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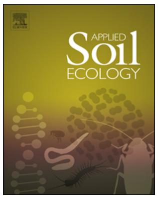

Stratification of soil chemical and microbial properties under no-till after liming

Victoria P. Barth[a], Catherine L. Reardon[b], Todd Coffey[c], Ann M. Klein[b], Carol McFarland[a], David R. Huggins[d], Tarah S. Sullivan[a,*]

[a] Washington State University, Department of Crop and Soil Sciences, Pullman, WA 99164, United States
[b] Soil and Water Conservation Research Unit, USDA Agricultural Research Service, Adams, OR 97810, United States
[c] Washington State University, Center for Interdisciplinary Statistical Education and Research, Pullman, WA 99164, United States
[d] Northwest Sustainable Agroecosystems Research Unit, USDA Agricultural Research Service, Pullman, WA 99164, United States

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ABSTRACT

Soils under continuous no-till (NT) often produce stratified soil acidification due to fertilizer placement and subsequent lack of mixing. Because aluminum (Al) becomes more bioavailable with lower soil pH, Al toxicity is an emerging problem in many soils throughout the Palouse region in the dryland cropping areas of the inland Pacific Northwest of the United States. When various lime materials are surface applied to NT soils, the depth to which these materials may impact soil pH, available Al, and microbial community response has not been explored in the fine-silty soils of this arid region. The objectives of the current study were to: (1) determine if soil sampling at small, discrete depth increments captures stratification of chemical and microbial properties in NT soils and (2) evaluate the impacts of two types of surface-broadcast lime on Al availability and microbial community composition at each depth interval. In April 2014 and 2015 (6 mo and 18 mo after liming), soil samples were collected at 2-cm depth increments and analyzed for soil pH and metals bioavailability, as well as microbial community composition using terminal restriction fragment length polymorphism analysis. In 2015, surface soil (0–2 cm) pH increased from 4.6 in untreated control to 6.6 in limed plots, and KCl-extractable Al decreased from approximately 50 mg kg^{-1} to below 10 mg kg^{-1} in the 2–4 cm depth of soil. The surface soil microbial community composition changed significantly in response to lime application, and was highly correlated with soil pH and Al concentrations. No significant effects of treatment were detected when data were pooled across the 10 cm depth. The 2-cm sampling increments provided statistically significant resolution in soil chemical stratification and related shifts in microbial community composition, revealing different effects at different depths. We are able to conclude from this study that (1) A finely resolved, spatially explicit sampling design is necessary to capture soil chemical stratification complexity within a variety of variables, and microbial community response over time; and (2) Surface application of lime in Palouse NT systems will take > 18 mo to be effective at depths below 6 cm.

1. Introduction

The fertile soils of the Palouse, a dryland cropping region of the inland Pacific Northwest (PNW) in the United States, have been under predominantly conventional tillage (CT) for nearly a century, meaning that soils were annually inverted to a depth of up to 0.3 m and thoroughly mixed. However, because much of the region is characterized by expansive, undulating hills of loess-derived soils, erosion has historically been significant, threatening the region's agricultural sustainability. While CT remains the dominant form of cultivation practiced in the region, the acreage of agricultural land under no-till (NT) (lacking soil inversion) has grown and is greatly reducing soil erosion losses (McCool et al., 2001).

Growers in the inland PNW have been converting to NT for many reasons, including increased concentrations of soil organic carbon (Brown and Huggins, 2012), increased microbial biomass and activity (Alvear et al., 2005; Peigné et al., 2007), reduced greenhouse gas emissions (Stockle et al., 2012; Gibbons et al., 2014), and increased overall soil health (Triplett and Dick, 2008; Morrow et al., 2016). The lack of soil disturbance under NT may also promote unwanted consequences (Sullivan et al., 2016). Reduced mechanical mixing of the soil, combined with subsurface (4–8 cm depth) banding of ammonia-

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* Corresponding author.
E-mail address: t.sullivan@wsu.edu (T.S. Sullivan).

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based fertilizers can lead to exacerbated soil nutrient stratification with extremely low pH, below 5.0 in many cases, reported at and below the fertilizer-placement zone (Brown et al., 2008; García-Marco et al., 2014; Karlen et al., 2013).

Soil acidification is becoming a significant concern in the Palouse, where the pH of agricultural surface soils (0–30 cm) have decreased from near-neutral pH in the 1960s (Mahler and Harder, 1984) to less than pH 5.2 in 21% of surveyed soils in 1995 (Mahler, 2002). The zone surrounding fertilizer placement is of particular interest in NT due to problems with exacerbated acidification. In one NT research field located in this region, the soil pH ranged from 5.1 in the top 0–5 cm to 6.3 in the lower 20–30 cm with a pH of 4.7 at the precise depth of fertilizer placement (Brown et al., 2008). This is particularly problematic because this pH is below the critical level for optimal yields of cereals (pH 5.2–5.4) or legumes (pH 5.4–5.6), which are the top two economically significant crops in the inland PNW (Mahler and McDole, 1987; Mahler and Harder, 1984).

Soil acidification poses a hurdle to agricultural productivity in many regions around the world, primarily due to the increased aluminum (Al) bioavailability that is associated with soil acidity. Aluminum-containing soil minerals undergo pH-dependent dissolution in acidic environments, which increases concentrations of bioavailable forms of Al in soil solution (Silva, 2012; Soti et al., 2015; Sposito, 2008). Dissolved Al^{3+} in soil solution interferes with crop growth by competing with plant nutrients, including calcium (Ca), manganese (Mn), phosphorous (P), and iron (Fe) (Seguel et al., 2015). This competition with plant nutrients results in deficiencies, which along with general Al phytotoxicity, can significantly reduce crop yields and soil productivity.

Soil acidification and impacts on crop yield in recent years have boosted interest in farm management practices that raise soil pH and/or slow the acidification process. Lime, or CaCO$_3$, applications are often effective at increasing soil pH in addition to improving overall soil health (Bennett et al., 2014) by increasing soil total organic carbon concentrations and enhancing many aspects of soil structure (Mrabent et al., 2017). In soils of many tropical regions, lime applications have increased soil productivity and yields (Ila'ava et al., 2000; Laxminarayana et al., 2015; Nolla et al., 2013) and can be effective to great depths, even in NT systems (Caires et al., 2008; Costa et al., 2016). However, lime represents a substantial cost to farmers (Gibbons et al., 2014), and finding local sources of lime may significantly reduce overall costs while also resulting in a variety of lime materials with distinct characteristics and impacts (Carrizo et al., 2014).

Both soil pH and Al bioavailability, as well as subsequent liming, can influence microbial community structure and function. While NT can intensify soil stratification of pH and Al bioavailability, little is known regarding the response of the microbial communities to zones of acidification in soils of the inland PNW. Even less is known concerning the dynamic interactions of the microbial community with locally-sourced liming materials on stratified soil pH and Al bioavailability (Brown et al., 2008). Additionally, detailed characterization of NT stratified soil at highly resolved depth increments (2-cm) has not been previously used to determine the effectiveness of liming in the fine-silty soils of the arid, dryland cropping region of the inland PNW. Therefore, the objectives of this study were to: (1) determine whether soil sampling at small, discrete depth increments captures stratification of chemical and microbial properties in NT soils, and (2) evaluate the soil chemical and microbial impacts of two types of locally-sourced, surface-broadcasted lime materials at each depth interval.

2. Materials and methods

2.1. Field sites and liming treatments

This study was initiated in the fall of 2013 at two sites within the Palouse region of the inland PNW with an established history of continuous NT. The first site is located on the Palouse Conservation Field Station (PCFS) near Pullman, WA (46° 45′N, 117° 11′W, 800 m a.s.l.) and is thoroughly described by Brown et al. (2008). Soil at the PCFS site formed under native prairie vegetation and the dominant soil series is Thatuna silt loam (Fine-silty, mixed, superactive, mesic, Oxyaquic Argixeroll) with 3–25% slopes and a Mediterranean type climate with 60% of the annual precipitation (460–580 mm yr^{-1}) occurring during the period from November to March (Soil Survey Staff 1990; McCool et al., 2001). The second site, Rockford (RF), is located near Freeman, WA (47° 31′N, 117° 11′W, 730 m a.s.l.), approximately 80 km north of the PCFS site. At RF, just as at the PCFS site, the dominant soil series is also Thatuna silt loam, with 3–7% slope, but precipitation at RF is slightly lower than at PCFS (averaging 350–400 mm yr^{-1}), and soils at RF historically formed under evergreen forest vegetation.

At each research locations, the experiment had a completely randomized block design with three replications of each treatment, including two individual lime treatments, and plots receiving no-lime (control), resulting in a total of nine experimental plots at each site. Experimental plots at PCFS were 5.5 m × 12.2 m, while at RF grower constraints led to a slightly adjusted plot size of 4.9 m × 9.1 m. At PCFS since 2010 and at RF since 2003, the sites have been continuously under NT management with a varying winter wheat-pulse crop rotation, using a drill equipped with inverted T-openers.

Soil liming treatments consisted of either a liquid-lime emulsion (NuCal, Columbia River Carbonates, Woodland, WA, USA), or a dry-particulate pulp derived from the processing of sugar beets (*Beta vulgaris* subsp. *vulgaris*). NuCal liquid lime (NLL) is a fluid CaCO$_3$ with an average particle size of 1–2 μm and a calcium carbonate equivalence (CCE) of 98%. Sugar beet lime (SBL, Moses Lake, WA, USA), a by-product of table sugar production, is a carbon-rich, mixed-nutrient, and mixed particle-size material with a CCE of 83% (Table 1).

The application technique varied between lime types due to the physical differences in the materials. A typical pesticide-sprayer mounted on a tractor was utilized for application of NLL, while the SBL was crushed, homogenized, and sieved to 2 mm for broadcast, hand-application. Both liming materials were applied over the undisturbed residue of the previous crop at a rate of 2240 kg ha^{-1} CCE in November 2013.

2.2. Soil sampling and processing

Soil samples from each site were collected in late April 2014 (6 mo after liming) and again in late April of 2015 (18 mo after liming). April dates in each year represented the fallow period between harvest of rotational crops, before planting of the new crop. Samples were

Table 1
Chemical constituents of NuCal liquid lime (NLL) compared to sugar beet lime (SBL).

	NLL[†]	SBL
	%	
CCE[‡]	98	83
H_2O	2	8
NO_3	–	0.7
NH4	–	1.0
OM	–	3.9
Mg	–	1.3
	mg kg^{-1}	
Al	–	1930
B	–	5.5
Cu	–	22
Fe	–	1010
Mn	–	83
Zn	–	21

[†] NLL contains only water and calcium carbonate, so all other components are absent and therefore represented with a dash.

[‡] Calcium carbonate equivalent, acid-neutralizing capacity.