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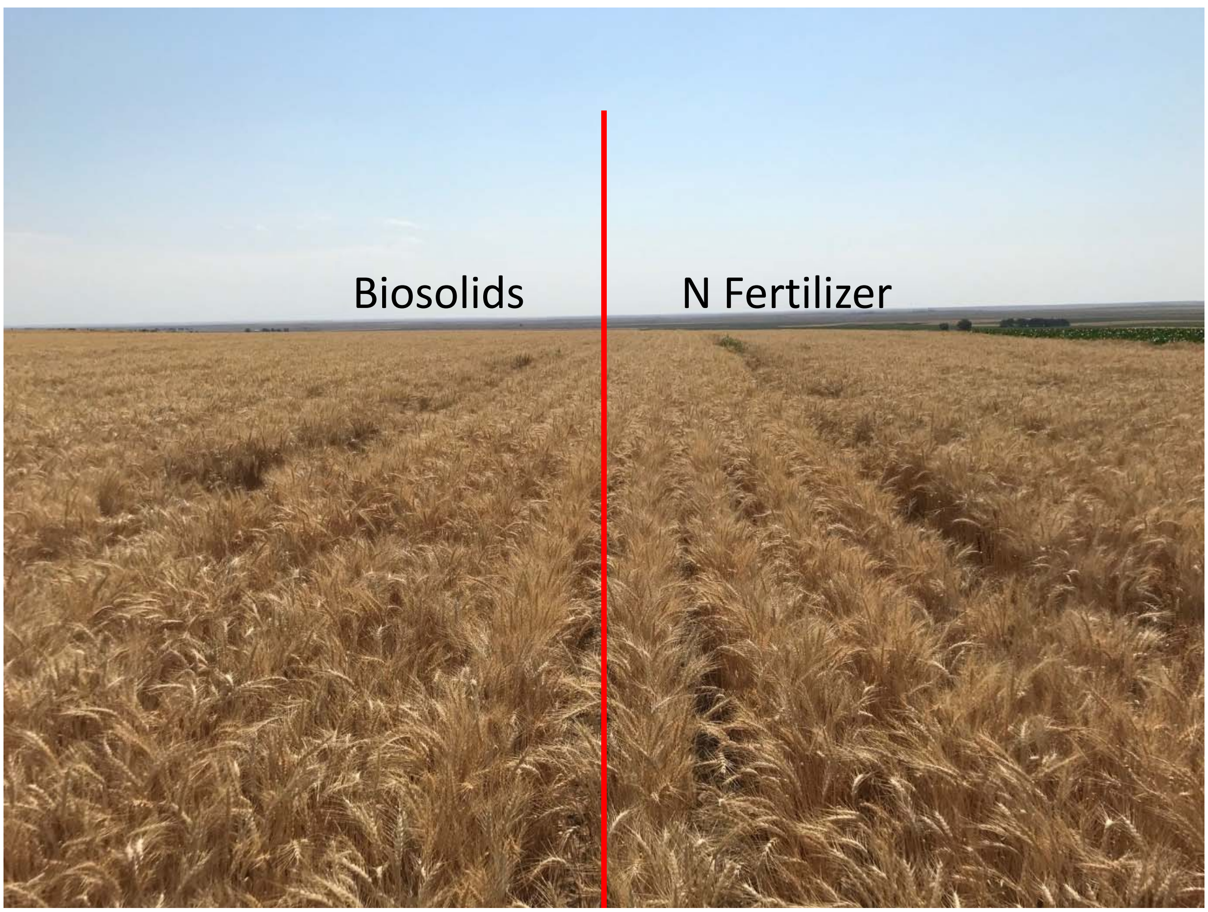
Biosolids Application to No-Till Dryland Rotations: 2016 Results



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Biosolids Application to No-Till Dryland Crop Rotations: 2016 Results

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INTRODUCTION

Biosolids recycling on dryland winter wheat (*Triticum aestivum*, L.) can supply a reliable, slow-release source of nitrogen (N) (Barbarick et al., 1992). Barbarick and Ippolito (2000, 2007) found that continuous application of biosolids from the Littleton/Englewood, CO wastewater treatment facility to dryland winter wheat-fallow rotations provides about 16 lbs N per dry ton. This research involved tilling the biosolids into the top 8 inches of soil. Questions related to soil management in a biosolids beneficial-use program are: Can biosolids be used in no-till agroecosystems? Furthermore, do surface-applied biosolids produce similar crop yields, grain elemental concentrations, and soil extractable elemental concentrations as compared to inorganic N fertilizer?

Our objective was to compare agronomic rates of commercial N fertilizer to an equivalent rate of biosolids in combination with WF and WCF crop rotations in a no-till agroecosystem. Our hypotheses were that biosolids addition, compared to N fertilizer, would:

1. Produce similar crop yields;
2. Not differ in grain P, Zn, and Cu levels;
3. Not differ in soil P, Zn, and Cu AB-DTPA extractable concentrations, a measure of plant availability (Barbarick and Workman, 1987); and
4. Not affect soil salinity (electrical conductivity of saturated soil-paste extract [EC]), pH or soil accumulation of nitrate-N (NO_3-N).

MATERIALS AND METHODS

In 1999, we established the experiment on land owned by the Cities of Littleton and Englewood (L/E) in eastern Adams County, approximately 28 miles east of Byers, CO. The latitude longitude for the plot corners are 39° 45'47"/103°47"50" (southwest), 39° 45'47"/103°47'17" (southeast), 39° 46'7"/103°47'50" (northwest), 39° 46'7"/103°47'17" (northeast). The Linnebur family manages the farming operations for L/E. Soils belong to the Adena-Colby association where the Adena soil is classified as an Ustollic Paleargid and Colby is classified as an Ustic Torriorthent. No-till management is used in conjunction with crop rotations of WF and WCF. We originally also included a wheat-wheat-corn-sunflower (*Helianthus annuus*, L.)-fallow rotation, but after the 2004 growing season it was abandoned because of persistent droughty conditions that restricted sunflower production.

We installed a Campbell Scientific weather station at the site in April 2000; Tables 1 and 2 present mean temperature and precipitation data, and growing season precipitation, respectively.

The first biosolids application occurred in August 1999. Planting sequences are given in Table 1. We used a randomized complete block design with four blocks. Each phase of each rotation was present every year. Each plot was 100 feet wide by approximately 0.5 mile (2640 feet) long. The width of each plot was split so that one 50-foot wide section received commercial N fertilizer applied with the seed and sidedressed after plant establishment (Table 1), and the second 50-foot wide section received biosolids applied by L/E with a manure spreader. We randomly selected which half of the strip in each rotation received N fertilizer or biosolids. Characteristics of the L/E biosolids are provided in Table 2. The N fertilizer and biosolids applications were based on soil test recommendations determined on each plot before planting each crop. The Cities of L/E completed biosolids application for wheat in August 1999, 2001, 2003, 2004, 2012, 2013, 2014, and 2015 for the summer crops in March 2000, 2001, 2002, 2003, 2004, 2005, 2012, 2013, 2014, and 2015. We planted the first corn crop in May 2000. We also established wheat rotations in September 2000 through 2015 and corn rotations in May 2001 through 2016, and sunflower plantings in June 2001, 2002, and 2003. Soil moisture was inadequate in June 2004 to plant sunflowers (see Table 3); hence, the sunflower portion of the study was abandoned in 2004.

At harvest, we cut biomass from four rows, approximately 3 foot long within each subplot. The wheat was then thrashed and dried. We determined the yield for each area and then took a subsample from each cutting for subsequent grain protein or N, P, Zn, and Cu analyses (Huang and Schulte, 1985).

Following each harvest, we collected soil samples using a Giddings hydraulic probe. We sampled to one foot and separated the samples into 0-2, 2-4, 4-8, and 8-12 inch depth increments for AB-DTPA extractable Cu, P, and Zn (Barbarick and Workman, 1987), and EC (Rhoades, 1996) and pH (Thomas, 1996). For soil NO_3-N (Mulvaney, 1996) analyses, we sampled to 6 feet and separated the samples into 0-2, 2-4, 4-8, 8-12, 12-24, 24-36, 36-48, 48-60, and 60-72 inch depth increments.

The overall experimental design was a split-plot design where type of rotation was the main plot and type of nutrient addition (commercial N fertilizer versus L/E biosolids) was the subplot. For crop yields and soil-sample analyses, main plot effects, subplot effects, and interactions were tested for significance using least significant difference (LSD) at the 0.10 probability level. Since we only had one corn rotation, we could only compare the commercial N versus L/E biosolids using a “t” test at the 0.10 probability level.

RESULTS AND DISCUSSION

Precipitation Data

Tables 3 and 4 present the monthly precipitation records from the time we established the weather station at the Byers research site. The plots received more than 11 inches of total annual rainfall in 2000, 2001, 2003, 2007, 2008, 2009, 2011, 2014, 2015, and 2016, between 5 and 6 inches in 2002 and 2012, and between 8 and 11 inches in 2004, 2005, 2006, 2010, and 2013. Precipitation received as snow is not recorded, thus the amounts reported are likely an underestimate of the annual total. The critical precipitation months for corn are July and August (Nielsen et al., 2010). The Byers site received 6.0, 3.8, 1.3, 2.6, 2.5, 3.5, 4.5, 5.4, 7.4, 4.4, 3.9, 5.2, 1.3, 5.2, 4.4, and 5.3 inches of precipitation in July and August 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, and 2016, respectively.

2016 Crop Grain Data

There were no differences between rotation (WF versus WCF), nutrient source (biosolids versus N fertilizer), or the rotation by nutrient source interaction for wheat yields (Figure 1), grain protein content (Figure 2), grain P concentration (Figure 3), or grain Cu concentration (Figure 5) in 2016. Wheat grain Zn concentration was greater within the WCF as compared to the WF rotation (Figure 4). Average wheat yield for our treatments was 43 bushels/acre while the Colorado state average was 48 bushels/acre (USDA NASS Colorado Field Office, 2016). Corn grain yield, protein content, P and Zn concentrations have been analyzed in the past (e.g., Table 5); however, a severe hailstorm in August 2016 decimated the corn crop and thus corn could not be harvest during this growing season.

2016 Soil Data

In the wheat phase of each rotation, biosolids addition did not have an effect on AB-DTPA P (Figure 6), AB-DTPA Cu (Figure 8), soil EC (Figure 9) or pH (Figure 10) in the top 12 inches of soil. The addition of biosolids resulted in greater AB-DTPA Zn (Figure 7) in the 0 to 2 inch depth as well as soil NO_3-N concentrations in the 4 to 8, 24 to 36, and 36 to 48 inch depths (Figure 11). Soil AB-DTPA P was greater in the 0 to 2 inch depth for the WCF as compared to the WF rotation (Figure 6). Soil EC (salinity) in the 0 to 2, 4 to 8, and 8 to 12 inch depths was greater for the WCF rotation than the WF rotation (Figure 9). Soil pH in the 0 to 2 and 2 to 4 inch depths were lower in the WF rotation as compared to the WCF rotation (Figure 10). Soil NO_3-N was greater in many of the soil depths under the WCF as compared to the WF rotation. All other results did not show consistent trends.

The corn phase of the rotation showed no differences in AB-DTPA extractable P, Zn, and Cu, and pH, EC, and soil NO_3-N in all soil depths (Table 6). This was likely due to corn being unable to significantly remove various constituents from the soil due to hail causing a crop failure.

CONCLUSIONS

Relative to our hypotheses listed on page 3, we found the following trends:

1. In the 2016 wheat, we observed that biosolids did produce crop yields, protein content, and grain P, Zn, and Cu concentrations similar to that of N fertilizer. This was also observed in past crop years (e.g., 2014). The wheat-corn-fallow (WCF) rotation produced greater wheat grain Cu concentrations as compared to the wheat-fallow (WF) rotation, likely due to greater biosolids applications in the WCF rotation. The 2016 corn was lost due to hail damage in August 2016.

2. For dryland wheat in 2016, we observed that biosolids additions did not increase soil AB-DTPA extractable P or Cu, but there was an increase in soil levels of AB-DTPA extractable Zn in the top 2 inches. This was also observed in 2015. For the 2016 corn soils, the addition of biosolids did not affect any AB-DTPA extractable elements.

3. The WCF rotation resulted in higher EC (salinity) in the 0-2 inch soil depth, and lower pH values in the 0-2 and 2-4 inch soil depths as compared to the WF rotation. Minor EC differences between crop rotations were observed in the 4-8 and 8-12 inch depths. A minor EC difference was also observed between biosolids and N fertilizer in the 4-8 inch soil depth; no pH differences were evident between biosolids and N fertilizer. In addition, no change in EC (salinity) was observed in the corn plots with biosolids application in any soil depth.

4. Biosolids application closely followed N application in terms of the soil NO_3-N concentrations within the soil profile. The wheat plots did show an effect of NO_3-N accumulation in the profile within top 2 inches, and some movement to between 48 and 72 inches. The 2016 corn plots did show any significant soil NO_3-N differences between biosolids and N fertilizer, yet some NO_3-N has accumulation in the 60-72 inch depth. With proper management, accumulated soil NO_3-N should be removed via future crop growth.

5. The results discussed in items 1 through 3 are similar to a majority of our past findings.

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Table 1. Biosolids and fertilizer applications and crop varieties used at the Byers research site, 1999-2016.

Year Planted	Date Planted	Crop	Variety	Biosolids Biosolids tons/acre	Treatment Bio/N equiv. lbs	Nitrogen N lbs/acre with seed	Fertilizer N lbs/acre after planting	Treatment Total N lbs/acre	P_2O_5 lbs/acre	Zn lbs/acre
1999	Early Oct.	Wheat	Halt	2.4	38.4	5	40	45	20	0
2000	May	Corn	Pioneer 3752	4	64	5	40	45	15	5
2000	June	Sunflowers	Triumph 765, 766 (confection type)	2	32	5	40	45	15	5
2000	9/25/00	Wheat	Prairie Red	0	0	4	0	4	20	0
2001	5/11/01	Corn	DK493 Round Ready	5.5	88	5	40	45	15	5
2001	6/20/01	Sunflowers	Triumph 765C	2	32	5	40	45	15	5
2001	09/17/01	Wheat	Prairie Red	Variable	Variable	5	Variable	Variable	20	0
2002		Corn	Pioneer 37M81	Variable	Variable	5	Variable	Variable	15	5
2002		Sunflowers	Triumph 545A	0	0	5	0	0	15	5
2002		Wheat	Stanton	Variable	Variable	5	Variable	Variable	20	0
2003	05/21/03	Corn	Pioneer K06							
2003	06/28/03	Sunflowers	Unknown							
2003		Wheat	Stanton	Variable	Variable	5	Variable	Variable	20	0
2004		Corn	Triumph 9066 Roundup Ready	Variable	Variable	5	Variable	Variable	15	5
2004		Sunflowers	Triumph 765 (confection type)	0	0	5	0	0	15	5
2004	09/17/04	Wheat	Yumar	3	54	0	50	50	15	5
2005	05/10/05	Corn	Pioneer J99	4	72	0	75	75	15	5

Table 1 (continued). Biosolids and fertilizer applications and crop varieties used at the Byers research site, 1999-2016.

Year Planted	Date Planted	Crop	Variety	Biosolids Biosolids tons/acre	Treatment Bio/N equiv. lbs	Nitrogen N lbs/acre with seed	Fertilizer N lbs/acre after planting	Treatment Total N lbs/acre	P_2O_5 lbs/acre	Zn lbs/acre
2006	Sept.	Wheat	Yumar	0	0	0	0	0	0	0
2007	May	Corn	Pioneer J99	0	0	0	0	0	0	0
2007	Sept.	Wheat	Yumar	0	0	0	0	0	0	0
2008	May	Corn	Pioneer J99	0	0	0	0	0	0	0
2008	Sept.	Wheat	Yumar	0	0	0	0	0	0	0
2009	May	Corn	Pioneer J99	0	0	0	0	0	0	0
2009	Sept.	Wheat	Yumar	0	0	0	0	0	0	0
2010	May	Corn	Pioneer J99	0	0	0	0	0	0	0
2010	Sept.	Wheat	Yumar	0	0	0	0	0	0	0
2011	May	Corn	Pioneer J99	0	0	0	0	0	0	0
2011	Sept.	Wheat	Snowmass	2	32	5	30	35	20	0
2012	May	Corn	Triumph 9958	2	32	5	30	35	20	0
2012	Sept.	Wheat	Snowmass	2	32	5	30	35	20	0
2013	May	Corn	Triumph 9958	2	32	5	30	35	15	5

Table 1 (continued). Biosolids and fertilizer applications and crop varieties used at the Byers research site, 1999-2016.

Year Planted	Date Planted	Crop	Variety	Biosolids Biosolids tons/acre	Treatment Bio/N equiv. lbs	Nitrogen N lbs/acre with seed	Fertilizer N lbs/acre after planting	Treatment Total N lbs/acre	P_2O_5 lbs/acre	Zn lbs/acre
2013	Sept.	Wheat	Byrd	2	32	5	30	35	20	0
2014	May	Corn	Triumph 9811	2	32	5	30	35	15	5
2014	Sept.	Wheat	Byrd	2	32	5	30	35	20	0
2015	May	Corn	Triumph 9811	2	32	5	30	35	15	5
2015	Sept.	Wheat	Snowmass	2	32	0	45	45	0	0
2016	May	Corn	Pioneer 0157	0	0	0	50	50	0	0

Table 2. Littleton/Englewood biosolids composition used at the Byers research site, 1999-2016.

Parameter	1999 Wheat	2000 Corn, Sunflowers	2001 Corn, Sunflowers	2001 Wheat	2003 Corn, Sunflowers	2003 Wheat	2004 Wheat	2005 Corn†	2012 Corn	2012 Wheat	2013 Corn	2013 Wheat
Solids, g kg^{-1}	217	---	210	220	254	192	197	211	170	488	205	750
pH	7.6	7.8	8.4	8.1	8.5	8.2	8.8	8.2	8.7	8.2	8.4	7.4
EC, dS m^{-1}	6.2	11.2	10.6	8.7	7.6	7.4	4.5	5.1	3.5	2.9	5.0	4.6
Org. N, g kg^{-1}	50	47	58	39	54	46	43	38	71	55	49	57
NH_4-N, g kg^{-1}	12	7	14	16	9	13	14	14	12	4	10	3
NO_3-N, g kg^{-1}	0.023	0.068	0.020	0.021	0.027	0.016	0.010	0	0.018	0.004	0.010	0.001
K, g kg^{-1}	5.1	2.6	1.6	1.9	2.2	2.6	2.1	1.7	1.8	1.0	1.5	13.3
P, g kg^{-1}	29	18	34	32	26	28	29	13	29	23	24	29
Al, g kg^{-1}	28	18	15	18	14	15	17	10	6	4	5	1
Fe, g kg^{-1}	31	22	34	33	23	24	20	20	24	16	20	3
Cu, mg kg^{-1}	560	820	650	750	596	689	696	611	812	602	624	949
Zn, mg kg^{-1}	410	543	710	770	506	629	676	716	824	666	693	981
Ni, mg kg^{-1}	22	6	11	9	11	12	16	4	24	12	15	16
Mo, mg kg^{-1}	19	22	36	17	21	34	21	13	11.8	9.2	<0.01	17.3
Cd, mg kg^{-1}	6.2	2.6	1.6	1.5	1.5	2.2	4.2	2.0	1.2	0.4	1.5	1.6
Cr, mg kg^{-1}	44	17	17	13	9	14	18	14	12	14	5	32
Pb, mg kg^{-1}	43	17	16	18	15	21	26	16	35	18	5	20
As, mg kg^{-1}	5.5	2.6	1.4	3.8	1.4	1.6	0.5	0.05	12	10	6	<0.01
Se, mg kg^{-1}	20	16	7	6	17	1	3	0.07	70.6	5.5	16.1	1.1
Hg, mg kg^{-1}	3.4	0.5	2.6	2.0	1.1	0.4	0.9	0.1	0.059	0.041	0.020	0.023
Ag, mg kg^{-1}	---	---	---	---	15	7	0.5	1.2	20.6	---	1.5	4.1
Ba, mg kg^{-1}	---	---	---	---	---	---	533	7	447	297	312	420
Be, mg kg^{-1}	---	---	---	---	---	---	0.05	<0.001	<0.01	<0.01	<0.01	0.05
Mn, mg kg^{-1}	---	---	---	---	---	---	239	199	429	234	341	395

† Biosolids were not applied from 2006 to 2011 due to excess soil nitrogen.

Table 2 (continued). Littleton/Englewood biosolids composition used at the Byers research site, 1999-2016.

Parameter	2014 Corn	2014 Wheat	2015 Corn	2015 Wheat	2016 Wheat	Avg.	Range
Solids, g kg^{-1}	201	175	167	179	181	*251*	*167-750*
pH	8.6	8.1	8.9	8.1	4.7	*8.0*	*4.7-8.9*
EC, dS m^{-1}	4.0	4.1	5.3	5.3	7.9	*6.1*	*2.9-11.2*
Org. N, g kg^{-1}	55	27	59	27	60	*37*	*10-60*
NH_4-N, g kg^{-1}	10	11	12	17	0.5	*8.8*	*0.5-17*
NO_3-N, g kg^{-1}	0.005	0.008	0.009	0.010	0.004	*0.013*	*0-0.068*
K, g kg^{-1}	19.9	17.2	1.8	0.09	0.90	*3.23*	*0.09-17.2*
P, g kg^{-1}	35	48	43	41	11	*24*	*5-48*
Al, g kg^{-1}	5	5	5	5	0.9	*9*	*0.4-28*
Fe, g kg^{-1}	30	31	32	31	22	*20*	*2-34*
Cu, mg kg^{-1}	955	965	120	984	618	*560*	*120-984*
Zn, mg kg^{-1}	975	1368	1143	1336	751	*653*	*140-1368*
Ni, mg kg^{-1}	22	28.1	19.8	26.0	13.5	*12.2*	*3-28*
Mo, mg kg^{-1}	10.9	12.3	7.8	9.3	14.5	*15.5*	*<0.01-36*
Cd, mg kg^{-1}	1.5	2.1	2.0	1.7	2.3	*1.9*	*0.2-6.2*
Cr, mg kg^{-1}	35	48	48	41	34	*21*	*1-48*
Pb, mg kg^{-1}	30	40	48	39	20	*21*	*1-48*
As, mg kg^{-1}	1	<0.001	<0.001	<0.001	0.011	*1.579*	*<0.001-5.5*
Se, mg kg^{-1}	17.4	8.6	<0.001	<0.001	0.012	*5.940*	*<0.001-20*
Hg, mg kg^{-1}	0.010	0.037	0.018	0.028	0.001	*0.655*	*0.001-3.4*
Ag, mg kg^{-1}	169.2	10	95	243	10.2	*35*	*0.3-243*
Ba, mg kg^{-1}	468	522	528	544	309	*285*	*7-544*
Be, mg kg^{-1}	<0.01	<0.01	<0.01	0.01	<0.01	*0.03*	*<0.01-0.05*
Mn, mg kg^{-1}	522	501	525	404	376	*264*	*70-525*

Table 3. Monthly mean maximum (Max) and minimum (Min) temperatures and precipitation (Precip) in inches at the Byers research site, 2000-2016. (Weather station was installed in April, 2000).

Month	2000			2001			2002			2003			2004		
	Max °F	Min °F	Precip inches	Max °F	Min °F	Precip inches	Max °F	Min °F	Precip inches	Max °F	Min °F	Precip inches	Max °F	Min °F	Precip inches
January	†	†	†	41.0	20.7	0.2	44.1	17.0	0.1	50.4	23.3	0.0	44.9	20.2	0.0
February	†	†	†	42.1	19.0	0.1	48.2	19.7	0.2	39.9	17.1	0.1	42.6	20.4	0.1
March	†	†	†	49.9	27.5	0.2	46.5	17.7	0.2	55.0	29.6	1.0	61.2	31.3	0.1
April	68.9	38.4	0.6	64.2	36.4	1.5	65.8	35.2	0.3	65.0	37.5	1.5	61.9	35.6	0.9
May	78.4	47.0	0.9	70.0	43.7	2.4	73.5	41.8	0.7	71.3	45.3	1.8	75.8	44.8	1.4
June	80.4	49.3	0.9	85.9	53.5	2.4	89.0	56.9	1.2	76.8	51.1	4.7	78.3	51.1	4.1
July	91.9	61.0	2.5	92.2	61.1	1.9	93.3	62.2	0.2	97.4	62.1	0.2	86.9	57.6	1.0
August	90.8	60.2	3.5	88.8	59.0	1.9	88.2	57.0	1.1	91.0	60.5	2.4	85.2	54.6	1.5
September	80.6	49.8	0.8	82.0	51.6	0.8	78.1	50.5	0.7	76.2	45.6	0.1	80.8	50.7	0.6
October	65.9	38.7	1.6	68.0	37.2	0.2	58.6	33.0	0.2	72.3	41.2	0.1	67.3	38.6	0.4
November	40.8	20.0	0.3	56.2	28.9	0.8	50.2	27.1	0.1	51.3	24.3	0.0	48.0	26.6	0.3
December	41.7	17.0	0.3	45.4	21.4	0.0	47.1	22.8	0.0	47.2	20.8	0.0	46.4	22.4	0.1
Total			11.4			12.4			5.0			11.9			10.5
Month	2005			2006			2007			2008			2009		
	Max °F	Min °F	Precip inches	Max °F	Min °F	Precip inches	Max °F	Min °F	Precip inches	Max °F	Min °F	Precip inches	Max °F	Min °F	Precip inches
January	43.9	21.5	0.1	52.2	24.6	0.0	30.9	11.1	0.1	39.2	15.1	0.0	47.1	21.8	0.0
February	49.4	24.5	0.0	41.2	15.3	0.0	34.7	16.3	0.1	45.7	20.2	0.1	52.3	23.3	0.0
March	53.0	27.2	0.2	52.9	25.5	0.6	59.1	33.5	0.7	53.2	23.8	0.2	56.4	27.0	0.5
April	59.0	34.0	1.1	65.0	34.5	0.4	57.8	32.8	1.8	61.4	31.6	0.3	58.5	33.3	2.2
May	72.0	44.6	0.8	76.5	44.6	0.7	73.2	45.3	1.5	71.2	41.4	0.8	71.1	45.8	3.2
June	80.1	50.4	2.4	86.5	54.2	0.2	81.3	52.0	0.4	83.1	51.5	1.1	78.1	51.7	2.9
July	94.2	61.1	1.3	90.6	61.8	1.9	91.5	61.6	2.8	92.9	61.6	0.6	86.8	57.1	1.6
August	84.6	56.7	2.2	86.1	59.0	2.6	89.3	61.5	2.6	83.4	57.7	6.8	86.1	55.3	2.8
September	83.3	51.9	0.1	69.5	43.3	1.4	80.8	51.3	0.6	76.2	47.6	0.5	77.4	49.2	1.3
October	65.1	39.1	1.3	62.5	35.9	1.1	68.7	38.8	0.3	66.5	38.3	0.7	53.9	31.0	1.1
November	56.5	29.7	0.5	53.3	26.9	0.0	56.9	27.9	0.1	56.0	30.1	0.3	55.7	30.2	0.2
December	41.6	17.5	0.0	42.2	21.1	0.1	38.5	15.8	0.2	40.3	13.7	0.1	36.1	12.4	0.0
Total			10.0			9.0			11.2			11.5			15.8

† We installed the weather station in mid-April, 2000. The tipping bucket rain gauge may not accurately measure precipitation received as snow.

Table 3 (continued). Monthly mean maximum (Max) and minimum (Min) temperatures and precipitation (Precip) in inches at the Byers research site, 2000-2016. (Weather station was installed in April, 2000).

Month	2010			2011			2012			2013			2014		
	Max °F	Min °F	Precip inches	Max °F	Min °F	Precip inches	Max °F	Min °F	Precip inches	Max °F	Min °F	Precip inches	Max °F	Min °F	Precip inches
January	44.6	19.9	0.1	40.8	17.6	0.3	49.8	20.6	0.1	44.4	18.4	0.0	43.1	17.6	0.3
February	39.7	18.0	0.2	42.8	15.4	0.0	36.1	16.8	0.2	42.9	18.0	0.1	40.3	14.3	0.1
March	53.7	28.2	0.4	57.2	28.1	0.2	62.8	33.1	0.2	50.0	24.7	0.2	55.1	25.7	0.3
April	62.4	33.6	2.5	61.4	29.9	0.9	68.3	37.2	1.4	55.4	28.5	0.1	62.4	34.4	1.5
May	68.4	38.1	1.6	66.0	38.7	3.8	75.8	44.4	0.6	72.4	43.1	0.1	71.1	44.2	1.4
June	83.6	54.6	1.4	83.3	53.2	0.6	91.0	57.1	0.4	88.9	54.5	0.1	83.1	51.4	2.7
July	89.1	59.7	2.3	92.9	57.4	3.6	93.4	62.5	1.2	89.0	59.9	1.4	88.6	60.0	1.8
August	88.8	59.4	1.6	87.3	60.9	1.6	89.7	57.8	0.1	90.1	60.0	1.2	85.7	57.4	3.4
September	84.2	50.5	0.0	77.8	49.5	1.0	78.6	50.3	1.1	79.9	54.5	4.5	79.5	50.9	1.5
October	69.5	39.9	0.1	67.0	38.1	0.9	63.4	36.3	0.4	60.7	35.3	0.7	69.1	40.9	0.2
November	52.3	25.1	0.2	55.3	25.4	0.2	59.6	30.7	0.1	54.8	27.3	0.0	49.8	21.8	0.3
December	47.8	22.0	0.0	41.1	16.8	0.1	44.3	19.6	0.0	42.6	16.3	0.0	42.8	19.2	0.0
Total			10.4			13.2			5.8			8.4			13.4

Month	2015			2016		
	Max °F	Min °F	Precip inches	Max °F	Min °F	Precip inches
January	45.1	20.2	0.1	43.9	21.6	0.3
February	46.2	22.4	0.1	48.8	25.0	0.0
March	60.0	31.9	0.2	56.3	28.2	0.2
April	64.1	36.1	2.7	60.1	34.4	1.8
May	63.8	42.1	5.1	68.8	41.2	1.9
June	83.7	56.6	1.0	87.7	56.5	1.9
July	88.1	58.6	2.7	90.9	59.5	2.7
August	89.1	58.5	1.7	85.0	56.5	2.6
September	85.2	53.8	0.1	80.9	50.8	0.1
October	69.8	43.8	1.6	74.3	41.7	0.1
November	51.4	26.7	1.1	59.1	32.2	0.1
December	41.7	20.3	0.1	43.3	16.7	0.2
Total			16.6			12.0

† We installed the weather station in mid-April, 2000. The tipping bucket rain gauge may not accurately measure precipitation received as snow.

Table 4. Growing season precipitation, 2000-2016.

Stage	Dates	Precipitation, inches	Stage	Dates	Precipitation, inches
Wheat vegetative	September 2000 - March 2001	3.3	Wheat vegetative	September 2007 - March 2008	1.5
Wheat reproductive	April 2001 - June 2001	6.3	Wheat reproductive	April 2008 - June 2008	2.2
Corn/Sunflowers preplant	July 2000 – April 2001	9.5	Corn preplant	July 2007 – April 2008	7.2
Corn/Sunflowers growing season	May 2001 – October 2001	9.6	Corn growing season	May 2008 – October 2008	10.5
Wheat vegetative	September 2001 - March 2002	2.1	Wheat vegetative	September 2008 - March 2009	2.1
Wheat reproductive	April 2002 - June 2002	2.2	Wheat reproductive	April 2009 - June 2009	8.3
Corn/Sunflowers preplant	July 2001 – April 2002	6.1	Corn preplant	July 2008 – April 2009	11.8
Corn/Sunflowers growing season	May 2002 – October 2002	3.9	Corn growing season	May 2009 – October 2009	12.9
Wheat vegetative	September 2002 - March 2003	1.1	Wheat vegetative	September 2009 - March 2010	3.3
Wheat reproductive	April 2003 - June 2003	3.3	Wheat reproductive	April 2010 - June 2010	5.5
Corn/Sunflowers preplant	July 2002 – April 2003	3.4	Corn preplant	July 2009 – April 2010	10.2
Corn/Sunflowers growing season	May 2003 – October 2003	9.2	Corn growing season	May 2010 – October 2010	7.0
Wheat vegetative	September 2003 - March 2004	0.3	Wheat vegetative	September 2010 - March 2011	0.8
Wheat reproductive	April 2004 - June 2004	2.3	Wheat reproductive	April 2011 - June 2011	5.2
Corn/Sunflowers preplant	July 2003 – April 2004	3.0	Corn preplant	July 2010 – April 2011	4.7
Corn/Sunflowers growing season	May 2004 – October 2004	8.6	Corn growing season	May 2011 – October 2011	11.4
Wheat vegetative	September 2004 - March 2005	1.7	Wheat vegetative	September 2011 - March 2012	2.7
Wheat reproductive	April 2005 - June 2005	4.3	Wheat reproductive	April 2012 - June 2012	2.4
Corn preplant	July 2004 – April 2005	5.3	Corn preplant	July 2011– April 2012	7.4
Corn growing season	May 2005 – October 2005	8.6	Corn growing season	May 2012 – October 2012	3.8
Wheat vegetative	September 2005 - March 2006	2.5	Wheat vegetative	September 2012 - March 2013	1.9
Wheat reproductive	April 2006 - June 2006	1.3	Wheat reproductive	April 2013 - June 2013	1.7
Corn preplant	July 2005 – April 2006	6.4	Corn preplant	July 2012– April 2013	3.3
Corn growing season	May 2006 – October 2006	7.9	Corn growing season	May 2013 – October 2013	8.0
Wheat vegetative	September 2006 - March 2007	3.5	Wheat vegetative	September 2013 - March 2014	5.9
Wheat reproductive	April 2007 - June 2007	3.7	Wheat reproductive	April 2014 - June 2014	5.6
Corn preplant	July 2006 – April 2007	8.8	Corn preplant	July 2013 – April 2014	10.0
Corn growing season	May 2007 – October 2007	8.2	Corn growing season	May 2014 – October 2014	11.0

Table 4 (continued). Growing season precipitation, 2000-2016.

Stage	Dates	Precipitation, inches
Wheat vegetative	September 2014 - March 2015	2.4
Wheat reproductive	April 2015 - June 2015	8.9
Corn preplant	July 2014 – April 2015	10.4
Corn growing season	May 2015 – October 2015	12.3
Wheat vegetative	September 2015 - March 2016	3.5
Wheat reproductive	April 2016 - June 2016	5.7
Corn preplant	July 2015 – April 2016	9.8
Corn growing season	May 2016 – October 2016	9.3

Table 5. Corn grain characteristics for the corn rotation (CFW) at the Byers research site for 2016.

Parameter, units	Biosolids	Nitrogen	Probability level
Yield, bushels/acre	---	---	---
Protein, %	---	---	---
P, g/kg	---	---	---
Zn, mg/kg	---	---	---

Table 6. Soil characteristics for the corn rotation (CFW) at the Byers research site for 2016. ***Highlighted parameters*** are significantly different at the 0.10 probability level according to the t-test.

Parameter, units	Depth, inches	Biosolids	Nitrogen	Probability level
ABDTPA P, mg kg^{-1}	0-2	36	31	0.705
	2-4	11	7	0.652
	4-8	3	2	0.399
	8-12	2	1	0.165
ABDTPA Zn, mg kg^{-1}	0-2	4.6	4.2	0.872
	2-4	1.0	0.6	0.504
	4-8	0.2	0.2	0.440
	8-12	0.2	0.1	0.253
ABDTPA Cu, mg kg^{-1}	0-2	7.42	7.54	0.981
	2-4	3.14	2.35	0.586
	4-8	3.22	2.68	0.335
	8-12	2.92	2.79	0.728
pH	0-2	6.9	7.0	0.789
	2-4	7.0	7.0	0.897
	4-8	7.1	7.1	0.994
	8-12	7.4	7.4	0.869
ECe, dS m^{-1}	0-2	0.61	0.70	0.539
	2-4	0.38	0.25	0.221
	4-8	0.30	0.29	0.845
	8-12	0.33	0.30	0.345
NO_3-N, mg kg^{-1}	0-2	23.4	20.4	0.671
	2-4	7.0	5.3	0.729
	4-8	3.5	2.4	0.269
	8-12	2.7	2.0	0.458
	12-24	2.2	2.5	0.808
	24-36	4.4	2.4	0.385
	36-48	5.8	4.3	0.595
	48-60	5.8	5.6	0.935
	60-72	11.9	6.7	0.198

Figure 1. Wheat grain yields for 2016 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).

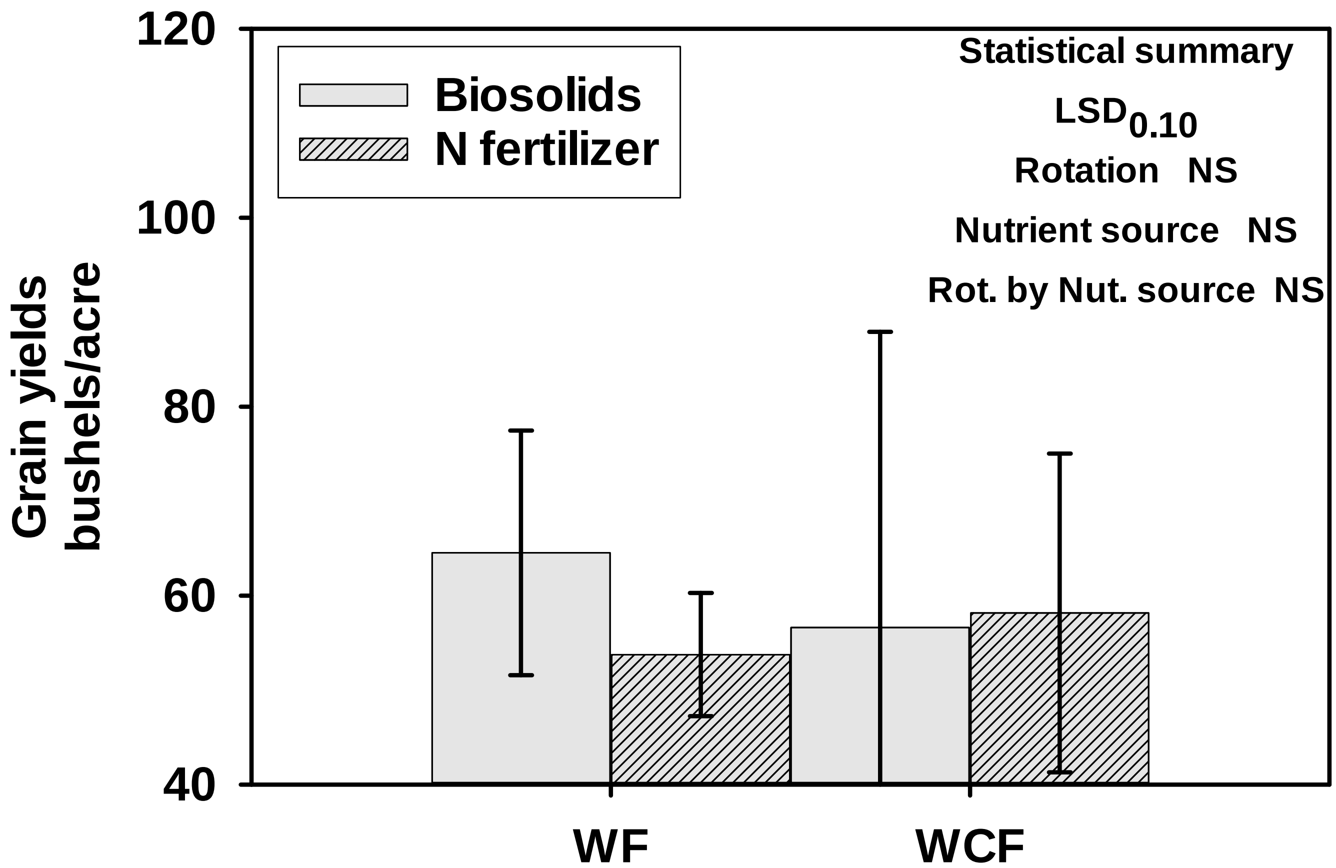


Figure 2. Wheat grain protein contents for 2016 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).

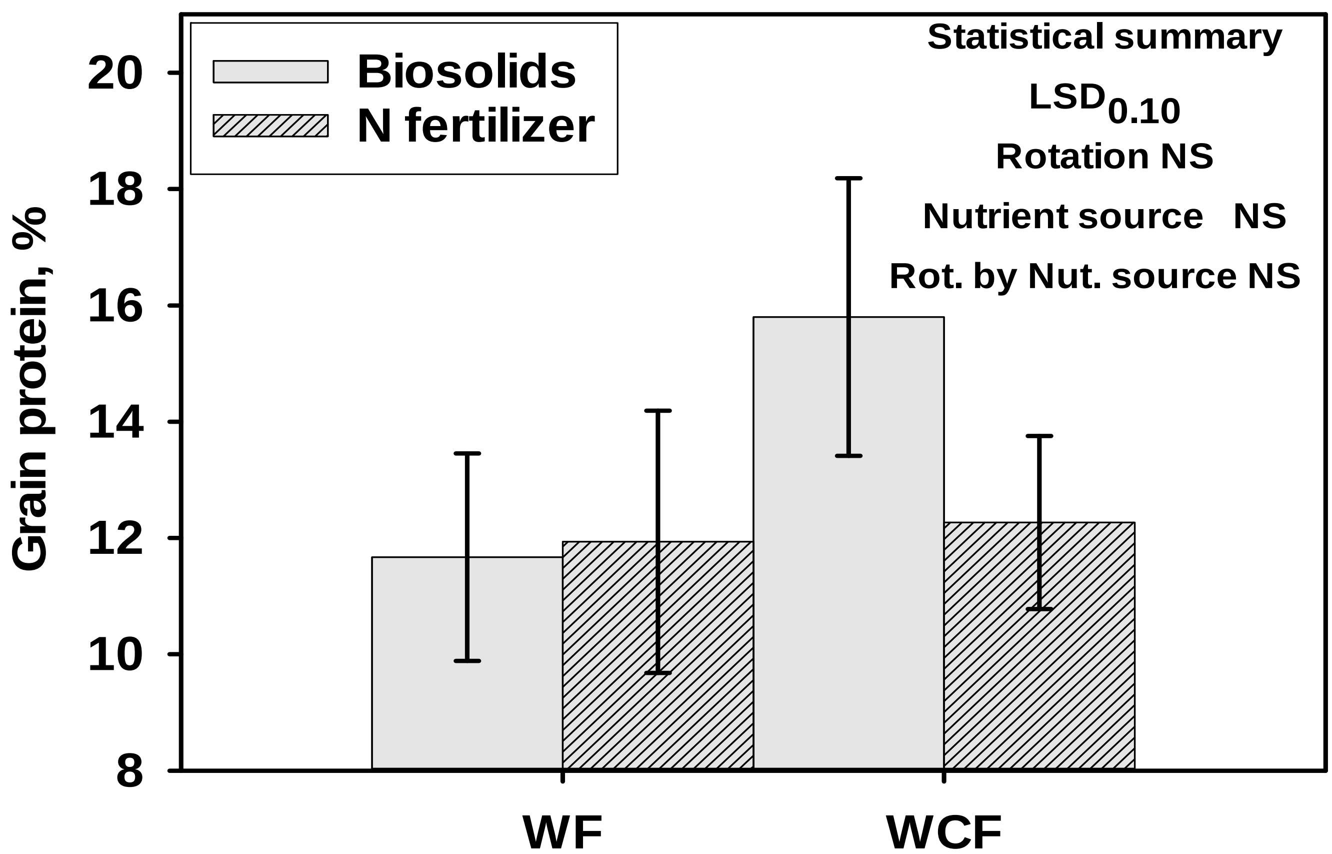


Figure 3. Wheat grain P concentrations for 2016 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).

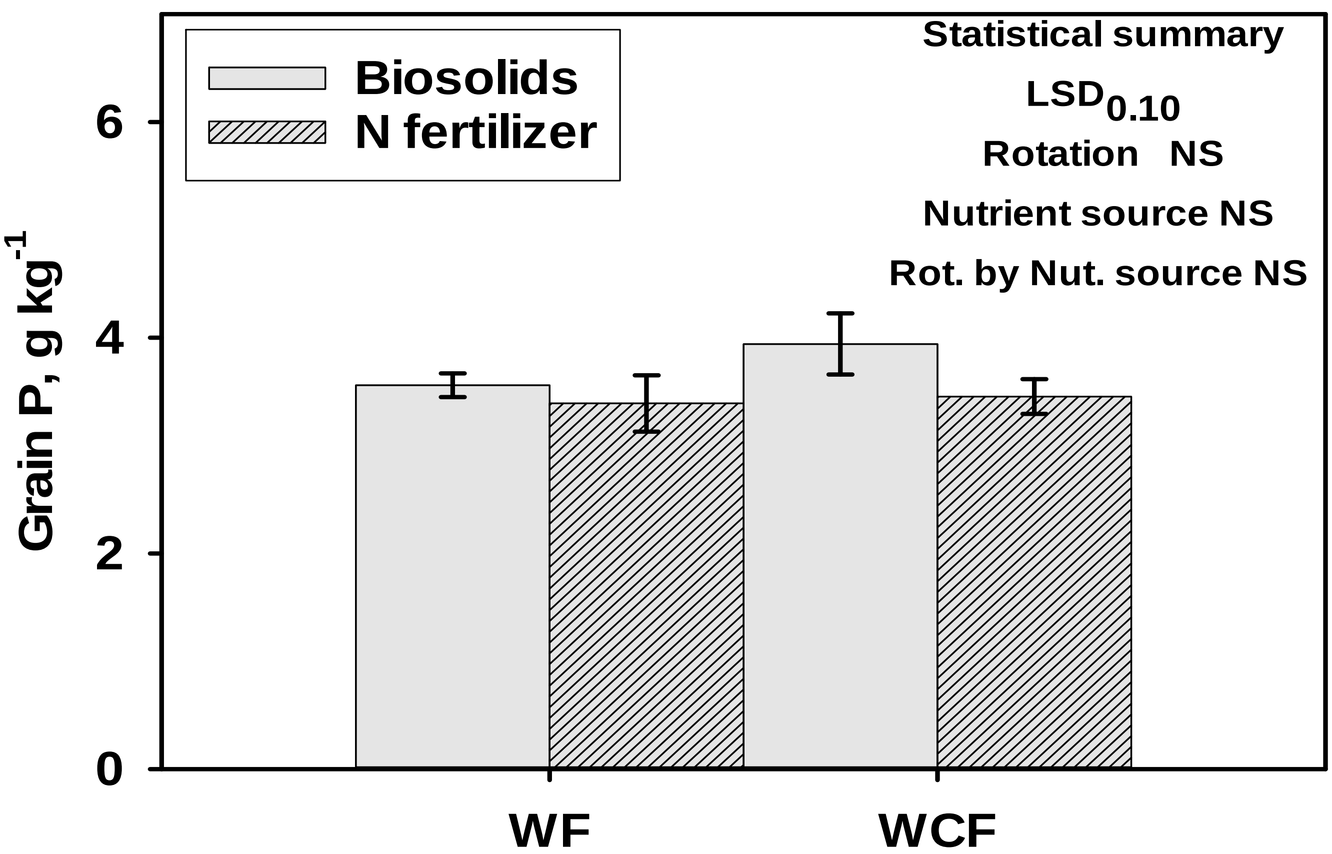


Figure 4. Wheat grain Zn concentrations for 2016 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).

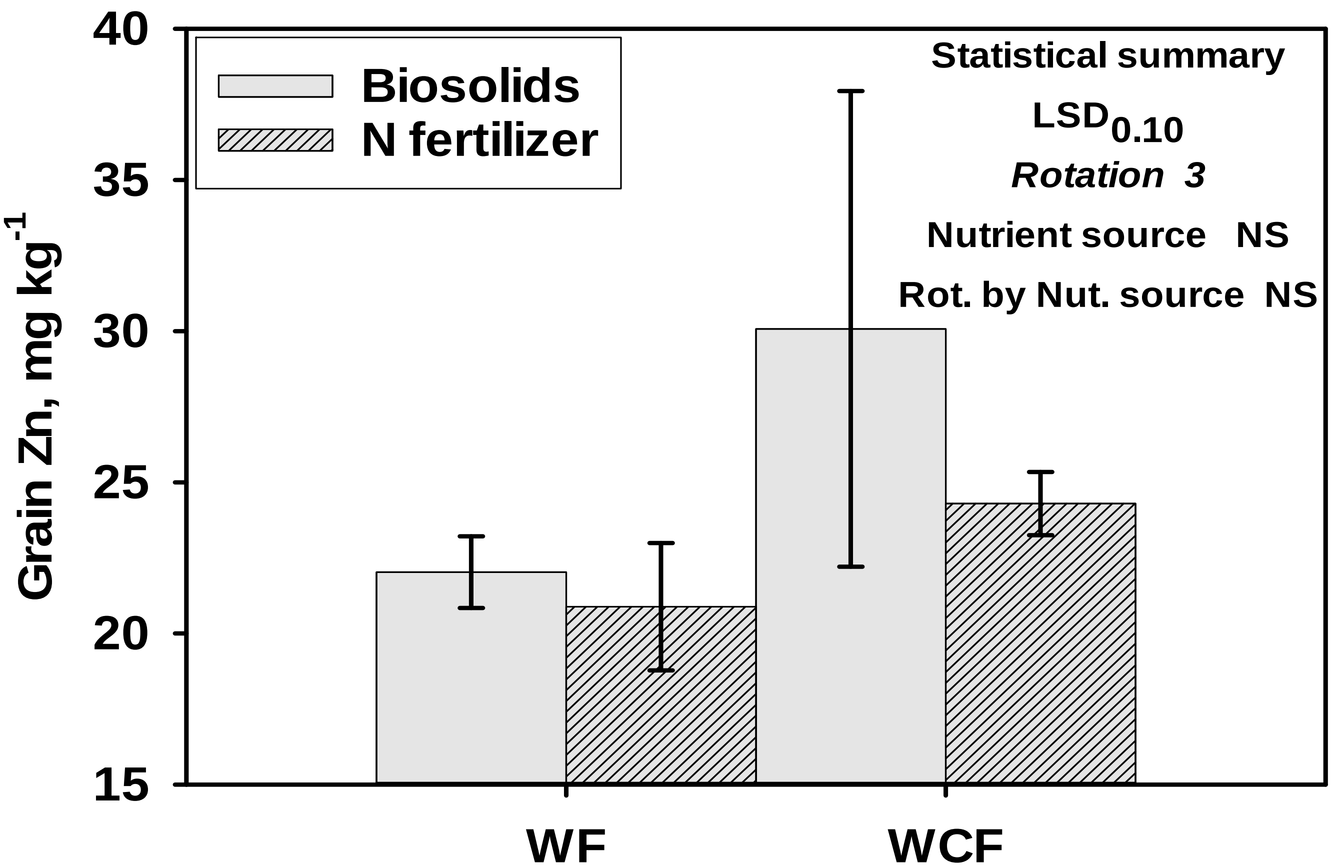


Figure 5. Wheat grain Cu concentrations for 2016 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, LSD0.10 represents the least significant difference at the 10% probability level and NS indicates non-significant differences WF = wheat-fallow and WCF = wheat-corn-fallow rotations).

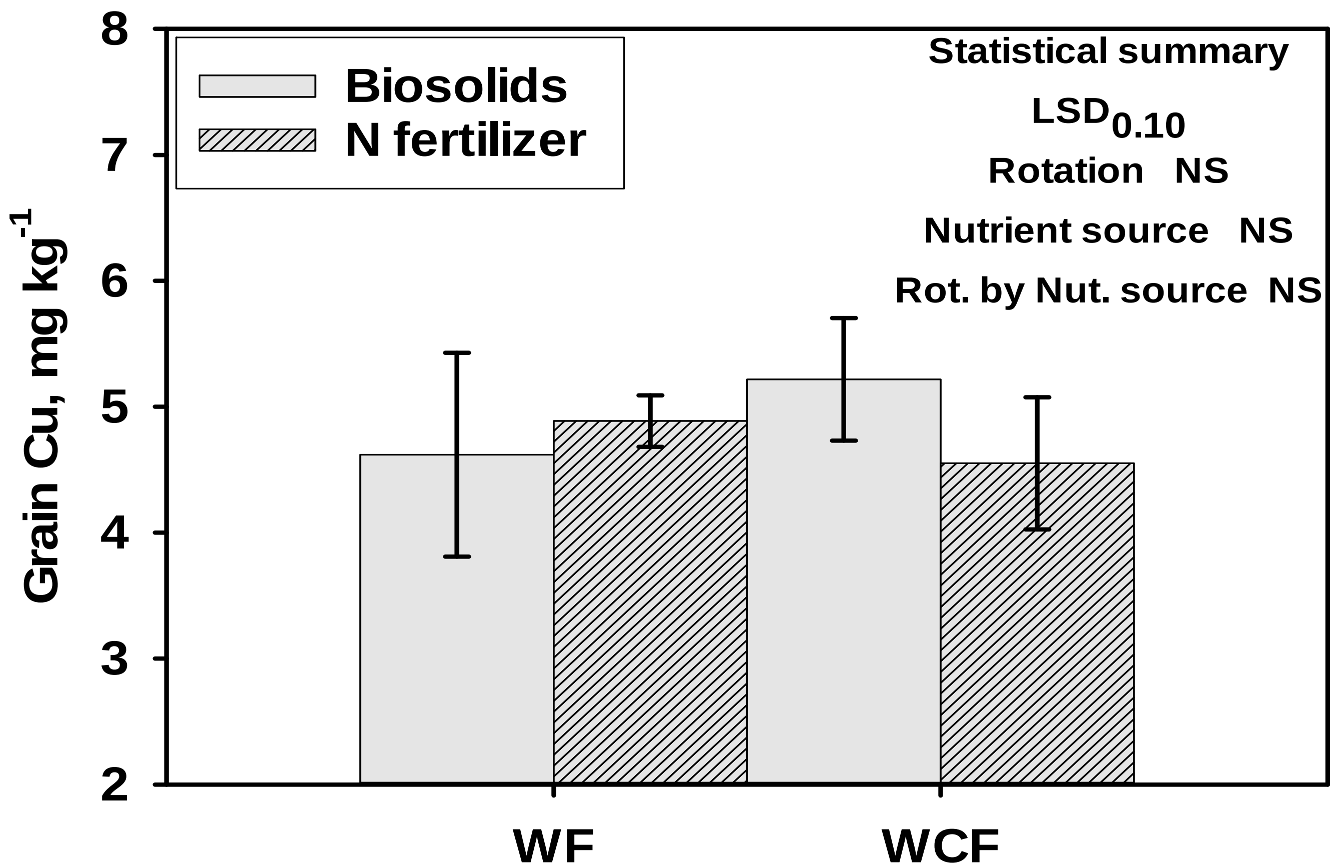
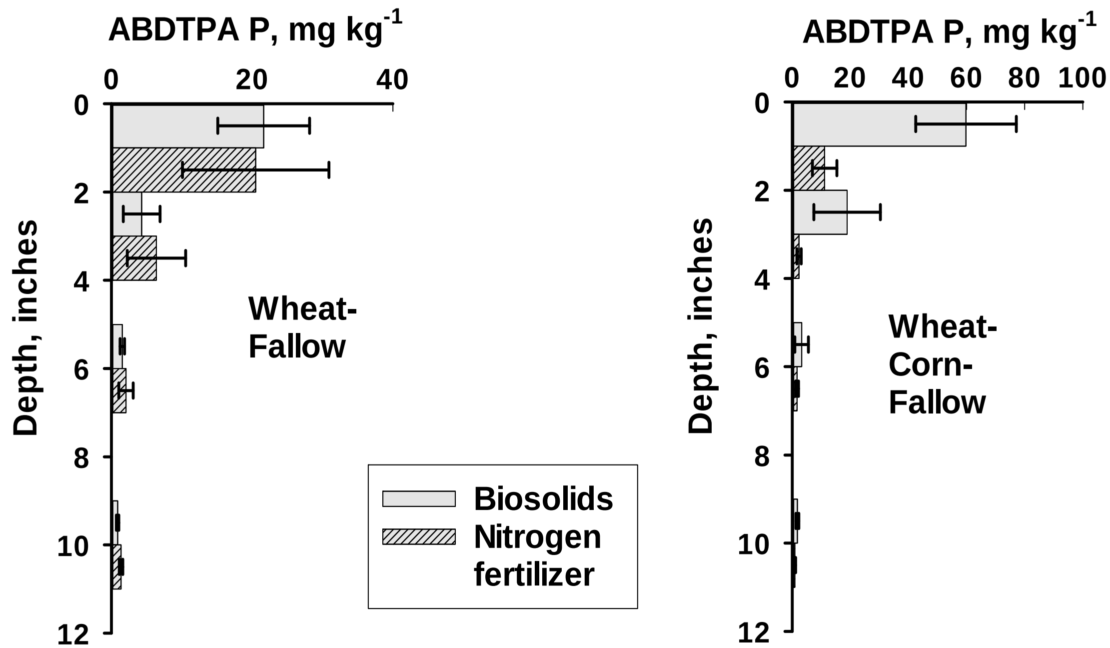


Figure 6. Soil ABDTPA-extractable P concentration following 2016 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.



Statistical summary by soil depth:

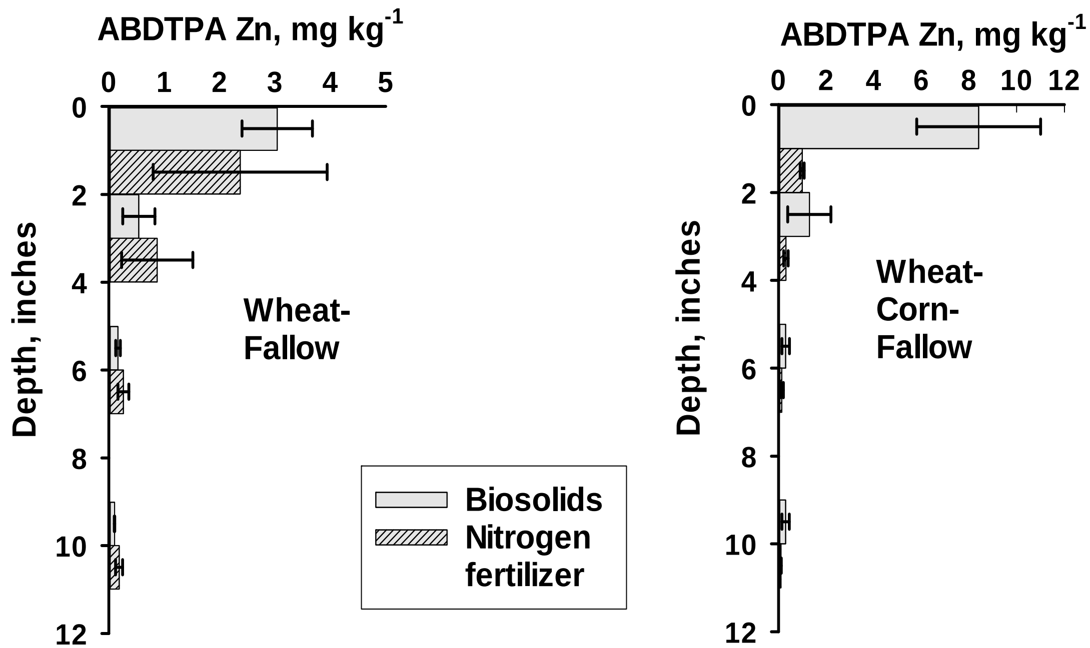
0-2 inches
$LSD_{0.10}$
Rotations 8
Treatment NS
Rot. X Treat. 25

2-4 inches
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

4-8 inches
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

8-12 inches
$LSD_{0.10}$
Rotations <1
Treatment NS
Rot. X Treat. 1

Figure 7. Soil ABDTPA-extractable Zn concentration following 2016 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.



Statistical summary by soil depth:

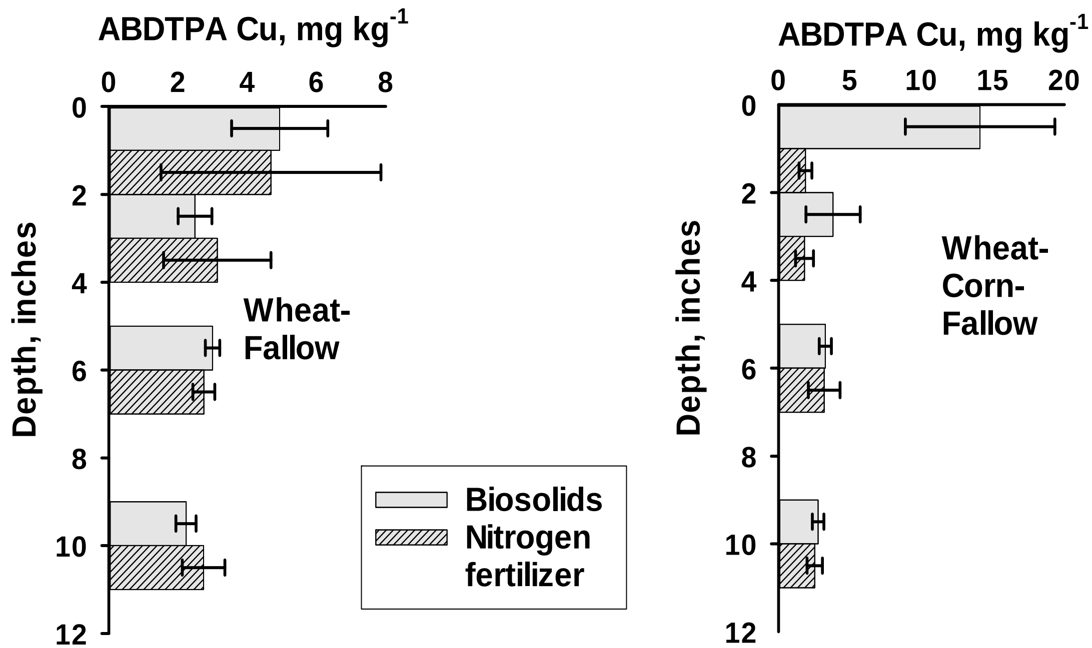
0-2 inches
$LSD_{0.10}$
Rotations NS
Treatment 2
Rot. X Treat. 4

2-4 inches
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

4-8 inches
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

8-12 inches
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

Figure 8. Soil ABDTPA-extractable Cu concentration following 2016 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.



Statistical summary by soil depth:

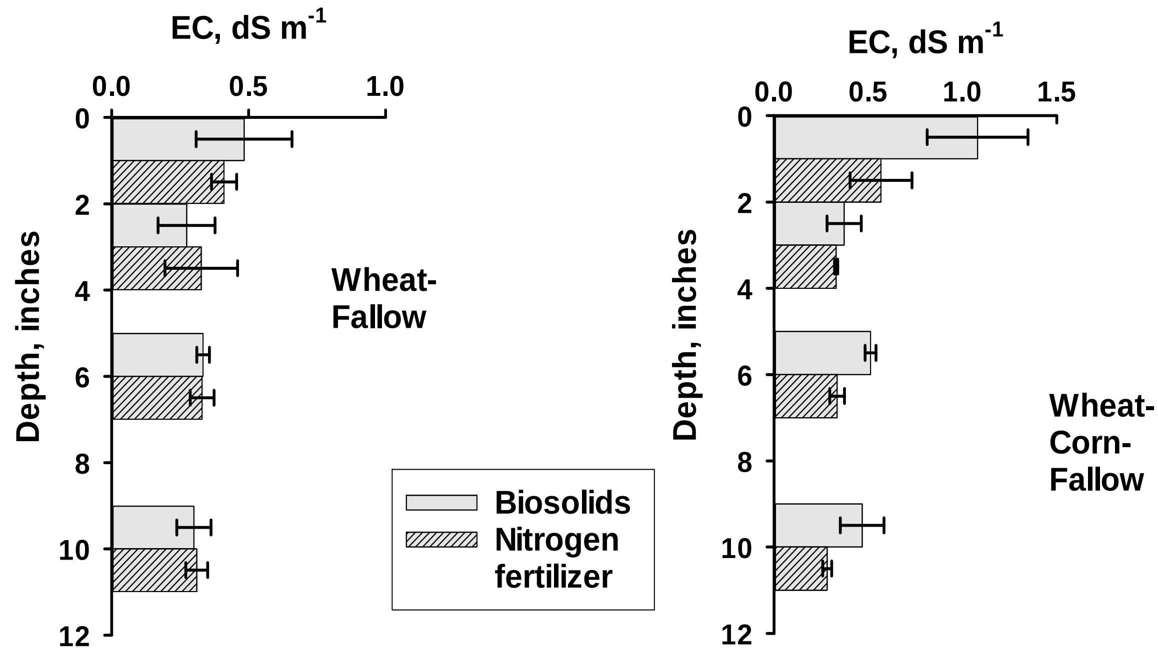
0-2 inches
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. 6

2-4 inches
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

4-8 inches
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

8-12 inches
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

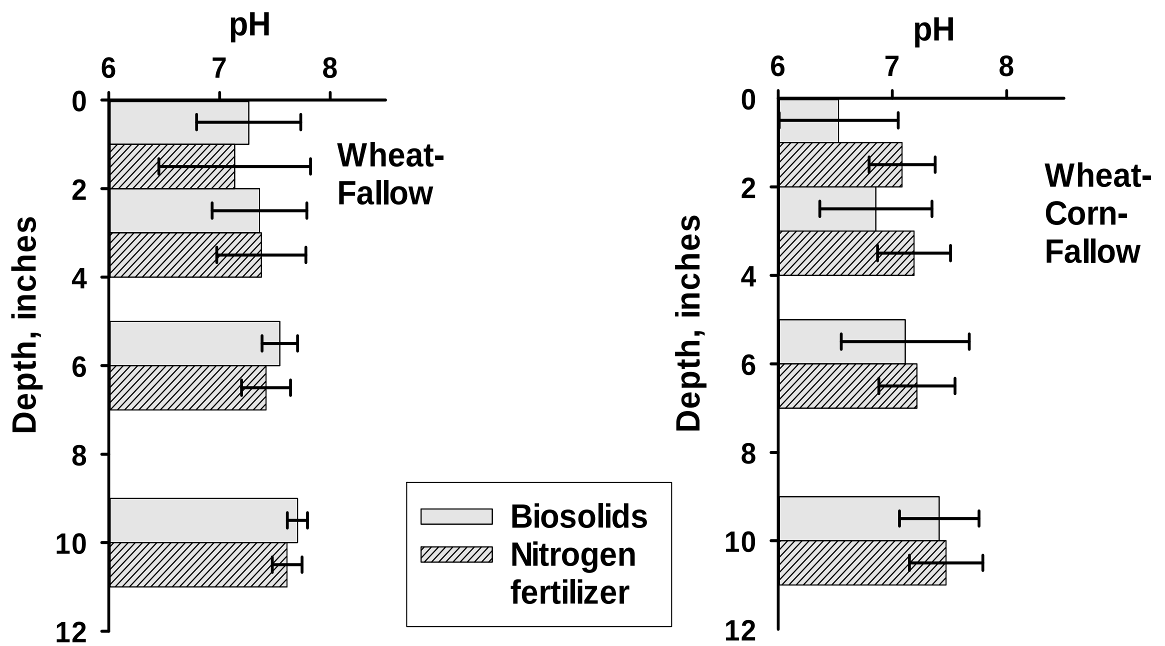
Figure 9. Soil saturated-paste electrical conductivity (EC) following 2016 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.



Statistical summary by soil depth:

<u>0-2 inches</u>	<u>2-4 inches</u>	<u>4-8 inches</u>	<u>8-12 inches</u>
$LSD_{0.10}$	**$LSD_{0.10}$**	**$LSD_{0.10}$**	**$LSD_{0.10}$**
Rotations 0.22	**Rotations NS**	***Rotations 0.04***	***Rotations 0.04***
Treatment NS	**Treatment NS**	***Treatment 0.05***	**Treatment NS**
Rot. X Treat. NS	**Rot. X Treat. NS**	***Rot. X Treat. 0.09***	***Rot. X Treat. 0.10***

Figure 10. Soil saturated-paste pH following 2016 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.



Statistical summary by soil depth:

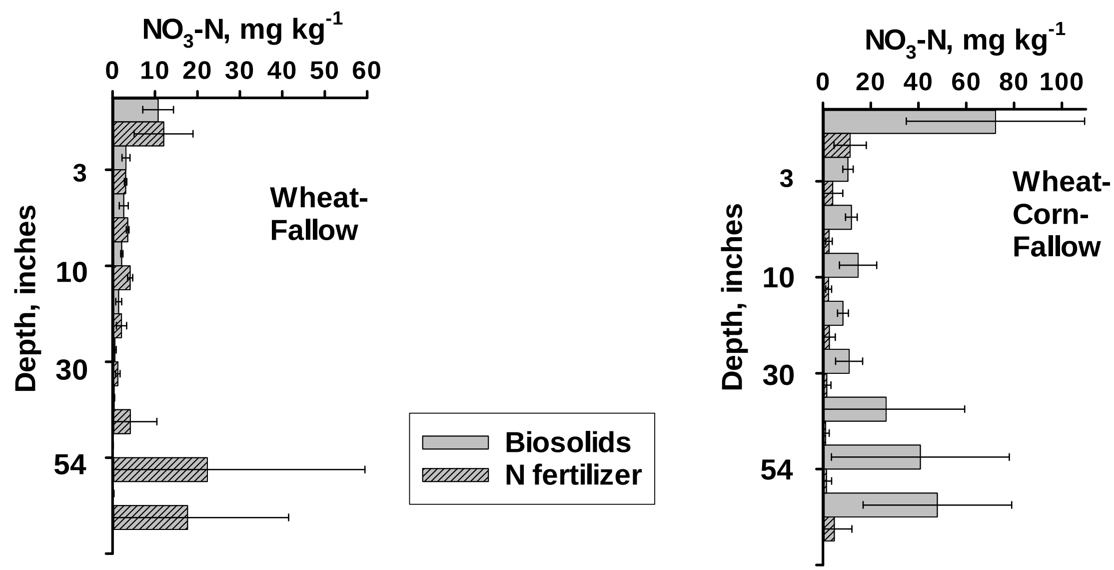
0-2 inches
$LSD_{0.10}$
Rotations 0.2
Treatment NS
Rot. X Treat. NS

2-4 inches
$LSD_{0.10}$
Rotations 0.2
Treatment NS
Rot. X Treat. NS

4-8 inches
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

8-12 inches
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

Figure 11. Soil NO_3-N concentrations following 2016 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.



Statistical summary by soil depth:

0-2 inches
$LSD_{0.10}$
Rotations 18
Treatment NS
Rot. X Treat. NS

2-4 inches
$LSD_{0.10}$
Rotations 2.4
Treatment NS
Rot. X Treat. NS

4-8 inches
$LSD_{0.10}$
Rotations 2.4
Treatment 1.9
Rot. X Treat. 5.3

8-12 inches
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. 7.4

12-24 inches
$LSD_{0.10}$
Rotations 2.0
Treatment NS
Rot. X Treat. NS

24-36 inches
$LSD_{0.10}$
Rotations 2.1
Treatment 2.9
Rot. X Treat. 5.3

36-48 inches
$LSD_{0.10}$
Rotations NS
Treatment 9.5
Rot. X Treat. NS

48-60 inches
$LSD_{0.10}$
Rotations 3.0
Treatment NS
Rot. X Treat. NS

60-72 inches
$LSD_{0.10}$
Rotations 11
Treatment NS
Rot. X Treat. NS