Ecological Indicators 58 (2015) 244–253

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Biological indicators provide short term soil health assessment during sodic soil reclamation

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ARTICLE INFO

Article history:
Received 31 December 2014
Received in revised form 10 May 2015
Accepted 27 May 2015

Keywords:
AOA
AOB
Bioindicators
Gene copy numbers
Gypsum
Nitrification
qPCR
Remediation
Soil enzyme
Sodicity
Soil health
Subsurface tile drainage

ABSTRACT

Sodic soil remediation is an expensive, lengthy process during which producers need tools to demonstrate that sodium (Na^+) remediation practices are improving soil health. The objective of this study was to determine if soil biological indicators can provide a short term assessment of the effectiveness of chemical management strategies used to remediate northern Great Plains sodium affected soils. This randomized complete block split-plot research experiment was conducted in a grassland which was converted to annual row crops. The soil at the site was an Exline (fine, smectitic, frigid Leptic Natrudolls). The experiment contained two drainage treatments (tile drained and no-drainage) and four chemical amendments (4.5 Mg ha^{-1} of gypsum, 9.1 Mg ha^{-1} of gypsum, 9.1 Mg ha^{-1} spent sugar beet lime, and a no amendment control). Base-line soil samples for biological assessment were collected in the fall of 2012 after tile drainage was installed. The sodium adsorption ratio (SAR) ranged from 0.4 to 16.7 with a range of electrical conductivity (EC) of 0.4–0.8 dS m^{-1}. Gypsum and lime amendments were applied in 2013. Soil samples were collected for assessing soil health before and after application of amendments and throughout the growing season. This study utilizes a novel application of successional vector trajectories to compare shifts in measured soil health parameters associated with land use change and remediation of sodicity. Soil samples were analyzed for percent total soil carbon (C), nitrifier and denitrifier gene copies, soil enzyme assays (nitrate reductase, ammonia monooxegenase, urease, β glucosidase, alkaline phosphatase, arylsulfatase and fluorescein diacetate hydrolysis), EC, pH, SAR, and soil texture. Gene copies and enzyme activities were successfully used to differentiate between land uses and amendment applications. Ammonia oxidizing bacterial gene copies were higher where cropland was amended with gypsum. Successional vectors verified a significant shift in soil health due to land use change and amendment application. Gypsum applications reduced SAR, but increased soil EC. This work demonstrates that soil enzyme activities and gene copy numbers can be used to detect improvements in soil health.

1. Introduction

Worldwide salt affected soils encompass 10% of Earth's terrestrial surface (Pessarakli and Szabolcs, 1999). Currently, the distribution of sodic soils worldwide is increasing due to poor land management decisions and irrigation with poor quality water (Qadir and Oster, 2004). Increases in sodic soil distribution have occurred in China, central Asia (Cai et al., 2003; Gupta and Abrol, 2000); and Australia, where nearly 60% of the agricultural land is sodic (Rengasamy, 2006). In the United States, sodic soils are defined as having a sodium adsorption ratio (SAR) (ratio of sodium to calcium and magnesium) of 13 or greater, an exchangeable sodium percentage greater than 15, electrical conductivity (EC) of less than 4 dS m^{-1}, and pH of 8.5 or greater (Richards, 1954). Excess Na^+ on the cation exchange sites causes clay particles to disperse or swell, and as a consequence these soils have poor structure, low aggregate stability, and reduced water infiltration (Rengasamy and Olsson, 1991). Overall, sodic soils are a poor rooting medium for plant growth and provide lowered or insufficient nutrients. Sodic soils also have reduced biological activity and function due to the

Abbreviations: EC, electrical conductivity; SAR, sodium adsorption ratio; AOA, ammonia-oxidizing archaea; AOB, ammonia-oxidizing bacteria; AOA:AOB, ratio of ammonia-oxidizing archaea to ammonia-oxidizing bacteria; TC, total carbon; IC, inorganic carbon.

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http://dx.doi.org/10.1016/j.ecolind.2015.05.059
1470-160X/

limited availability of C substrates that are likely the result of lowered net primary productivity in these soils (Rao and Pathak, 1996).

Remediating the effects of excess Na^+ in sodic soils can be accomplished with soil amendments and land management. Calcium amendments have been shown to reduce the effects of sodicity. Calcium flocculates clay particles leading to improvements in soil structure (Frenkel et al., 1989). Calcium also replaces Na^+ on soil exchange sites and is frequently correlated with increases in soluble Na^+ (Ilyas et al., 1997). Rates of gypsum application can be calculated by taking into account soil cation exchange capacity, target SAR, and current SAR values (Ashworth et al., 1999). After chemical treatment subsurface tile drainage may be used to remove excess sodium from the rooting zone (Pessarakli and Szabolcs, 1999). Subsurface drainage can also prevent salt accumulation due to fluctuations in water table depth, capillary rise, and evaporation (Abrol et al., 1988).

In order to provide advice to growers with respect to whether their management strategies have begun to bring about the changes they anticipated, a tool capable of detecting short term improvements is needed. Successful remediation of sodicity may take years and can be costly (Qadir and Oster, 2002). Soil health is defined as "the capacity of soil to function within ecosystems and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant, animal, and human health" (Doran and Parkin, 1994). Use of biological indicators of soil health as a proxy for shifts in nutrient cycling resulting from land use change, amendment application and tile drainage installation will aid in the early detection of effective remediation strategies, potentially reducing the cost and environmental impact of remediation (Ritz et al., 2009; Wessén and Hallin, 2011; Wessén et al., 2011; Fortuna et al., 2012). Additionally, identifying soil health indicators and monitoring changes in these soil properties will aid land owners in ensuring the long–term productivity of the land. Currently, biological soil health indicators are not widely used to assess remediation progress.

The objectives of this study were to: (1) derive a set of soil health indicators that include functional gene copy numbers and soil enzyme activities in order to assess the effectiveness of these bioindicators in differentiating among land use change, application of soil amendments, and tile drainage treatments used for Na^+ remediation; and (2) determine the magnitude of shifts in soil health parameters using successional vector trajectories following land use and management changes in a northern Great Plains sodic soil.

2. Materials and methods

2.1. Study site

The study area was located in Richland County, North Dakota (46°16′53.843″ N, 97°15′26.893″ W) and has a continental climate with an average temperature of 5.8 °C with a 20 year mean annual precipitation of 465 mm (NDAWN, 2014). The cumulative rainfall throughout the study period is shown in Fig. 1. The study site was located on a sodic Exline loam, sandy substratum soil (Fine, smectitic, frigid Leptic Natrudolls) (Soil Survey Staff, 2014). This soil series was formed from Glacial Lake Agassiz sediments, is characterized by high water tables and is affected by excess sodium chloride (NaCl), sodium sulfate ($NaSO_4$), calcium sulfate ($CaSO_4$), and magnesium sulfate ($MgSO_4$) salts (Franzen, 2003).

2.2. Experimental design

At the onset of the experiment the field was managed as a long-term cool-season perennial hayland. In 2012, tile drainage was installed and the field was plowed, disked, and prepared to be seeded with annual crops. The field experimental design was a randomized complete block split-plot. The experiment contained 3 blocks and each plot was 24 × 24 m. The factorial treatments were 2 drainage treatments and 4 chemical amendments. Whole plot treatments included free drainage and a no drainage control. Tile drainage (10.2 cm diameter, sleeved) was installed to a 1.2 m depth. Four soil amendments were applied on May 14 and 15, 2013. Split plot treatments included soil amendments of 4.5 Mg ha^{-1} of gypsum, 9.1 Mg ha^{-1} of gypsum, 9.1 Mg ha^{-1} spent sugar beet lime, and a no amendment control. Sugar beet lime, which is predominantly calcium carbonate is a by-product of sugar purification (American Crystal Sugar, 2008) and is readily available locally. The 9.1 Mg ha^{-1} gypsum was spread using a spinner type broadcast spreader. The 9.1 Mg ha^{-1} lime and 4.5 Mg ha^{-1} gypsum were spread evenly across plots by hand. Fertilizer was applied prior to planting at a rate of 168.0 kg N ha^{-1}, 67.3 kg P ha^{-1}, 16.8 kg K ha^{-1} potassium and 1.9 kg Zn ha^{-1}. Corn (*Zea mays* L.) was planted on May 15 and 16 of 2013.

2.3. Soil sampling

Soils were sampled from a 1 m^2 geo-referenced area offset by 6 m of the installed tile drainage lines or from the plot center in no drain plots. Three composited soil samples were collected from each plot to a 0–30 cm depth using a JMC mud auger (8.3 cm diameter, Clements Associates, Inc., Newton, IA, USA). Soils were stored at −20 °C until further analysis. Soil was collected on October 2 (fall 2012), May 10 (spring 2013), August 1, 2013 (corn silking), and September 27 (fall 2013) (Fig. 1).

2.4. Chemical and physical analysis of soil

The chemical analysis for pH, EC, SAR, concentration of Mg^{2+}, Ca^{2+}, and Cl^-, total soil carbon (TC), and inorganic soil carbon (IC) was conducted on air-dried ground (<2 mm) soil. Both soil pH and EC were measured on a 1:1 soil to water ratio as described by Combs and Nathan (1998) and on saturated paste extracts as described by Rhodes (1996). An atomic adsorption spectrophotometer (Buck Scientific Model 200A, East Norwalk, CT, USA) was used to determine concentrations of Na^+, Mg^{2+}, and Ca^{2+} in saturated paste extracts. The SAR was then calculated as outlined by Richards (1954). An ion specific electrode (Cole–Parmer combination chloride electrode, Vernon Hills, IL, USA) was used to measure Cl^- on the saturated paste extract. An Elementar Vario MACRO cube CNHS analyzer was used to test TC (Elementar Americas Inc. Mt. Laurel, NJ, USA). Inorganic C was removed using 1 M phosphoric acid and the difference between TC and IC was considered to be total organic carbon (TOC). Total soil C and IC were measured once and assumed to be constant throughout the study.

Soil texture was determined once on air dried, ground soils sampled in fall 2012. Silt and clay contents were measured using the hydrometer method outlined by Gee and Bauder (1986). Sand contents were determined by sieving. Gravimetric water content was determined for all field samples on each sample date.

2.5. DNA extraction and functional gene quantification

DNA was extracted from soils in order to determine if functional gene copy numbers can be used as a sensitive indicator of nutrient cycling and overall soil health. Functional gene copy numbers represent the population of organisms capable of producing an enzyme required for the turnover of a given nutrient such as N, P, or S. Rapid changes in copy numbers can occur as organisms reduce or increase their metabolic response to shifts in nutrient availability. Gene copy numbers can be used as either short-term or long-term indicators