DRAMATIC SOIL HEALTH CHANGES AFTER 18 YEARS OF DIFFERENT NITROGEN RATES AND CROPPING SYSTEMS IN THE NORTHERN GREAT PLAINS

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ABSTRACT

Relatively few long-term cropping and nitrogen (N) rate studies have been conducted in the semi-arid northern Great Plains that assess soil health changes. A cropping system study was initiated in 2002 in Bozeman, Montana (~16 in. annual precipitation) with wheat grown in even years, and either tilled fallow or one of the following no-till systems in odd years alternated with wheat: fallow (NTF-W), wheat (CW), pea grain (Pgrain-W), pea hay (Phay-W), pea green manure (PGM), and an alfalfa-grass until 2012 followed by pea grain (CRP/Pgrain-W). N was applied at either 50% or 100% of the recommended N rate based on soil nitrate levels, yield goals and pulse N credits. After 18 years, pH was nearly 1 unit higher in Pgrain-W and PGM, than CW, likely due in part to much lower N rates in pulse-systems. The fraction of water stable aggregates (1-2 mm) was lower in both fallow systems and PGM than in Pgrain-W and CW, likely due to differences in residue returned. Infiltration rates (double ring) were 7-fold higher in recrop than fallow treatments, likely because of more aggregates in recrop, but possibly due to more permanent root channels in recrop favoring preferential flow. The geometric mean of four enzyme concentrations was higher in the CRP/Pgrain-W than in either fallow wheat system. These results demonstrate the importance of cropping systems and N rates on soil health in a semi-arid region, and the value of long-term studies at detecting soil health changes.

INTRODUCTION

While it is generally understood that cropping systems and N rate can affect soil health for a myriad of reasons, often related to residue quantity (Engel et al. 2017) and quality, it is generally challenging to detect soil health changes in short-term studies especially in semi-arid regions because of low amounts of residue returned. Therefore, it is important to evaluate soil health from long-term cropping studies in semi-arid regions such as the northern Great Plains. A study was commenced in 2002 near Bozeman, Montana to initially assess the effects of cropping system and N rate on greenhouse gas emissions, grain yield, grain quality, and net revenue. For 2009-2012 of this study, Miller et al. (2015) found that net revenue was consistently much higher for Pgrain-W than the other six rotations evaluated, regardless of N rate or assumed protein discount. The perennial system had reduced net revenue for four years after it was converted to an annual system (2012-2016), due to deep water use of perennials combined with excess N that might have resulted in excess water use early in the growing season of annuals (Miller et al. 2019). This study, hereafter referred to the greenhouse gas rotations study (GGRS), has provided an excellent opportunity to also evaluate soil health response to cropping system and N rate.

O'Dea et al. (2015) found that 8-years of cropping in GGRS resulted in 50% higher PMN and 30% higher microbial biomass carbon (MBC) for legume-containing rotations (Pgrain-W and PGM-W) than wheat only systems (NTF and CW). The 1 – 2 mm water stable aggregate (WSA) fraction was nearly 2-fold higher in the higher residue CW and Pgrain-W systems than PGM-W and NTF. Engel et al. (2017) found that soil organic carbon (SOC) pools (equivalent mass in top foot) after ten years were 1-3 ton C ac^{-1} higher in all recrop systems than in tilled fallow. Residue C returned (measured shoot plus calculated root from published root:shoot ratios) was highly correlated ($r^2 = 0.86$) to change in SOC pool over the ten years, despite differences in C:N ratios among residues. This analysis determined that a 'critical' level of 1.2 ton ac^{-1} per year of residue was needed to maintain SOC levels, which is challenging to accomplish in a 16 in. rainfall zone. This critical residue C level was not attained in either fallow system at either N rate in the first ten years of the study but was exceeded in both the CW and Pgrain-W systems when averaged across N rate (residue returned for the CRP system, where roots would have dominated, was not evaluated).

The final year of the GGRS's annual cropping x N rate study was completed in 2020, 18 years after initiation of the study. This provided an excellent opportunity to evaluate long term effects of cropping and N rate on a range of biological, chemical, and physical soil parameters.

MATERIALS AND METHODS

Site

The study is located approximately four miles west of Bozeman, Montana, at the Arthur Post Research Farm. The site receives 16.3 inches of annual precipitation, and soils are Amsterdam silt loams (fine-silty, mixed, superactive, frigid Typic Haplustolls).

Design

The GGRS design is described in more detail in previous studies (Miller et al. 2015; Engel et al. 2017) but the rotations are summarized in Table 1 (next page). The cropping systems that our project focused on included tilled wheat fallow (TillF), and no-till fallow wheat (NTF), continuous wheat (CW), wheat alternated with a pulse (Pgrain, Phay, or PGM), and a mixed perennial/annual system (CRP/ Pgrain-W). The study has 4 blocks in a randomized complete block design. Each plot was split and wheat received either 3 lb available N bu^{-1} or 1.5 lb available N bu^{-1}, where available N = soil nitrate-N to 3 ft + pulse N credit + fertilizer N.

Table 1. Crops grown and total N fertilizer applied in GGRS study near Bozeman, Montana.

Year	Till F	NTF	CW	Pgrain	Phay	PGM	CRP/P
2003	Ftill	Fnt	SWht	WPea	WPha	WPha	Alf/grs
2004	WWh	WWh	WWh	WWht	WWht	SWht	Alf/grs
2005	Ftill	Fnt	SWht	WPea	WPha	WPha	Alf/grs
2006	WWh	WWh	WWh	WWht	WWht	SWht	Alf/grs
2007	Ftill	Fnt	SWht	WPea	WPha	WPha	Alf/grs
2008	WWh	WWh	WWh	WWht	WWht	SWht	Alf/grs
2009	Ftill	Fnt	SWht	SPea	SPhay	SPbm	Alf/grs
2010	SWht	SWht	SWht	SWht	SWht	SWht	Alf/grs
2011	Ftill	Fnt	WWh	WPea	WPha	WPb	Alf/grs
2012	WWh	WWh	WWh	WWht	WWht	WWht	Alf/grs
2013	Ftill	Fnt	SWht	SPea	SPhay	SPbm	SPea
2014	SWht	SWht	SWht	SWht	SWht	SWht	SWht
2015	Ftill	Fnt	WWh	WPea	WPha	WPb	WPea
2016	WWh	WWh	WWh	WWht	WWht	WWht	WWht
2017	Ftill	Fnt	SWht	Lentil	CCMh	CCMb	Lentil
2018	SWht	SWht	SWht	SWht	SWht	SWht	SWht
2019	Ftill	Fnt	WWh	WPea	WPha	WPb	WPea
2020	WWh	WWh	WWh	WWht	WWht	WWht	WWht
Full N (lb/ac)	1496	1547	2840	1426	1336	1115	659
½ N (lb/ac)	516	588	1655	481	340	266	146

Ftill -tilled fallow; Fnt – no till fallow, WP – winter pea, CCMhay – cover crop mixture, hayed, SWht- spring wheat, Wwht – winter wheat, bm – brown manure (sprayed out cover)

Analyses

Biological (Enzymes, Potentially Mineralizable N, Microbial Biomass).

To test the effects of fertilizer N and cropping system on biological aspects of the soil, we measured soil enzyme activity, potentially mineralizable N, and substrate induced respiration (SIR) as an estimate of microbial biomass. Soils were sampled with a hand probe to a depth of 6 inches at the end of May 2020 (a few weeks after fertilization but while the plants were still small) for enzyme activity and subsampled again in in mid-October 2020. We measured activity of soil enzymes associated with N cycling (B-glucosaminidase), P cycling (acid and alkaline phosphatase), S cycling (arylsulfatase), and OM decomposition (B-glucosidase), by incubating 1 g of soil with a dye-labeled substrate. Activity was measured colorimetrically in the lab. Geometric mean was the 4th root of the product of the four enzymes (acid and alkaline phosphatase were summed to created one value). PMN was measured with a 14-d anaerobic incubation (Keeney and Nelson, 1982). Substrate induced respiration was analyzed with additions of autolyzed yeast and reported here as microbial biomass (Fierer et al. 2003).

Wheat was grown across all treatments during 2020, so comparison of spring versus fall measures of soil enzymes will tell us whether the subsequent wheat crop homogenizes any differences brought about by contrasting cropping systems of the previous growing season.

Chemical (pH, SON, SOC).

Soil was sampled with a hydraulic probe truck after harvest in 2020 and analyzed for SOC and SON via combustion on an acidified sample to remove carbonates (0-4, 4-8, and 8-12 in.) and for pH on a 1:1 soil:water (0-4 and 4-8 in.)

Physical (Water stable aggregates, infiltration rates).

Water stable aggregates were analyzed in the top 6 in. of all subplots by air drying and dry sieving to obtain aggregates that were 1 to 2 mm in diameter. These were then subjected to humidification and shaking in a water bath followed by re-sieving to determine the percent of water stable aggregates. Infiltration rate was determined only on the full N treatments given the extensive time involved in infiltration measurements. Three double ring infiltrometers (12 in. outer, 6 in. inner) were pounded into the soil in each tested subplot from Sep 23 to 25, 2020, avoiding noticeable tire tracks, filled with water, and equilibrated until infiltration rate was steady. The rings were then topped with water, and the water level in the inner ring monitored 3 to 5 times until all the water infiltrated. Infiltration rates were determined by linearly regressing water level versus time.

RESULTS AND DISCUSSION

Results for all data are below except for SON and SOC which we hope to have in time for the conference.

Biological

The CRP/Pgrain-W system had 90% higher geometric mean enzyme activity than tilled fallow, and all rotations with pulses had higher geometric means than tilled fallow (Table 1). That pattern roughly follows our hypotheses that including N-fixing crops and increasing biomass available to the soil increases enzyme activities, and hence nutrient cycling rates. Surprisingly, crop rotation did not affect PMN at P=0.05, like it did ten years previously when the two pulse-containing systems had higher PMN than wheat-only systems (O'Dea et al 2015). In both studies, soils were collected for PMN analysis about nine months after crop harvest or PGM termination, although we used a 14-d anaerobic incubation while O'Dea et al. measured PMN with a 112-d aerobic incubation. Interestingly, O'Dea et al. found increasing significance of the pulse-containing v. wheat-only contrast when incubation time increased from 7-d (P=0.38) to 14-d (P=0.08) to 112-d (P=0.01). In addition, N rate did not affect PMN. Substrate induced respiration was 40% higher in the CRP/Pgrain treatment than in tilled fallow (Table 1), demonstrating the benefits of no-till and high amounts of residue, especially roots, on biological activity. The SIRs of all other treatments were intermediate.

Chemical

Soil pH in the CW treatment applied with the full N rate was about 5.8 which was more than 1 unit lower than pH in the Pgrain-W and CRP/Pgrain-W, likely because CW had by far the most N applied (Table 1). The other four treatments had intermediate pH levels. N fixation is reduced below about pH 6, although cereals generally don't exhibit aluminum toxicity symptoms until below about pH 5.2. The pH of Pgrain-W system was only slightly lower than the initial pH level of 7.4 in 2002. Soil pH was about 0.2 units higher in the ½ N rate treatments and soil pH in the 4 – 8" depth was 0.1 to 0.6 units higher than in the 0 – 4" depths (data not shown). Soil pH had dropped by 0.4 units since last measured in 2016 (Engel unpub. data), which is concerning, especially in the CW treatment.

Table 1. Selected soil health parameters for GGRS study near Bozeman after 18 years.

Rotation	Enzyme geometric mean^{1,2} (mg PNP g soil^{-1} hr^{-1})	Substrate induced respiration^{1} (uL CO_2 g^{-1}-soil hr^{-1})	Soil pH (1:1) for full N rate^{3}	Water stable aggregates in top 6 in.^{1} (g g^{-1}-soil)
Till fallow	477 c^{4}	40.9 b	6.79 ab	0.318 c
NT fallow	563 bc	47.9 ab	6.70 ab	0.375 bc
CW	780 abc	52.3 ab	5.76 b	0.442 a
Pgrain-W	812 ab	50.6 ab	7.15 a	0.438 a
Phay-W	672 ab	41.8 ab	6.37 ab	0.427 ab
PGM-W	812 ab	46.7 ab	6.81 ab	0.376 bc
CRP/Pgrain-W	923 a	57.6 a	6.89 a	0.412 ab
Rotation P-value	0.01	0.10	0.03	0.05
N rate P-value	0.14	0.31	<0.01	0.89

[1] Averaged across two N rates

[2] Fourth root of product of four enzyme concentrations

[3] Soil pH values are for the full N rate

Values that have no matching letters are different with 90% probability

Physical

The range of infiltration rates among treatments was remarkable (Fig 1). Recrop treatments had 7-fold higher infiltration rates than the two fallow treatments, though surprisingly there were no differences between the no till and tilled fallow systems. Higher rates of infiltration in recrop might be due to conditions at the soil surface where the soil is protected for longer periods from rain splash, higher aggregation associated with higher SOC, or producing and maintaining more macropores, and hence increased preferential flow. Higher infiltration rates should decrease runoff and ponding and move water more quickly below the soil surface, which should decrease evaporative losses. The WSA fractions were 20 to 35% higher in the CW and Pgrain-W systems than in the two fallow treatments and PGM treatment with the other two treatments

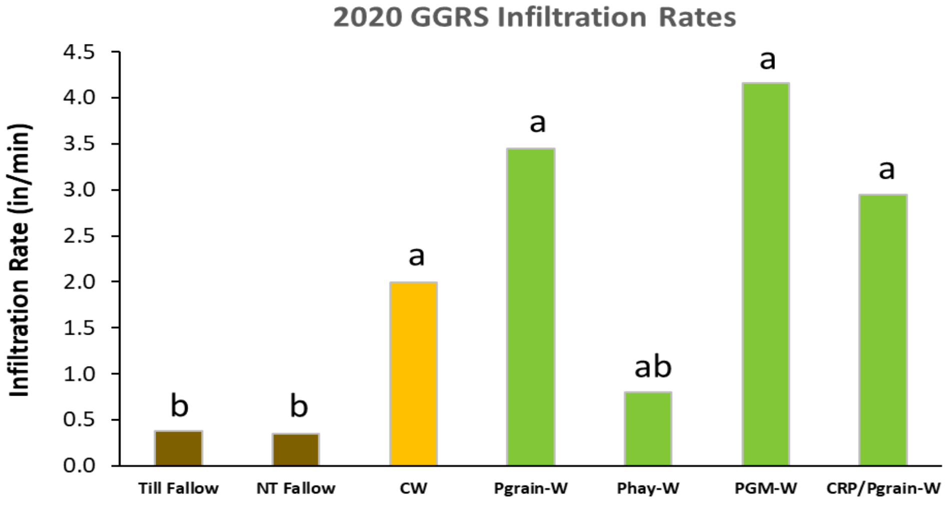

Figure 1. Infiltration rates following 18 years of seven crop rotations (full N rate) near Bozeman. Lack of the same letter above 2 bars indicates that the mean infiltration rates of those treatments are different with at least 90% probability.

intermediate. This is generally in agreement with residues returned (Engel et al. 2017), which makes sense given the importance of SOC and dissolved carbon on promoting aggregation (Schoenau and Campbell 1996); however, given the much smaller differences in WSA than infiltration, the combined results strongly suggest that infiltration rates are controlled by more than aggregate stability.

SUMMARY

In general, recrop systems generally produced higher levels of soil health parameters than fallow, and especially more than tilled fallow. Infiltration rates were dramatically lower for fallow than recrop systems (except Phay). Within the five recrop systems, Pgrain-W and CRP/Pgrain-W had similar levels of soil health parameters as CW, except for pH, which was much higher in the two legume systems than the CW treatment, where pH had fallen 1.5 units in only 18 years due to much higher N rates. Despite increasing popularity in cover crops and annual forages, largely due to connections with soil health, the PGM-W and Phay-W treatments generally did not improve soil health over systems where grain was harvested. Most importantly, this study showed the power of cropping systems to affect soil health in a semi-arid region.

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