected TOC models in Tables 4 and 8 (ecoregion), where *U* unmineralized, *M* mineralized (Cu/Mo porphyry), *all* abiotic + microbial, *biotic* microbial. Values for those results extending beyond the *y* axis are listed on the graph. *Different letters* represent significant differences between sampling levels ($p < 0.05$). *Negative values* indicate that the explanatory variables were present in concentrations below the range of the calibration dataset, resulting in a negative, predicted TOC value

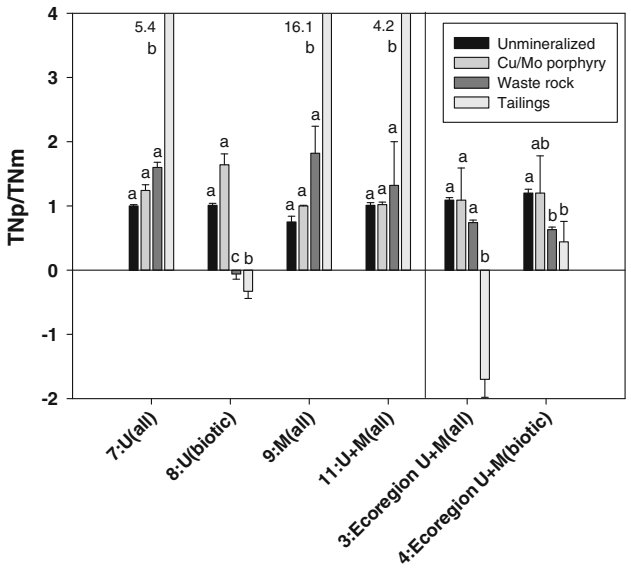

Fig. 6 Battle Mountain (Cu/Mo porphyry) SQI values (ratio of predicted TN (TNp) to measured TN (TNm)]. The *x* axis models correspond to selected TN models in Tables 4 and 8 (ecoregion), where *U* unmineralized, *M* mineralized (Cu/Mo porphyry), *all* abiotic + microbial, *biotic* microbial. Values for those results extending beyond the *y* axis are listed on the graph. *Different letters* represent significant differences between sampling levels ($p < 0.05$). *Negative values* indicate that the explanatory variables were present in concentrations below the range of the calibration dataset, resulting in a negative, predicted TN value

Table 7 Best set of explanatory variables for TOC and TN as modeled by multiple linear regression for the combined data sets of all the undisturbed soils (both unmineralized and mineralized) within the Intermountain semi-desert and desert ecoregion (Castle Peak, Masonic, Battle Mountain)

Dependent variable	Model number[a] and name	Data set	Explanatory variables[b]	r^2	Cp[c]	VIF[d]	n
TOC	1:U + M (all)	Ecoregion	FDA****; DTPA-K****	0.742	−0.89	1.6	49
	2:U + M (biotic)	Ecoregion	FDA****; Microbial biomass-C**	0.674	−0.26	1.6	49
TN	3:U + M (all)	Ecoregion	Arylsulfatase****; Mineralized-C**; Alkaline-P**; DTPA-Al***, DTPA-K****, DTPA-Na**; Water-soluble-P***	0.834	7.9	7.0	49
	4:U + M (biotic)	Ecoregion	FDA****; Arylsulfatase**	0.795	2.4	4.7	49

M mineralized, *U* unmineralized, *A* abiotic parameters, *B* biotic (microbial) parameters, *n* total number of samples used in each model

[a] Model numbers correspond to the numbered regression equations listed below

[b] Values are significant at * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$; **** $p < 0.001$

[c] Mallows' Cp statistic

[d] Variance inflation factor

model 4, Fig. 6) again from the Cu/Mo porphyry site differentiated both waste rock and tailings from the undisturbed sites based on SQI values. As with the individual sites, the 'biotic' models tend to perform better than the 'all' models in terms of differentiating between disturbed and undisturbed sites. The overall decreased performance for the ecoregion models demonstrates the difficulty in scaling up this approach across disparate ecosystems and mineralization types. This may be due in part to the increasing variance associated with the independent variables hampering the ability of the MLR model to distinguish the explanatory variables.

Comparison with previous MLR index approaches

A comparison of studies using this type of SQI approach in non-agricultural ecosystems revealed that predictive equations relied on two to five variables to explain variability in TOC or TN. As soil TOC and TN are generally highly correlated with each other, it is not surprising that either of the two tends to produce a workable model, and that the same explanatory variables were often used for both TOC and TN models (e.g. Zornoza et al. 2007; current study). Enzyme assays were common model parameters found in the current study (where 71 % of all models contained one or more enzyme assay) as well as previous studies. For example, Trasar-Cepeda et al. (1998) developed an SQI for a Spanish oak-wood ecosystem based upon the relation between total soil N, microbial biomass-C, mineralized-N, phosphatase activity, β-glucosidase activity, and urease activity, and Chaer et al. (2009) developed an SQI using the relation between soil organic carbon, microbial biomass-C, and phosphatase activity in a forested Pacific NW ecosystem. Only one study found correlative abiotic parameters (water holding capacity and available P; Zornoza et al. 2007), though in most studies these parameters were not measured. Models based solely on microbial variables tended to differentiate between disturbed and undisturbed sites to a greater extent than models that also include abiotic parameters.

Zornoza et al. (2007) validated their MLR models by comparing them to degraded soils, an approach utilized in the current study by comparing undisturbed soils to the soils disturbed by mining activity. They noted that deviations from the predicted model were likely due to different equilibrium conditions based on disturbance, which we believe is driving discrepancies between the models and disturbed sites of the current study. However, drastically disturbed areas (i.e. tailings) are typically so different from the undisturbed reference soils in terms of soil organic matter dynamics that this method is generally not a viable monitoring tool.

Conclusions

Though developed and used primarily in forested systems, study results showed the potential application of this MLR-based SQI approach in more arid shrubland ecosystems. As seen in previous studies, enzyme assays often correlate well with soil TOC and TN; their relative ease of analysis and low cost adds to their utility. This SQI approach tends to greatly over or under predict highly disturbed sites (e.g. tailings); further illustrating the disequilibrium between soil organic matter and the explanatory variables in these extremely disturbed areas.

However, this approach presents a means of comparing less disturbed areas (e.g. waste rock) to undisturbed reference sites in a variety of ecosystems. Even when the same explanatory variables exist across study sites, the ability to differentiate between disturbed and undisturbed systems tends to decline when combining the data sets

across sites. Although identifying common indicators can be both time saving and allow for more equivalent comparisons across sites, combining data from disparate sites does not seem warranted using this approach given the decreased ability to differentiate between disturbed and undisturbed sites.

Combining this approach with more traditional measures of vegetation community structure and composition could provide a more complete picture of ecosystem recovery for disturbed lands. Certain facets of this study could be incorporated into existing soil monitoring frameworks such as those associated with rangeland and forest assessments, although additional temporal and spatial sampling may be necessary to more effectively apply this type of soil quality index over larger areas.

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Appendix

Tables 8, 9, 10, and 11 contain the multiple linear regression equations associated with Tables 4, 5, 6, and 7.

Table 8 Multiple linear regression equations associated with Table 4

1: TOC = 0.276 + 1.18 (DTPA-Zn) + 0.018 (mineralized-N)
2: TOC = −0.909 + 0.062 (mineralized-N) + 3.22×10^{-3} (Acid-P)
3: TOC = 0.036 + 0.153 log(DTPA-Mn) + 1.73 (water soluble-P)
4: TOC = −1.08 + 0.698 log (mineralized-N)
5: TN = 0.071 + 7.99×10^{-3} log (total S) + 0.025 (DTPA-P)
6: TN = −0.017 + 7.04×10^{-4} (FDA) + 7.10×10^{-3} (arylsulfatase) − 2.35×10^{-3} (mineralized-N)
7: TN = 0.016 − 1.94×10^{-3} log(DTPA-S) + 0.034 log + 1(water-soluble-P) + 7.28×10^{-4} (FDA)
8: TN = 9.21×10^{-3} + 6.22×10^{-4} (FDA) + 2.83×10^{-3} (arylsulfatase) − 0.019 log (Acid-P) + 4.17×10^{-4} (microbial biomass-C)

Table 9 Multiple linear regression equations associated with Table 5

1: TOC = 0.151 + 0.014 (Microbial biomass-C) + 3.42×10^{-3} (alkaline-P)
2: TOC = 0.426 + 3.01×10^{-3} (acid-P) − 5.54×10^{-3} (mineralized-C) + 0.012 (Microbial biomass-C)
3: TOC = 0.0374 + 0.124 log + 1 (NO_3) + 0.022 (Microbial biomass-C)
4: TOC = 0.039 + 0.024 (Microbial biomass-C) + 2.51×10^{-3} (alkaline-P)
5: TN = 0.020 − 2.10×10^{-4} (DTPA-Na) + 5.09×10^{-3} (arylsulfatase)
6: TN = -7.85×10^{-4} + 2.92×10^{-4} (alkaline-P) + 6.81×10^{-4} (FDA) + 2.05×10^{-3} (mineralized-N)
7: TN = -9.73×10^{-4} − 0.016 log + 1 (water soluble-P) + 5.63×10^{-4} (FDA) + 5.64×10^{-3} (arylsulfatase) − 3.95×10^{-5} (acid-P)
8: TN = 0.014 + 8.85×10^{-4} (FDA) + 3.90×10^{-4} (alkaline-P) − 1.65×10^{-4} (mineralized-C)

Table 10 Multiple linear regression equations associated with Table 6

1: TOC = 0.632 + 2.32 log + 1 (EC) + 0.349 log + 1 (DTPA-P) − 0.132 log + 1 (DTPA-SO_4)
2: TOC = −0.540 + 4.60×10^{-3} (alkaline-P) + 1.38×10^{-3} (mineralized-C) + 7.92×10^{-3} (Microbial biomass-C)
3: TOC = −0.158 + 0.504 (DTPA-P) + 1.05 log + 1 (NO_3)
4: TOC = −0.319 + 6.12×10^{-3} (acid-P) + 0.032 (mineralized-N)
5: TOC = 0.299 + 0.355 log + 1 (NO_3) + 6.89×10^{-3} (FDA) + 0.118 log (DTPA-P)
6: TOC = -2.56×10^{-3} + 0.012 (arylsulfatase) + 2.34×10^{-3} (acid-P) + 0.019 (mineralized-N)
7: TN = 0.053 + 0.095 log + 1 (EC) + 9.00×10^{-4} (mineralized-N)
8: TN = -9.88×10^{-3} + 5.48×10^{-4} (alkaline-P) + 9.69×10^{-4} (Microbial biomass-C) − 8.31×10^{-4} (arylsulfatase)
9: TN = 0.046 − $0.0002.88 \times 10^{-4}$ (arylsulfatase) + 0.025 log + 1 (NH_4) + 5.13×10^{-3} (DTPA-Mn)
10: TN = 0.013 + 3.06×10^{-4} (acid-P) + 1.01×10^{-3} (mineralized-N)
11: TN = 0.072 + 0.040 log + 1 (NO_3) − 9.02×10^{-3} log (total-Zn) + 6.90×10^{-4} (mineralized-N)
12: TN = 0.033 + 0.057 (AWCD) + 1.88×10^{-3} (mineralized-N)

Table 11 Multiple linear regression equations associated with Table 7

1: $TOC = -0.278 + 9.26 \times 10^{-3}$ (FDA) + 0.138 log (DTPA-K)

2: $TOC = -0.353 + 9.34 \times 10^{-3}$ (FDA) + 0.216 log (Microbial biomass-C)

3: $TN = 1.72 \times 10^{-3} + 0.019 \log + 1$ (arylsulfatase) + 5.64×10^{-5} (mineralized-C) − $2.60 \times 10^{-3} \sqrt{}$ (alkaline-P) − 6.24×10^{-3} log (DTPA-Al) + 0.014 log (DTPA-K) − 6.23×10^{-3} log(DTPA-Na) − 0.026 log + 1 (water soluble-P)

4: $TN = 5.79 \times 10^{-3} + 5.78 \times 10^{-4}$ (FDA) + 9.21×10^{-3} log + 1 (arylsulfatase)

References

Aanderud ZT, Shuldman MI, Drenovsky RE, Richards JH (2008) Shurb-interspace dynamics alter relationships between microbial community composition and belowground ecosystem characteristics. Soil Biol Biochem 40:2206–2216

Amacher MC (1996) Nickel, cadmium, and lead. In: Bartels JM (ed) Methods of soil analysis, Part 3: Chemical methods. Soil Science Society of America, Madison, pp 739–768

Bailey RG, Avers PE, King T, McNab WH (eds) (1994) Ecoregions and subregions of the United States (map) (supplementary table of map unit descriptions, compiled and edited by W. H. McNab and R. G. Bailey). USDA Forest Service. 1:7,500,000, Washington, DC

Bastida F, Zsolnay A, Hernandez T, Garcia C (2008) Past, present, and future of soil quality indices: a biological perspective. Geoderma 147:59–171

Blecker SW, Stillings LL, Amacher MC, Ippolito JA, DeCrappeo N (2010) Ecosystem health in mineralized terrane. Data from Podiform Chromite (Chinese Camp mining district, CA), Quartz Alunite (Castle Peak and Masonic mining districts, NV/CA), and Mo/Cu porphyry (Battle Mountain mining district, NV) deposits. US Geological Survey Open-File Report, 2010-1040

Briggs PH, Meier AL (2002) Chapter I, The determination of forty-two elements in geologic materials by inductively coupled plasma-mass spectrometry. In: Taggart JE Jr (ed) Analytical methods for chemical analysis of geologic and other materials. US Geological Survey Open-File Report 02-223-I, Denver, pp 1–20

Chaer GM, Myrold DD, Bottomley PJ (2009) A soil quality index based on the equilibrium between soil organic matter and biochemical properties of undisturbed coniferous forest soils of the Pacific Northwest. Soil Biol Biochem 41:822–830

Dalal RC (1998) Soil microbial biomass—what do the numbers really mean? Australian J Exp Agric 38:649–665

DeLucia EH, Schlesinger WH, Billings WD (1989) Edaphic limitations to growth and photosynthesis in Sierran and Great Basin vegetation. Oecologia 78:184–190

Dick RP, Breakwell DP, Turco RF (1996) Soil enzyme activities and biodiversity measurements as integrative microbiological indicators. In: Doran JW, Jones AJ (eds) Methods for assessing soil quality. Soil Science Society of America, Special Publication 49, Madison, pp 247–271

Doran JW, Parkin TB (1994) Defining and assessing soil quality. In: Doran JW et al (eds) Defining soil quality for a sustainable environment. Soil Science Society of America Special Publication 35, Madison, pp 3–21

Doran JW, Parkin TB (1996) Quantitative indicators of soil quality: a minimum data set. In: Doran JW, Jones AJ (eds) Methods for assessing soil quality. Soil Science Society of America, Special Publication 49, Madison, pp 25–37

Elliott ET, Heil JW, Kelly EF, Monger HC (1999) Soil structural and other physical properties. In: Robertson GP, Coleman DC, Bledsoe CS, Sollins P (eds) Standard soil methods for long-term ecological research. Oxford University Press, New York, pp 74–85

Garland JL (1996) Analytical approaches to the characterization of samples of microbial communities using patterns of potential C source utilization. Soil Biol Biochem 28:213–221

Gil-Sotres F, Trasar-Cepeda C, Leiros MC, Seoane S (2005) Different approaches to evaluating soil quality using biochemical properties. Soil Biol Biochem 37:877–887

Green VS, Stott DE, Diack M (2006) Assay for fluorescein diacetate hydrolytic activity: optimization for soil samples. Soil Biol Biochem 38:693–701

Halvorson JJ, Smith JL, Papendick RI (1996) Integration of multiple soil parameters to evaluate soil quality: a field experiment example. Biol Fertil Soils 21:207–214

Hill GT, Mitkowski NA, Aldrich-Wolfe L, Emele LR, Jurkonie DD, Ficke A, Maldonado- Ramirez S, Lynch ST, Nelson EB (2000) Methods for assessing the composition and diversity of soil microbial communities. Appl Soil Ecol 15:25–36

Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF, Schuman GE (1997) Soil quality: a concept, definition, and framework for evaluation. Soil Sci Soc Am J 61:4–10

Mallows CL (1973) Some comments on Cp. Technometrics 15: 661–675

Marquard DW (1970) Generalized inverses, ridge regression, biased linear estimation, and nonlinear estimation. Technometrics 12:591–612

Nortcliff S (2002) Standardization of soil quality attributes. Agric Ecosys Environ 88:161–168

Papendick RI, Parr JF (1992) Soil quality-the key to a sustainable agriculture. Am J Altern Agric 7:2–3

Rhoades JD (1996) Salinity: Electrical conductivity and total dissolved solids. In: Bartels JM (ed) Methods of soil analysis, Part 3: Chemical methods. Soil Science Society of America, Madison, pp 417–435

Robertson GP, Wedin D, Groffman PF, Blair JM, Holland EA, Nadelhoffer KJ, Harris D (1999) Soil carbon and nitrogen availability: nitrogen mineralization, nitrification, and soil respiration potential. In: Robertson GP, Coleman DC, Bledsoe CS, Sollins P (eds) Standard soil methods for long-term ecological research. Oxford University Press, New York, pp 258–271

Schlesinger WH, DeLucia EH, Billings WD (1989) Nutrient-use efficiency of woody plants on contrasting soils in the western Great Basin, Nevada. Ecology 70:105–113

Sikora LJ, Stott DE (1996) Soil organic carbon and nitrogen. In: Doran JW, Jones AJ (eds) Methods for assessing soil quality. Soil Science Society of America Special Publication 49, Madison, pp 157–168

Sinsabaugh RL, Klug MJ, Collins HP, Yeager PE, Petersen SO (1999) Characterizing soil microbial communities. In: Robertson GP, Coleman DC, Bledsoe CS, Sollins P (eds) Standard soil methods for long-term ecological research. Oxford University Press, New York, pp 318–348

Sojka RE, Upchurch RR (1999) Reservation regarding the soil quality concept. Soil Sci Soc Am J 63:1039–1054

Theodore TG, Blake DW, Loucks TA, Johnson CA (1992) Geology of the Buckingham stockwork molybdenum deposit and surrounding area, Lander County, Nevada. US Geological Survey Professional Paper 798-D

Thomas GW (1996) Soil pH and soil acidity. In: Bartels JM (ed) Methods of soil analysis, Part 3: Chemical methods. Soil Science Society of America, Madison, pp 475–490

Trasar-Cepeda C, Leiros C, Gil-Sotres F, Seoane S (1998) Towards a biochemical quality index for soils: an expression relating several biological and biochemical properties. Biol Fertil Soils 26:100–106

Winding A, Hund-Rinke K, Rutgers M (2005) The use of microorganisms in ecological soil classification and assessment concepts. Ecotox Environ Safe 62:230–248

Zornoza R, Mataiz-Solera J, Guerrero C, Arcenegui V, García-Orenes F, Mataix-Beneyto J, Morugan A (2007) Evaluation of soil quality using multiple lineal regression based on physical, chemical and biochemical properties. Sci Total Environ 378:233–237