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Biosolids Application to No-Till Dryland Rotations: 2010 and 2011 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 rotation provides about 16 lbs N per dry ton. This research involved tilling the biosolids into the top 8 inches of soil. A new question related to soil management in a biosolids beneficial-use program is: How much N would be available if the biosolids were surface-applied in a no-till dryland agroecosystem with winter wheat-fallow (WF) and winter wheat-corn (*Zea mays*, L.)-fallow (WCF) crop rotations?

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. 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 our research on land owned by the Cities of Littleton and Englewood (L/E) in eastern Adams County, approximately 28 miles east of Byers, CO. 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 used a wheat-wheat-corn-sunflower (*Helianthus annuus*, L.)-fallow rotation. After the 2004 growing season, we abandoned this rotation 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.

We initiated the study in August 1999 with biosolids application. Planting sequences are given in Table 3. We used four replications of each rotation following the 2004 growing season (WF and WCF) and we completely randomized each replicated block. Each phase of each rotation was present every year for 20 total plots. 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 3), and the second 50-foot wide section received biosolids applied by L/E with a manure spreader. We randomly selected which strip in each rotation received N fertilizer or biosolids. Characteristics of the L/E biosolids are provided in Table 4. We based the N fertilizer and biosolids applications 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, and 2004 and for the summer crops in March 2000, 2001, 2002, 2003, 2004, and 2005. We planted the first corn crop in May 2000. We also established wheat rotations in September 2000 through 2011 and corn rotations in May 2001 through 2011, and sunflower plantings in June 2001, 2002, and 2003. Soil moisture was inadequate in June 2004 to plant sunflowers (see Table 1). We abandoned the sunflower portion of the study in 2004.

We completed wheat harvests in July 2000, 2001, 2002, 2003, 2004, 2005, 2007, 2008, 2009, 2010, and 2011, and corn and sunflowers in October 2000 and 2001, sunflowers in December 2003, and corn in 2004, 2006, 2007, 2008, 2009, 2010, and 2011. We experienced corn and sunflower crop failures in 2002, a corn crop failure in 2003 and 2005, and a wheat-crop failure in 2006 due to lack and proper timing of precipitation (Table 1). For each harvest, we cut grain from four areas of 5 feet by approximately 100 feet within each subplot. 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. For AB-DTPA extractable Cu, P, and Zn (Barbarick and Workman, 1987) and EC (Rhoades, 1996) and pH (Thomas, 1996), we sampled to one foot and separated the samples into 0-2, 2-4, 4-8, and 8-12 inch depth increments. 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.

For the wheat rotations, the 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

Table 1 presents 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, 2007, 2008, 2009 and 2011, only 5 inches in 2002, about 12 inches in 2003, 10 inches in 2004, 2005, and 2010, and 9 inches in 2006. 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, and 5.2 inches of precipitation in July and August 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, and 2011, respectively.

2010 Crop Grain Data

No significant wheat (Figure 1) or corn yield (Table 5) differences were found for type of rotation or nutrient source. Average wheat and corn yields for all treatments exceeded the Colorado state average of 42 and 38 bushels/acre, respectively (USDA NASS Colorado Field Office, 2011).

Neither rotation nor nutrient source affected the wheat grain characteristics (Figures 2-4). The biosolids treatment increased corn-grain protein, P, and Zn compared to commercial N fertilizer (Table 5).

2010 Soil Data

Several rotation effects were found for ABDTPA P, Zn, and Cu and for EC and NO_3-N (Figures 5-10) in the WF and WCF rotations; however, no consistent trend with soil depth was noted. In the CFW rotation, we found that the biosolids produced higher ABDTPA P, Zn, and Cu in the top 2 inches (Table 6). We expected this result since the biosolids were surface applied and not incorporated.

2011 Crop Grain Data

For the 2011 wheat crop, the biosolids produced significantly higher grain yields and protein, P, and Zn concentrations than N fertilizer (Figures 11-14). Also, the WF rotation resulted in higher yields and Zn concentrations than the WCF rotation (Figures 11 and 14). For the 2011 corn crop, the biosolids produced higher grain P and Cu than N fertilizer (Table 7).

2011 Soil Data

Figures 16 through 21 present the 2011 soils data for the WF and WCF rotations. The WF rotation produced higher ABDTPA P in the top 2 inches (Figure 16), higher EC in the 2 to 4 inch depth (Figure 19), and higher NO_3-N in the 4 to 8 and 8 to 12 inch soil depths (Figure 21). Compared to N fertilizer, biosolids addition resulted in higher ABDTPA P, Zn, and Cu in the 0 to

2 inch soil depth (Figures 16-18), higher EC in the 4 to 8 inch depth (Figure 19), and higher NO_3-N in the 0 to 2, 2 to 4, 4 to 8, 8 to 12, and 36 to 48 inch depths (Figure 21).

For the CFW rotation, biosolids increased ABDTPA P, Zn, and Cu in the top 2 inches and NO_3-N in the 0 to 2, 2 to 4, 8 to 12, 12 to 24, 24 to 36 and 36 to 48 inch soil depths (Table 8). We anticipated these results since the biosolids added P, Zn, Cu, salts (measured by EC), and N and the biosolids were surface applied without incorporation.

CONCLUSIONS

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

1. In the wheat 2011 plots, we observed that biosolids compared to N fertilizer increased yields and grain concentrations of protein, P, and Zn. For the corn plots, biosolids produced higher grain protein, P, and Zn in 2010 and higher grain P and Cu in 2011.

2. For dryland wheat in 2010 and 2011, we observed that biosolids additions did increase some soil levels of ABDTPA-extractable P, Zn, and Cu and soil NO_3-N concentrations.

3. We found that biosolids application did not consistently produce higher soil salinity (EC) levels in the top 60 inch depth in the wheat or corn plots as compared to N fertilizer applications. No consistent trends were found for soil pH.

4. We will again apply biosolids beginning with the 2012 corn crop.

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Table 1. Monthly mean maximum (Max) and minimum (Min) temperatures and precipitation (Precip) in inches at the Byers research site, 2000-2011. (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.

Table 1 (continued). Monthly mean maximum (Max) and minimum (Min) temperatures and precipitation (Precip) in inches at the Byers research site, 2000-2011. (Weather station was installed in April, 2000).

Month	2010			2011		
	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
February	39.7	18.0	0.2	42.8	15.4	0.0
March	53.7	28.2	0.4	57.2	28.1	0.2
April	62.4	33.6	2.5	61.4	29.9	0.9
May	68.4	38.1	1.6	66.0	38.7	3.8
June	83.6	54.6	1.4	83.3	53.2	0.6
July	89.1	59.7	2.3	92.9	57.4	3.6
August	88.8	59.4	1.6	87.3	60.9	1.6
September	84.2	50.5	0.0	77.8	49.5	1.0
October	69.5	39.9	0.1	67.0	38.1	0.9
November	52.3	25.1	0.2	55.3	25.4	0.2
December	47.8	22.0	0.0	41.1	16.8	0.1
Total			10.4			13.2

† We installed the weather station in mid-April, 2000.

Table 2. Growing season precipitation.

Stage	Dates	Precipitation, inches	Stage	Dates	Precipitation, inches
Wheat vegetative	September 2000 - March 2001	3.3	Wheat vegetative	September 2006 - March 2007	3.5
Wheat reproductive	April 2001 - June 2001	6.3	Wheat reproductive	April 2007 - June 2007	3.7
Corn/Sunflowers preplant	July 2000 – April 2001	9.5	Corn preplant	July 2006 – April 2007	8.8
Corn/Sunflowers growing season	May 2001 – October 2001	9.6	Corn growing season	May 2007 – October 2007	8.2
Wheat vegetative	September 2001 - March 2002	2.1	Wheat vegetative	September 2007 - March 2008	1.5
Wheat reproductive	April 2002 - June 2002	2.2	Wheat reproductive	April 2008 - June 2008	2.2
Corn/Sunflowers preplant	July 2001 – April 2002	6.1	Corn preplant	July 2007 – April 2008	7.2
Corn/Sunflowers growing season	May 2002 – October 2002	3.9	Corn growing season	May 2008 – October 2008	10.5
Wheat vegetative	September 2002 - March 2003	1.1	Wheat vegetative	September 2008 - March 2009	2.1
Wheat reproductive	April 2003 - June 2003	3.3	Wheat reproductive	April 2009 - June 2009	8.3
Corn/Sunflowers preplant	July 2002 – April 2003	3.4	Corn preplant	July 2008 – April 2009	11.8
Corn/Sunflowers growing season	May 2003 – October 2003	9.2	Corn growing season	May 2009 – October 2009	12.9
Wheat vegetative	September 2003 - March 2004	0.3	Wheat vegetative	September 2009 - March 2010	3.3
Wheat reproductive	April 2004 - June 2004	2.3	Wheat reproductive	April 2010 - June 2010	5.5
Corn/Sunflowers preplant	July 2003 – April 2004	3.0	Corn preplant	July 2009 – April 2010	10.2
Corn/Sunflowers growing season	May 2004 – October 2004	8.6	Corn growing season	May 2010 – October 2010	7.0
Wheat vegetative	September 2004 - March 2005	1.7	Wheat vegetative	September 2010 - March 2011	0.8
Wheat reproductive	April 2005 - June 2005	4.3	Wheat reproductive	April 2011 - June 2011	5.3
Corn preplant	July 2004 – April 2005	5.3	Corn preplant	July 2010 – April 2011	5.6
Corn growing season	May 2005 – October 2005	8.6	Corn growing season	May 2011 – October 2011	11.5
Wheat vegetative	September 2005 - March 2006	2.5			
Wheat reproductive	April 2006 - June 2006	1.3			
Corn preplant	July 2005 – April 2006	6.4			
Corn growing season	May 2006 – October 2006	7.9			

Table 3. Biosolids and fertilizer applications and crop varieties used at the Byers research site, 1999-2009.

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
2005	Sept.	Wheat	Yumar	0	0	0	0	0	0	0

Table 3. (continued) Biosolids and fertilizer applications and crop varieties used at the Byers research site, 1999-2009.

2006	May	Corn	Pioneer J99	0	0	0	0	0	0	0
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

Table 4. Littleton/Englewood biosolids composition used at the Byers research site, 1999-2005.

Parameter	1999 Wheat	2000 Corn, Sunflowers	2001 Corn, Sunflowers	2001 Wheat	2003 Corn, sunflowers	2003 Wheat	2004 Wheat	2005 Corn	Avg.	Range
Solids, g kg^{-1}	217	---	210	220	254	192	197	211	214	192-254
pH	7.6	7.8	8.4	8.1	8.5	8.2	8.8	8.2	8.2	7.6-8.8
EC, dS m^{-1}	6.2	11.2	10.6	8.7	7.6	7.4	4.5	5.1	7.7	4.5-11.2
Org. N, g kg^{-1}	50	47	58	39	54	46	43	38	47	38-58
NH_4-N, g kg^{-1}	12	7	14	16	9	13	14	14	12	7-16
NO_3-N, g kg^{-1}	0.023	0.068	0.020	0.021	0.027	0.016	0.010	0	0.023	0-0.068
K, g kg^{-1}	5.1	2.6	1.6	1.9	2.2	2.6	2.1	1.7	2.5	1.6-5.1
P, g kg^{-1}	29	18	34	32	26	28	29	13	26	13-34
Al, g kg^{-1}	28	18	15	18	14	15	17	10	17	10-28
Fe, g kg^{-1}	31	22	34	33	23	24	20	20	26	20-34
Cu, mg kg^{-1}	560	820	650	750	596	689	696	611	672	560-820
Zn, mg kg^{-1}	410	543	710	770	506	629	676	716	620	410-770
Ni, mg kg^{-1}	22	6	11	9	11	12	16	4	11	4-22
Mo, mg kg^{-1}	19	22	36	17	21	34	21	13	23	13-36
Cd, mg kg^{-1}	6.2	2.6	1.6	1.5	1.5	2.2	4.2	2.0	2.7	1.5-6.2
Cr, mg kg^{-1}	44	17	17	13	9	14	18	14	18	9-44
Pb, mg kg^{-1}	43	17	16	18	15	21	26	16	22	15-43
As, mg kg^{-1}	5.5	2.6	1.4	3.8	1.4	1.6	0.5	0.05	2.1	0.05-5.5
Se, mg kg^{-1}	20	16	7	6	17	1	3	0.07	8.8	0.07-20
Hg, mg kg^{-1}	3.4	0.5	2.6	2.0	1.1	0.4	0.9	0.1	1.4	0.1-3.4
Ag, mg kg^{-1}	---	---	---	---	15	7	0.5	1.2	5.9	0.5-15
Ba, mg kg^{-1}	---	---	---	---	---	---	533	7	270	7-533
Be, mg kg^{-1}	---	---	---	---	---	---	0.05	<0.001	0.05	<0.05
Mn, mg kg^{-1}	---	---	---	---	---	---	239	199	219	199-239

Table 5. Corn grain characteristics for the corn rotation (CFW) at the Byers research site for 2010. ***Highlighted parameters*** are significant at the 0.10 probability level.

Parameter, units	Biosolids	Nitrogen	Probability level
Yield, bushels/acre	63.9	63.7	0.483
Protein, %	***11.1***	***10.2***	***<0.001***
P, g/kg	***0.28***	***0.25***	***<0.001***
Zn, mg/kg	***11.7***	***10.6***	***0.018***
Cu, mg/kg	1.64	1.57	0.326

Table 6. Soil characteristics for the corn rotation (CFW) at the Byers research site for 2010. ***Highlighted parameters*** are significant at the 10% probability level.

Parameter, units	Depth, inches	Biosolids	Nitrogen	Probability level
ABDTPA P, mg kg^{-1}	***0-2***	***34.1***	***9.5***	***0.010***
	2-4	2.3	1.4	0.631
	4-8	0.1	0.0	0.347
	8-12	0.1	0.0	0.347
ABDTPA Zn, mg kg^{-1}	***0-2***	***3.21***	***0.90***	***0.014***
	2-4	0.35	0.26	0.480
	4-8	0.17	0.14	0.517
	8-12	0.19	0.13	0.300
ABDTPA Cu, mg kg^{-1}	***0-2***	***7.17***	***2.32***	***0.005***
	2-4	3.29	2.76	0.343
	4-8	2.99	2.81	0.535
	8-12	2.31	2.60	0.418
pH	0-2	6.8	7.1	0.459
	2-4	7.4	7.2	0.619
	4-8	7.7	7.5	0.462
	8-12	***7.8***	***7.7***	***0.086***
ECe, dS m^{-1}	0-2	0.59	0.37	0.253
	2-4	0.32	0.31	0.880
	4-8	0.32	0.26	0.119
	8-12	0.30	0.26	0.278
NO_3-N, mg kg^{-1}	0-2	23.8	10.4	0.333
	2-4	7.2	5.5	0.396
	4-8	5.5	5.3	0.902
	8-12	5.5	5.3	0.874
	12-24	5.8	6.3	0.799
	24-36	9.1	6.7	0.411
	36-48	23.7	12.9	0.425
	48-60	15.8	11.4	0.619
	60-72	7.3	6.9	0.892

Table 7. Corn grain characteristics for the corn rotation (CFW) at the Byers research site for 2011. ***Highlighted parameters*** are significant at the 0.10 probability level.

Parameter, units	Biosolids	Nitrogen	Probability level
Yield, bushels/acre	35.1	59.7	0.172
Protein, %	10.7	10.3	0.156
P, g/kg	***0.40***	***0.34***	***0.010***
Zn, mg/kg	20.6	19.9	0.545
Cu, mg/kg	***2.38***	***1.59***	***0.058***

Table 8. Soil characteristics for the corn rotation (CFW) at the Byers research site for 2011. ***Highlighted parameters*** are significant at the 10% probability level.

Parameter, units	Depth, inches	Biosolids	Nitrogen	Probability level
ABDTPA P, mg kg^{-1}	***0-2***	***34.1***	***9.5***	***0.010***
	2-4	2.3	1.4	0.631
	4-8	0.1	0.0	0.347
	8-12	0.1	0.0	0.347
ABDTPA Zn, mg kg^{-1}	***0-2***	***3.21***	***0.90***	***0.014***
	2-4	0.35	0.26	0.480
	4-8	0.17	0.14	0.517
	8-12	0.19	0.13	0.300
ABDTPA Cu, mg kg^{-1}	***0-2***	***7.2***	***2.3***	***0.005***
	2-4	3.3	2.8	0.343
	4-8	3.0	2.8	0.535
	8-12	2.3	2.6	0.418
pH	0-2	7.0	6.8	0.303
	2-4	7.2	6.7	0.118
	4-8	7.7	7.5	0.323
	8-12	8.0	7.9	0.656
ECe, dS m^{-1}	0-2	0.61	0.56	0.757
	2-4	0.64	0.71	0.692
	4-8	0.57	0.58	0.939
	8-12	0.46	0.56	0.177
NO_3-N, mg kg^{-1}	***0-2***	***3.9***	***1.3***	***0.056***
	2-4	***3.0***	***0.9***	***0.041***
	4-8	1.9	0.9	0.118
	8-12	***1.5***	***0.5***	***0.064***
	12-24	***1.9***	***0.8***	***0.066***
	24-36	***4.8***	***1.0***	***0.002***
	36-48	***10.0***	***2.0***	***0.026***
	48-60	5.1	2.5	0.359
	60-72	3.8	3.1	0.835

Figure 1. Wheat grain yields for 2010 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).

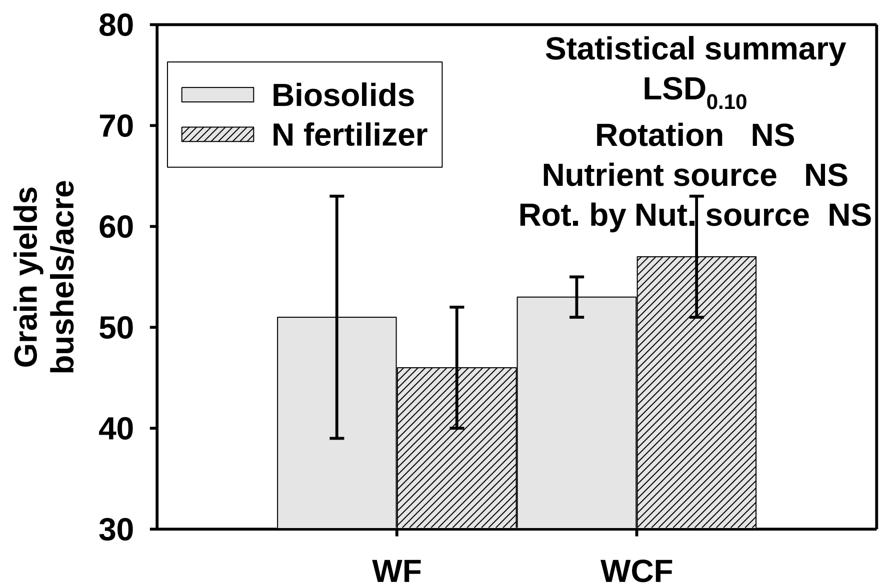


Figure 2. Wheat grain P concentrations for 2010 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).

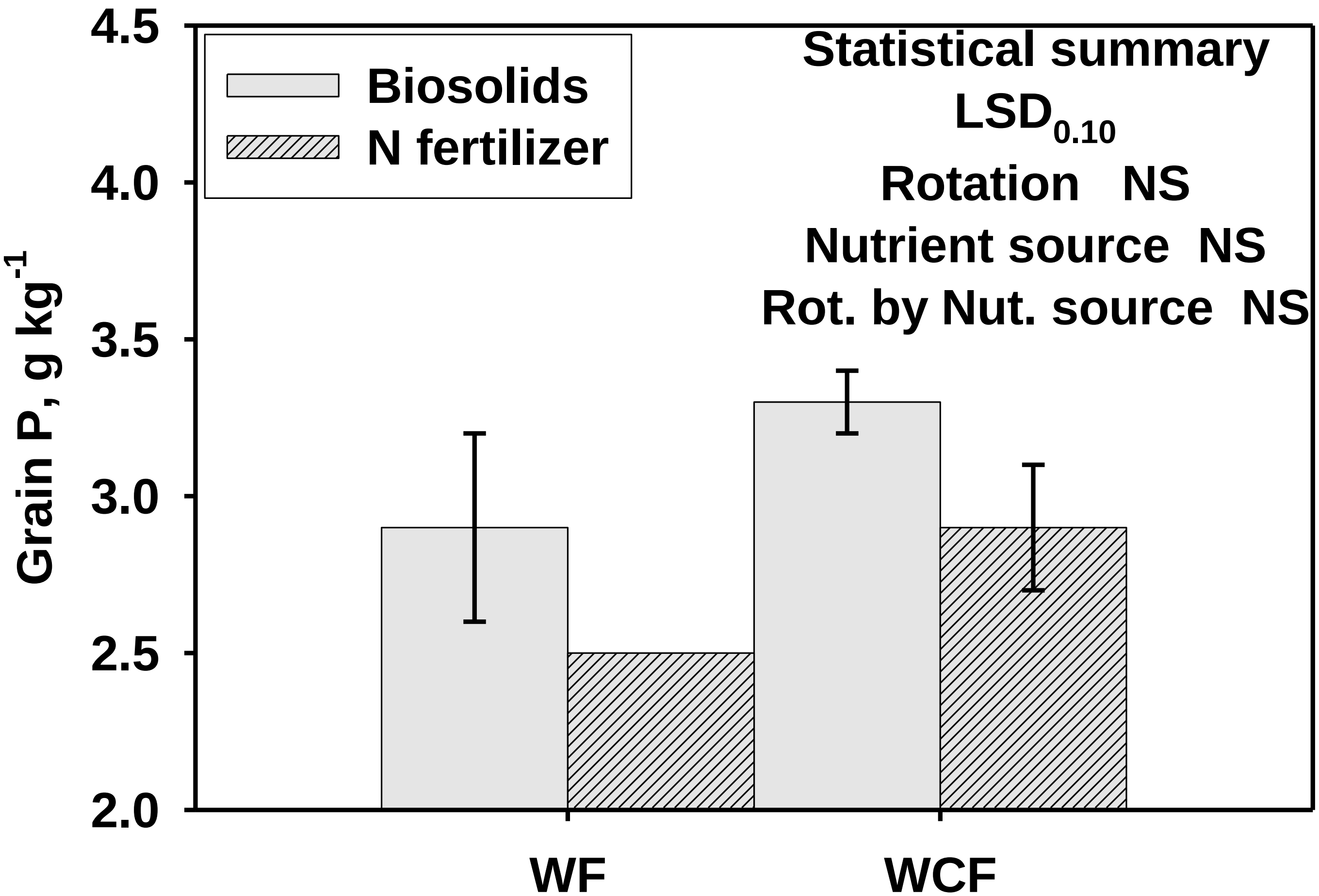


Figure 3. Wheat grain Zn concentrations for 2010 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).

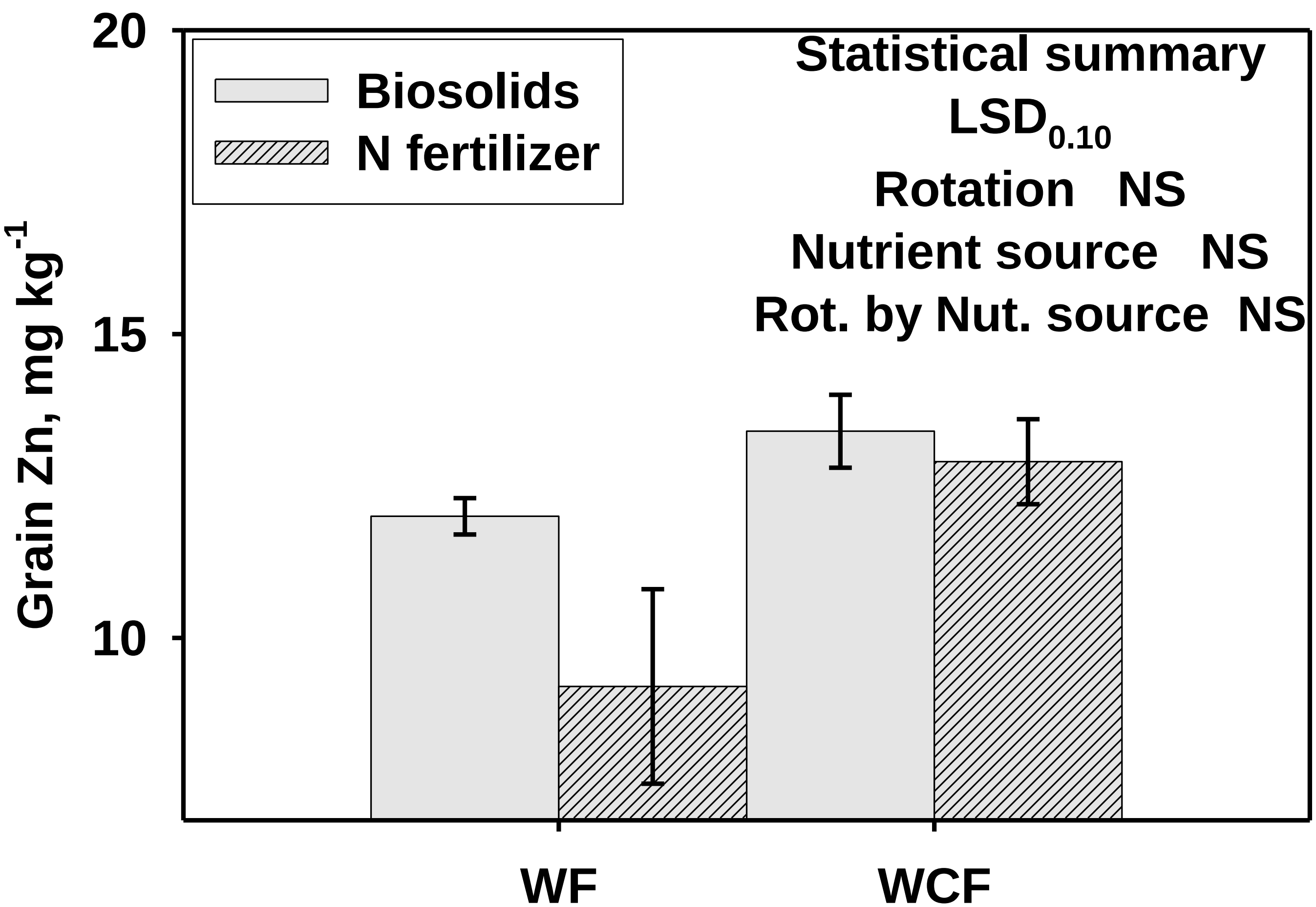


Figure 4. Wheat grain Cu concentrations for 2010 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).

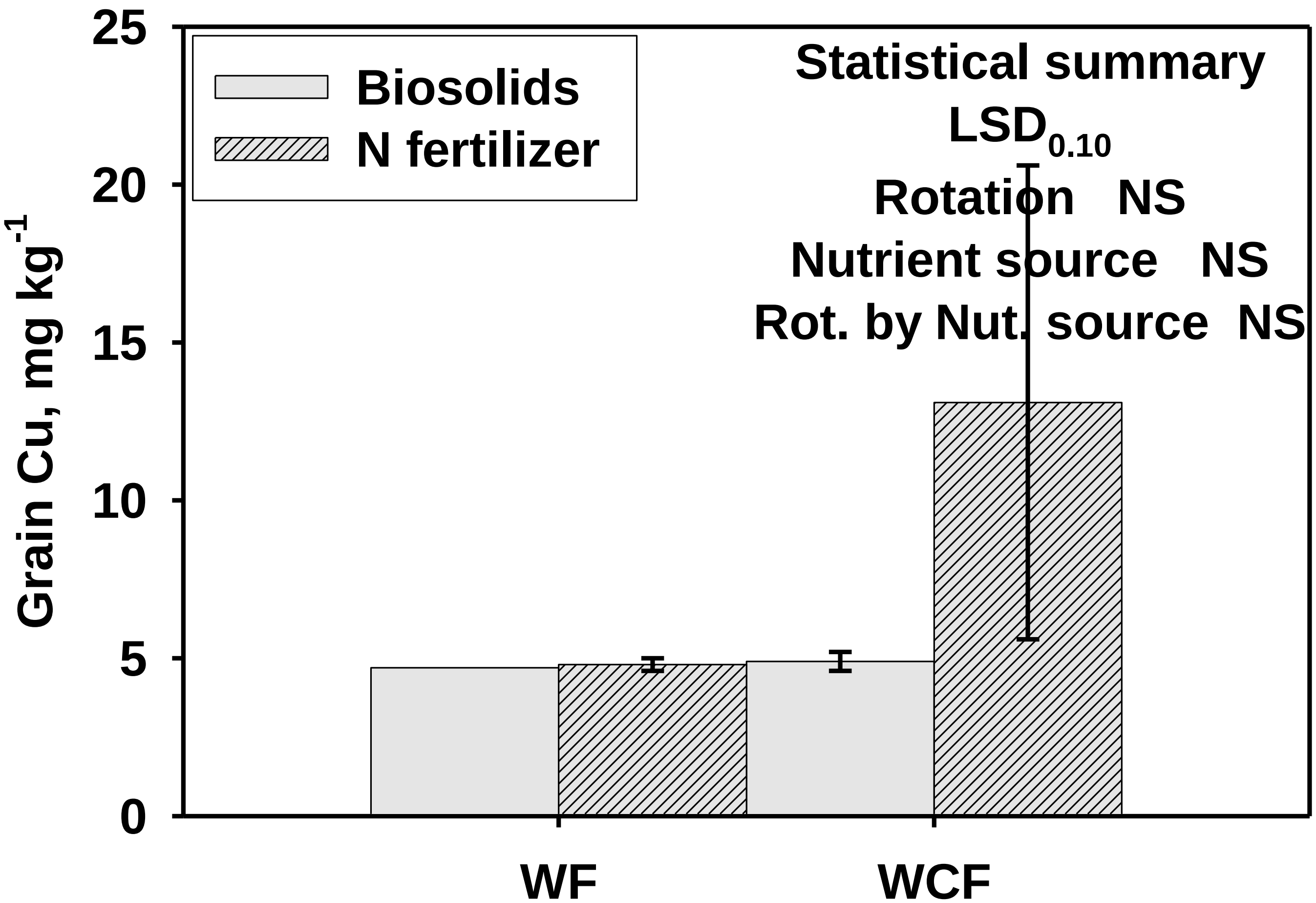
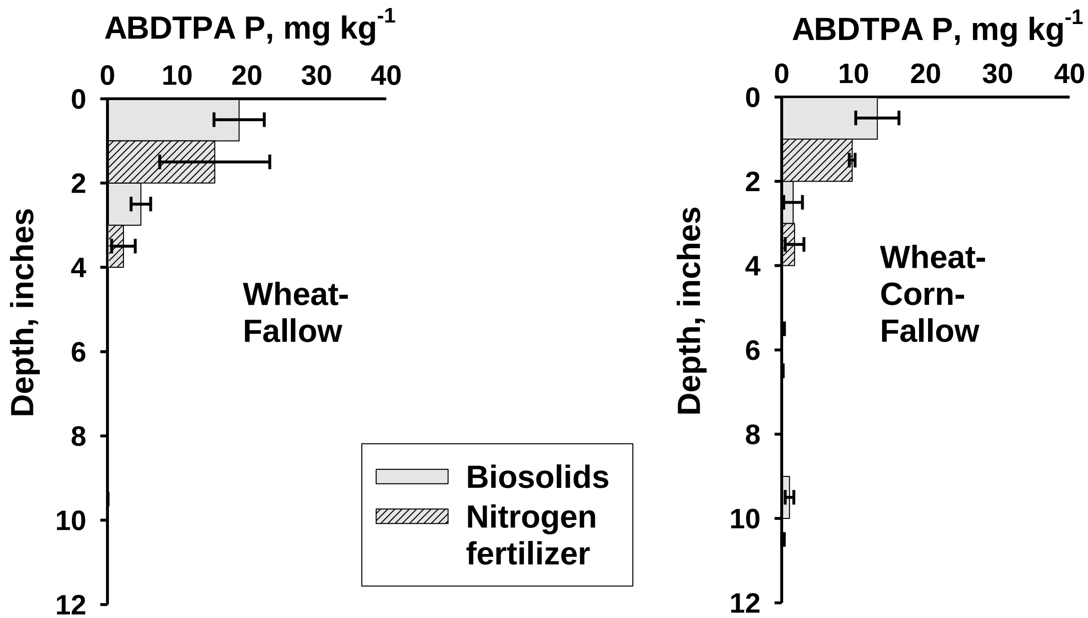


Figure 5. Soil ABDTPA-extractable P concentration following 2010 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.



Statistical summary by soil depth:

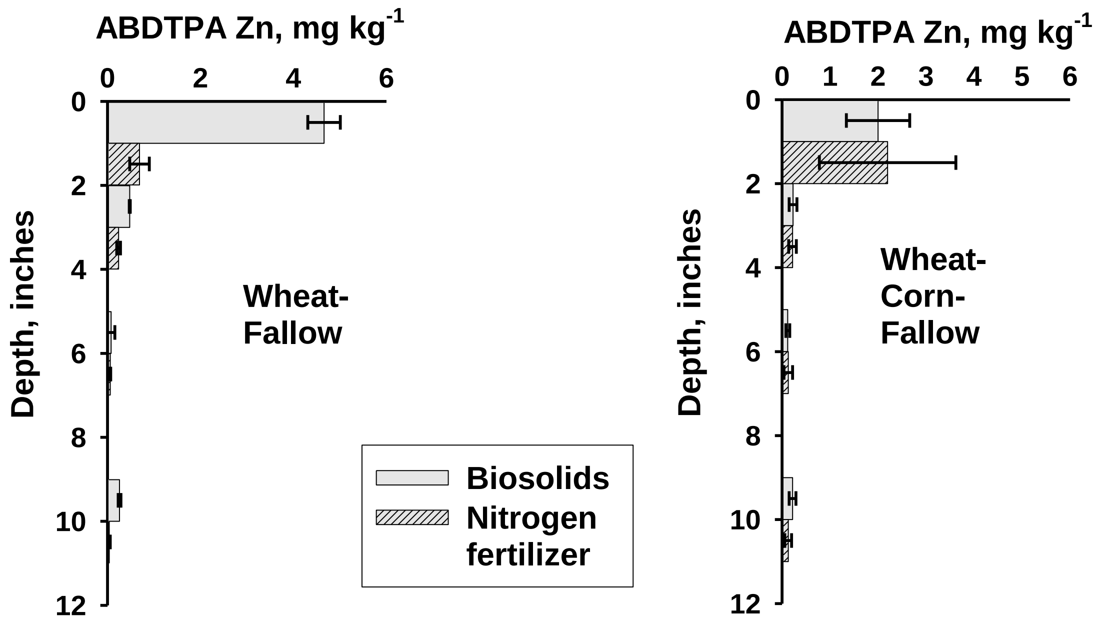
<u>0-2 inches</u>
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

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

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

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

Figure 6. Soil ABDTPA-extractable Zn concentration following 2010 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:

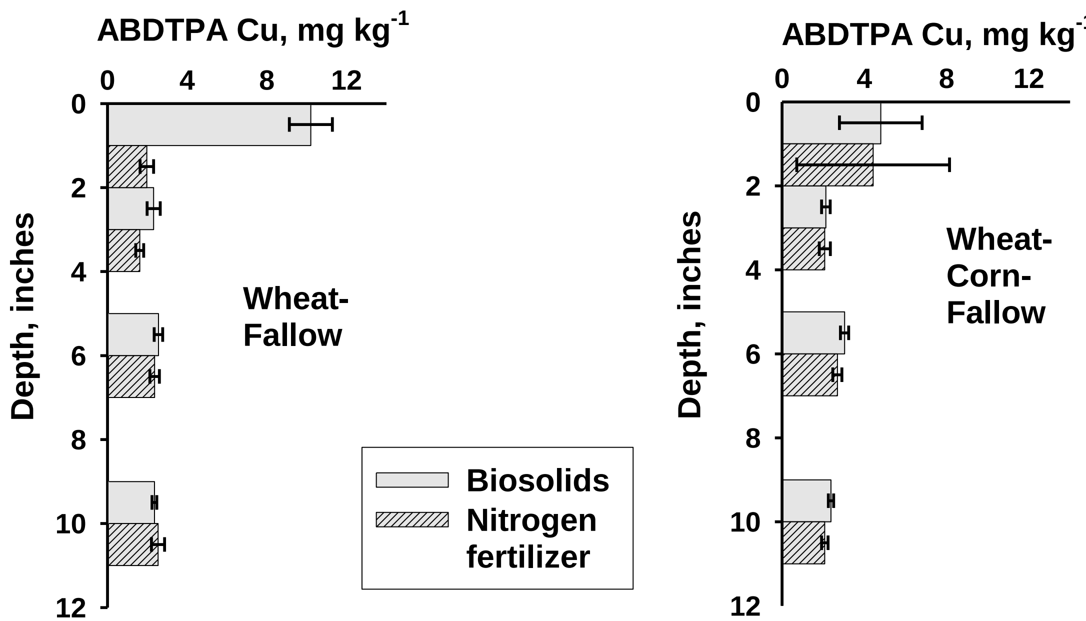
<u>0-2 inches</u>
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

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

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

<u>8-12 inches</u>
$LSD_{0.10}$
Rotations 0.33
Treatment NS
Rot. X Treat. NS

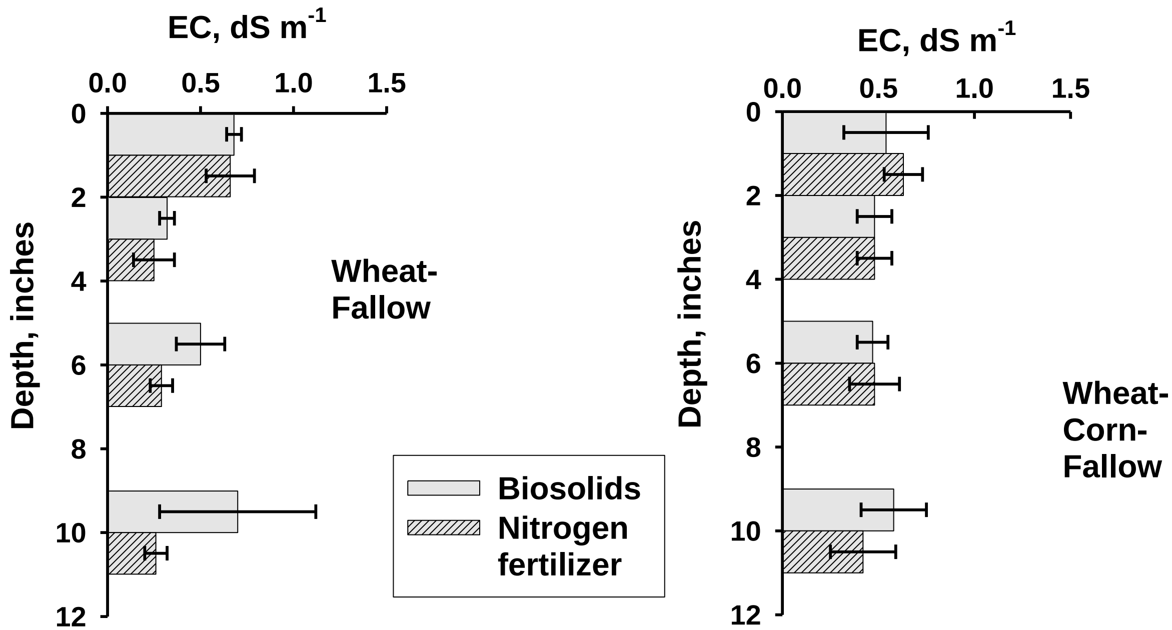
Figure 7. Soil ABDTPA-extractable Cu concentration following 2010 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.



Statistical summary by soil depth:

0-2 inches	2-4 inches	4-8 inches	8-12 inches
$LSD_{0.10}$	$LSD_{0.10}$	$LSD_{0.10}$	$LSD_{0.10}$
Rotations	Rotations NS	Rotations NS	Rotations NS
Treatment NS	Treatment NS	*Treatment 0.95*	Treatment NS
Rot. X Treat. NS	Rot. X Treat. NS	*Rot. X Treat. 0.28*	Rot. X Treat. NS

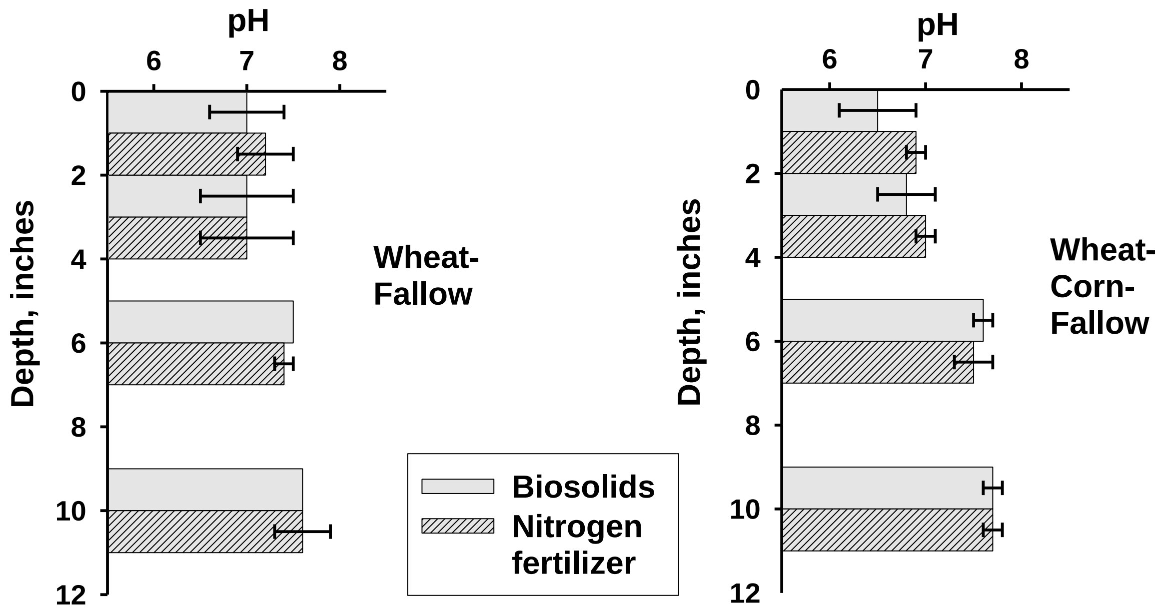
Figure 8. Soil saturated-paste electrical conductivity (EC) following 2010 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.



Statistical summary by soil depth:

0-2 inches	2-4 inches	4-8 inches	8-12 inches
$LSD_{0.10}$	$LSD_{0.10}$	$LSD_{0.10}$	$LSD_{0.10}$
Rotations NS	Rotations NS	Rotations NS	*Rotations 0.06*
Treatment NS	Treatment NS	Treatment NS	Treatment NS
Rot. X Treat. NS	Rot. X Treat. NS	Rot. X Treat. NS	Rot. X Treat. NS

Figure 9. Soil saturated-paste pH following 2010 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:

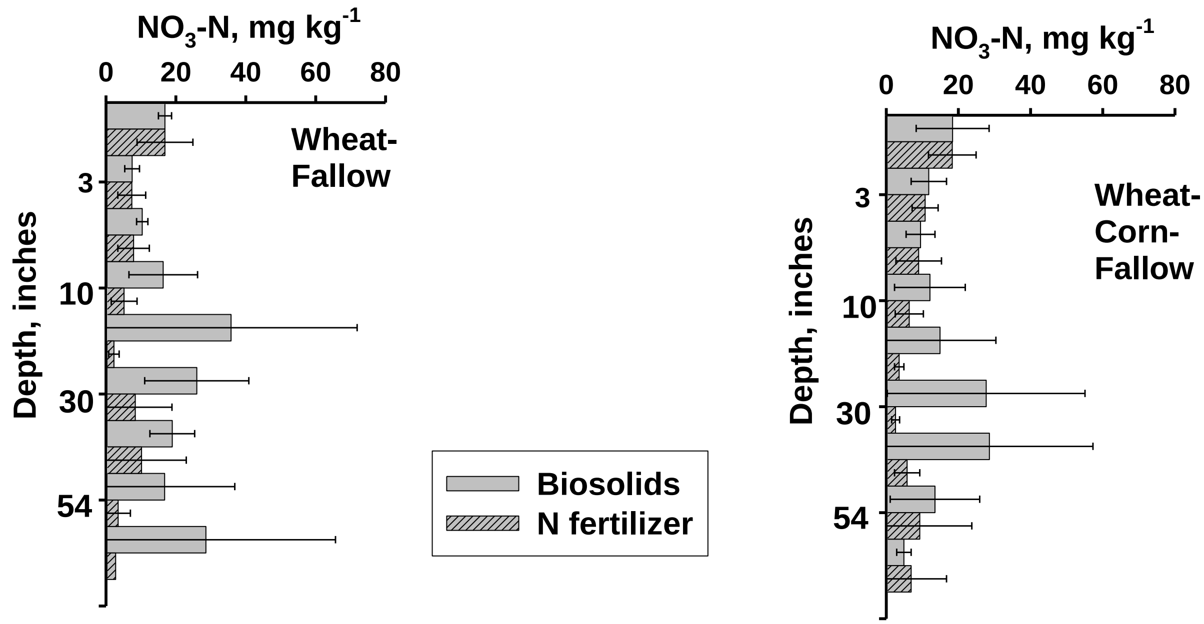
0-2 inches
LSD$_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

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 10. Soil NO_3-N concentrations following 2010 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 1.8
Treatment NS
Rot. X Treat. NS

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

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

24-36 inches
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

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

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

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

Figure 11. Wheat grain yields for 2011 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).

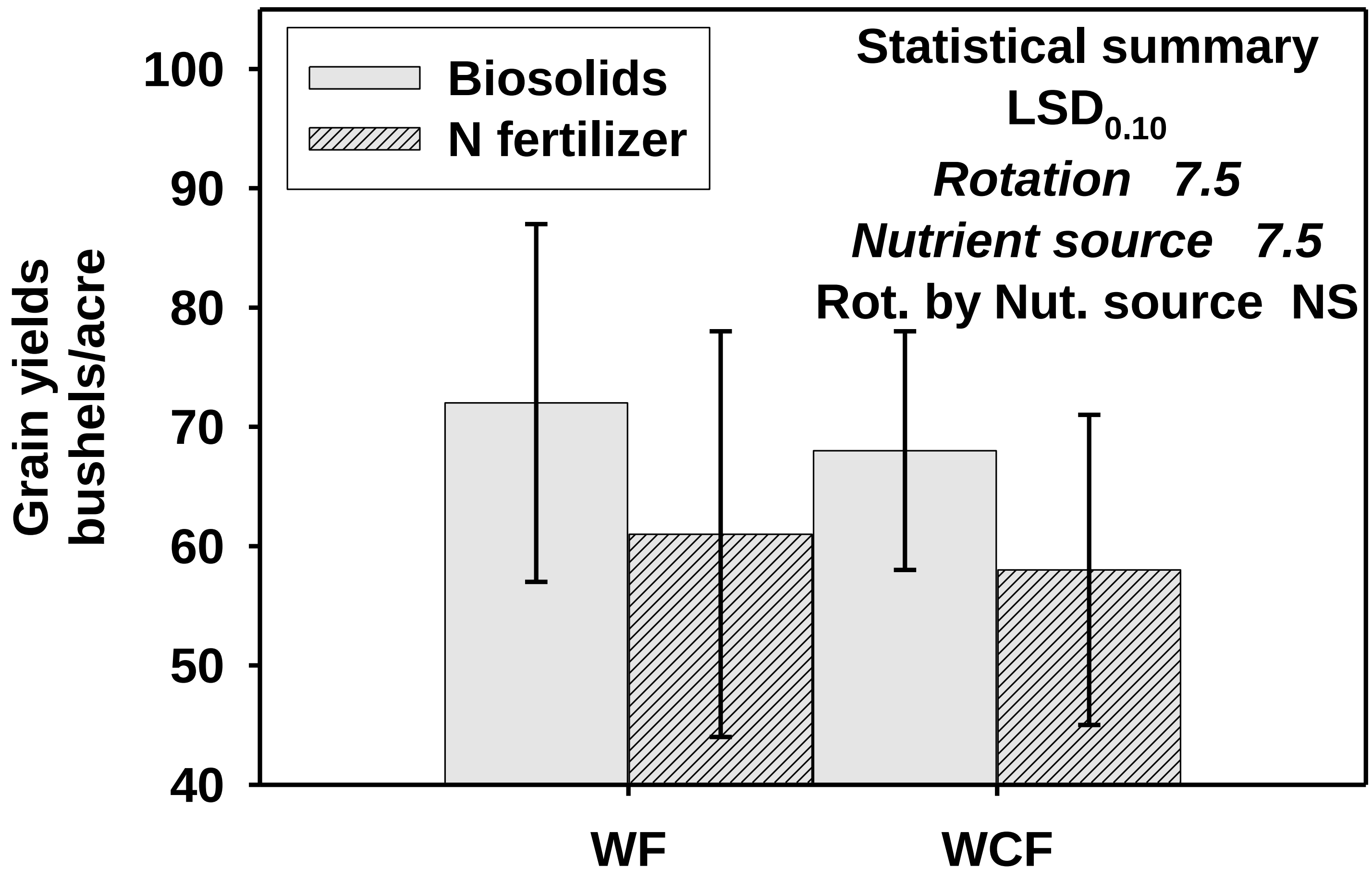


Figure 12. Wheat grain protein for 2011 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).

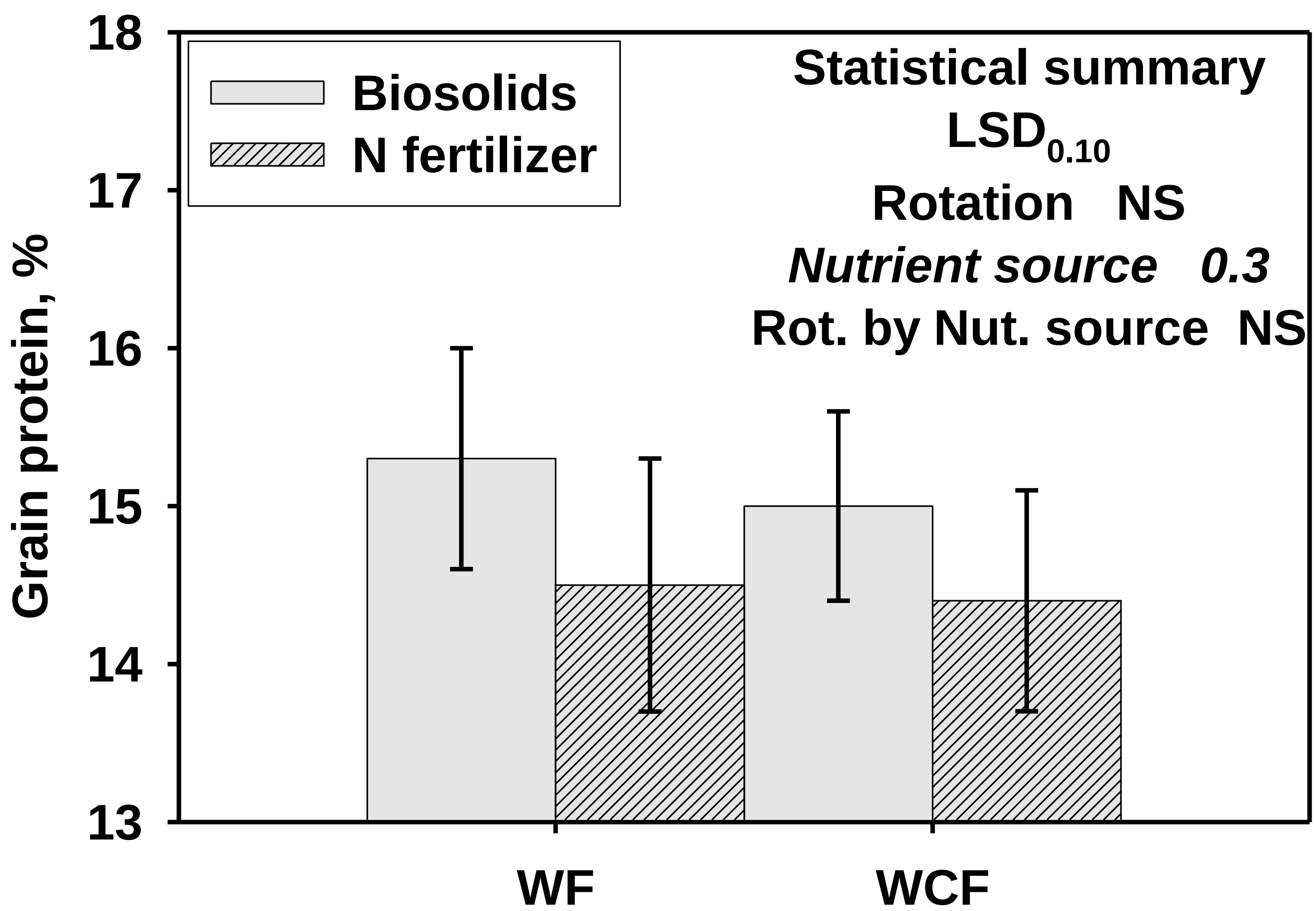


Figure 13. Wheat grain P concentrations for 2011 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).

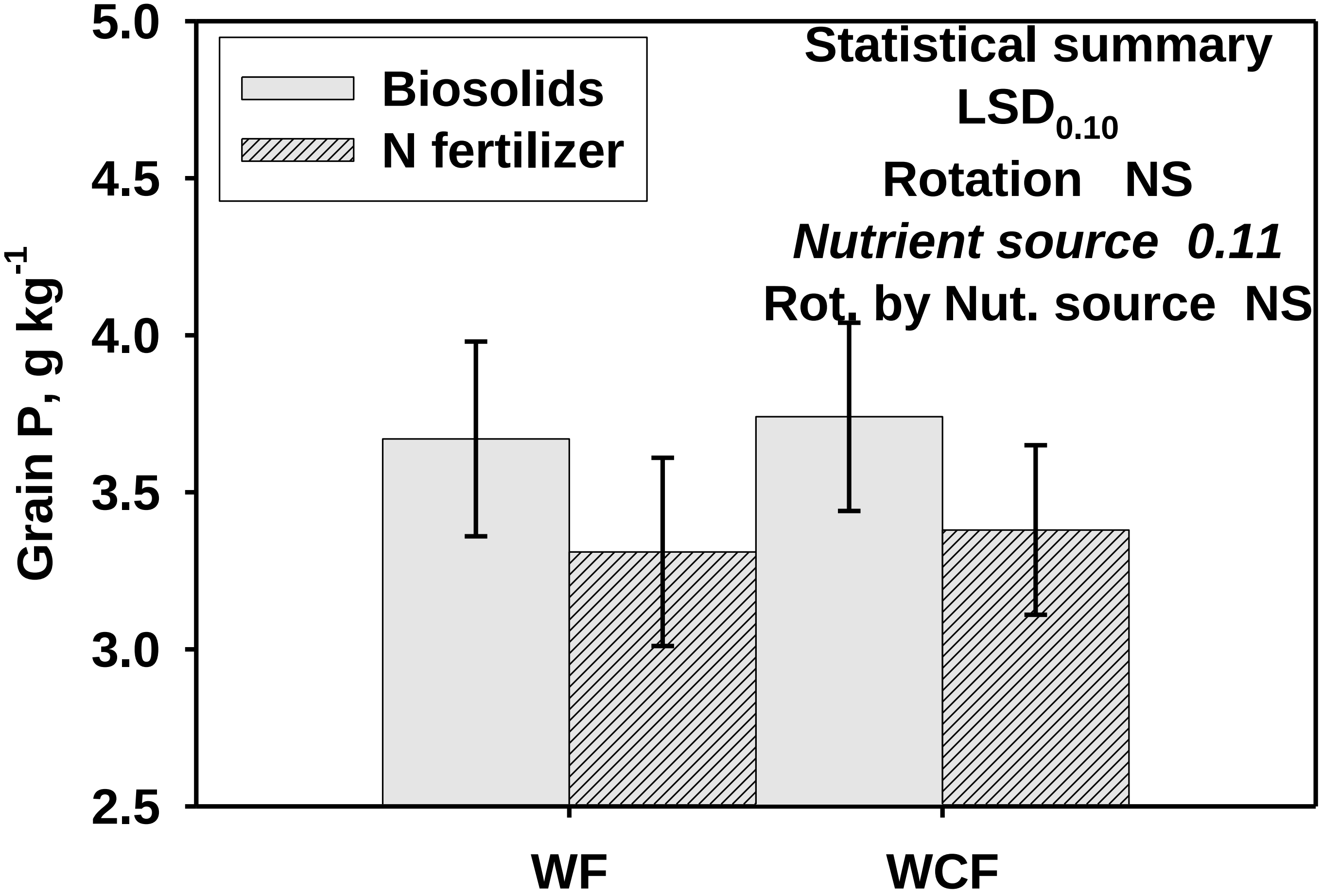


Figure 14. Wheat grain Zn concentrations for 2011 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).

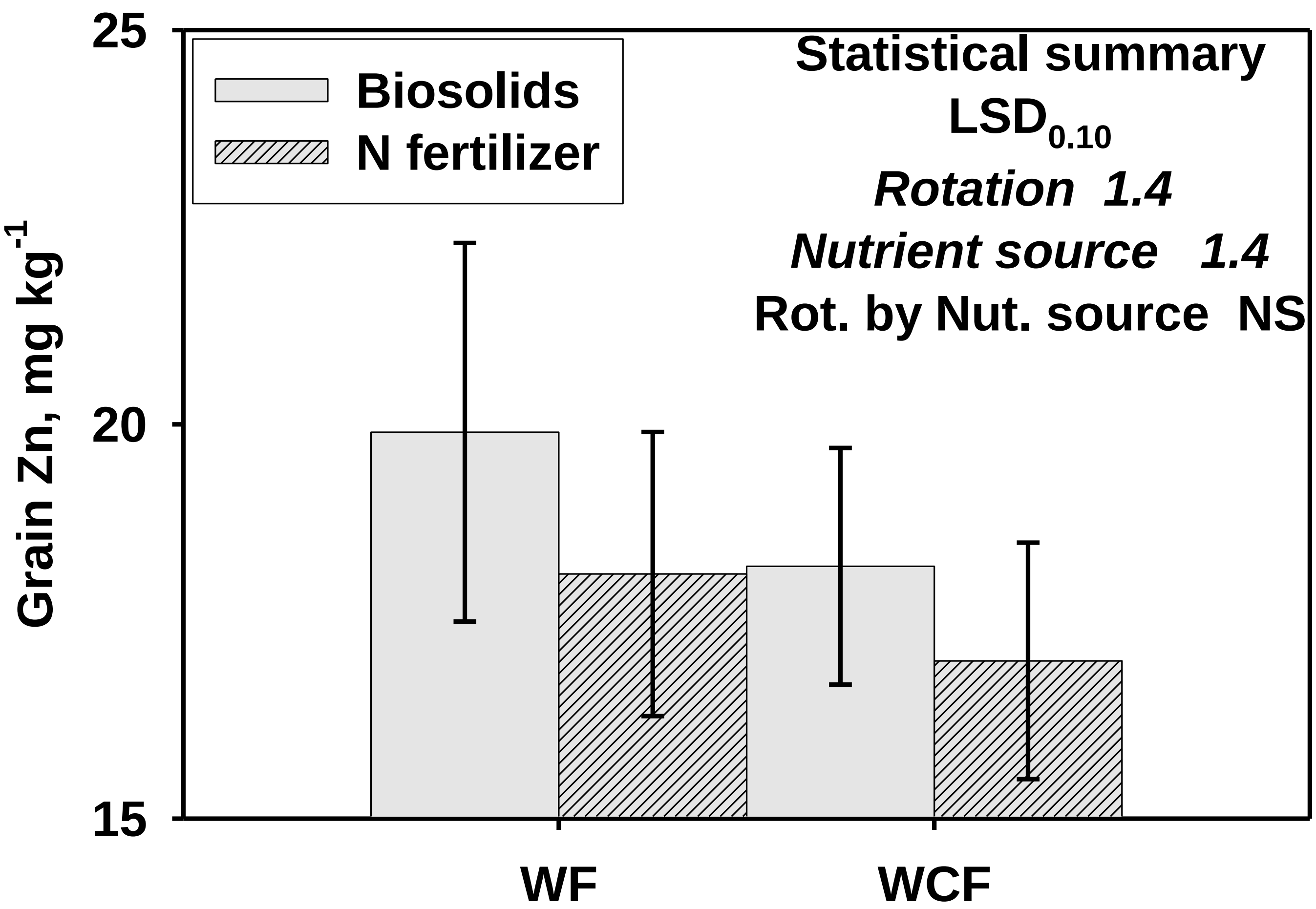


Figure 15. Wheat grain Cu concentrations for 2011 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).

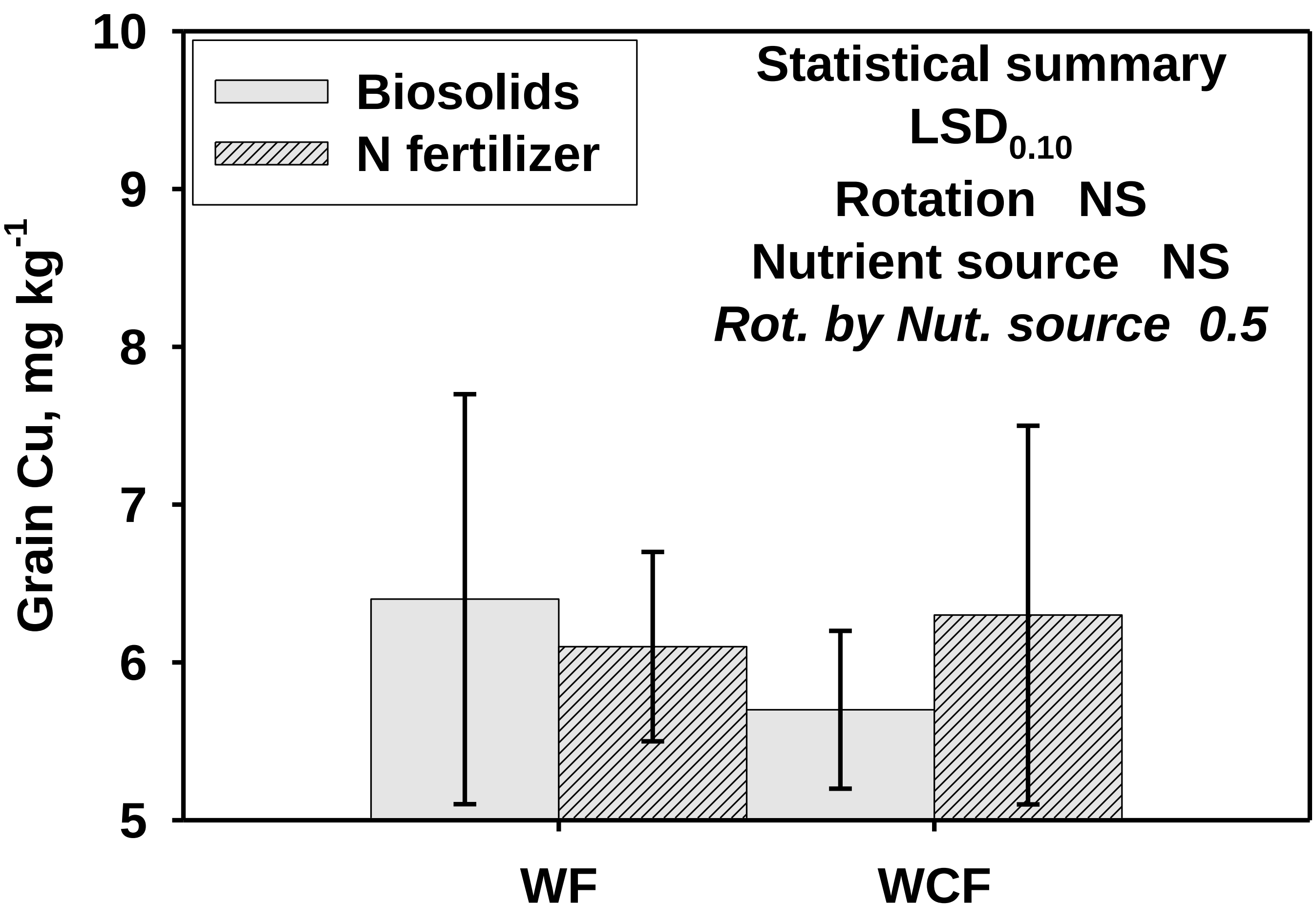
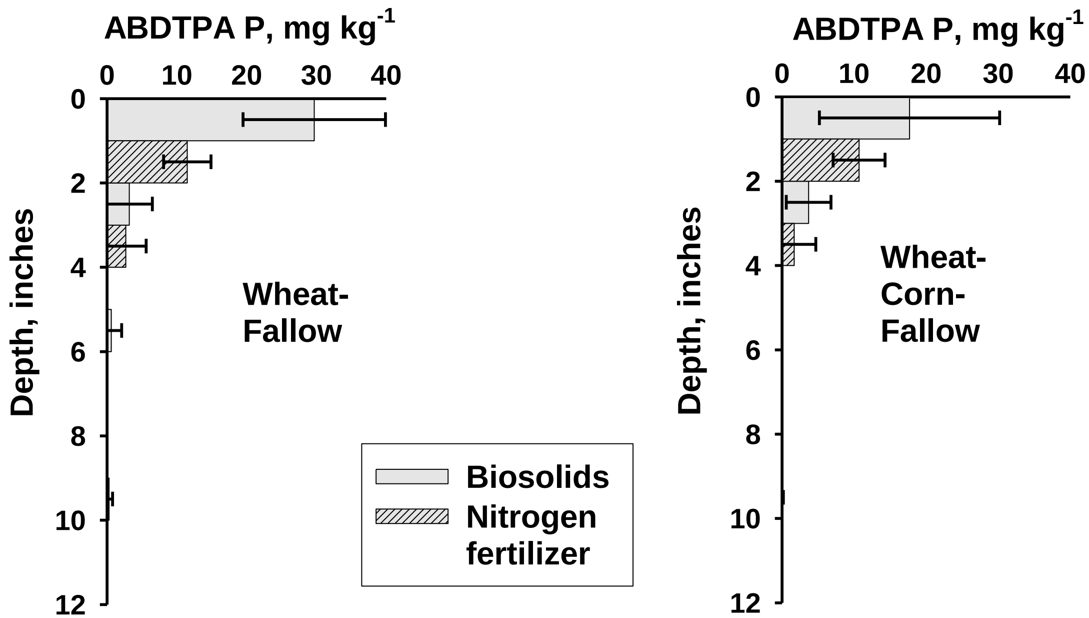


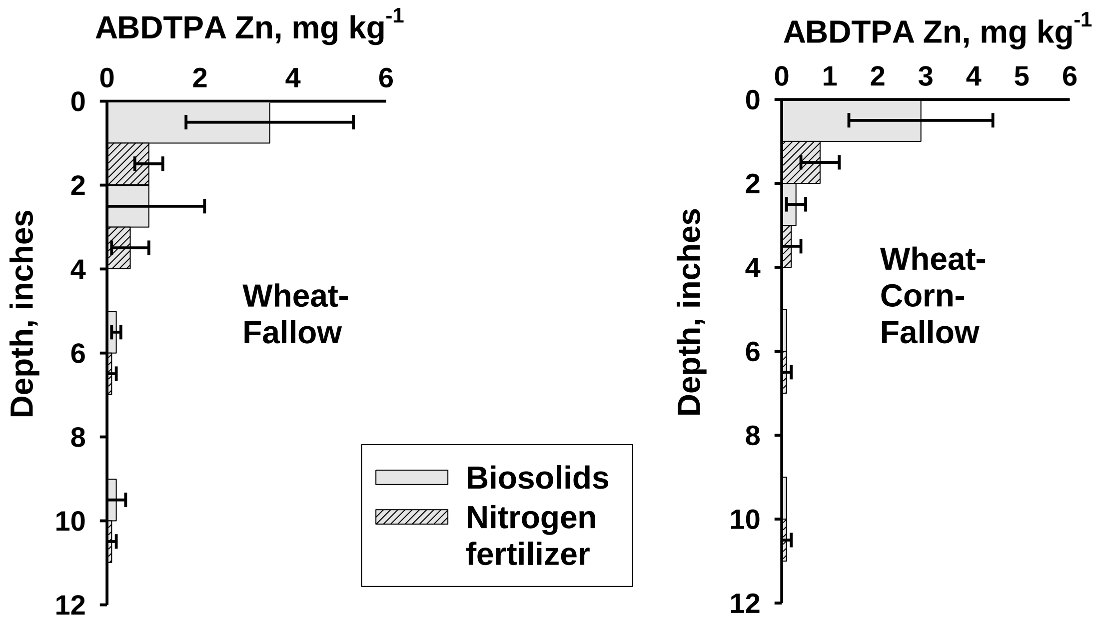
Figure 16. Soil ABDTPA-extractable P concentration following 2011 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.



Statistical summary by soil depth:

0-2 inches	2-4 inches	4-8 inches	8-12 inches
$LSD_{0.10}$	$LSD_{0.10}$	$LSD_{0.10}$	$LSD_{0.10}$
Rotations 6.5	Rotations NS	Rotations NS	Rotations NS
Treatment 5.2	Treatment NS	Treatment NS	Treatment NS
Rot. X Treat. NS	Rot. X Treat. NS	Rot. X Treat. NS	Rot. X Treat. NS

Figure 17. Soil ABDTPA-extractable Zn concentration following 2011 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:

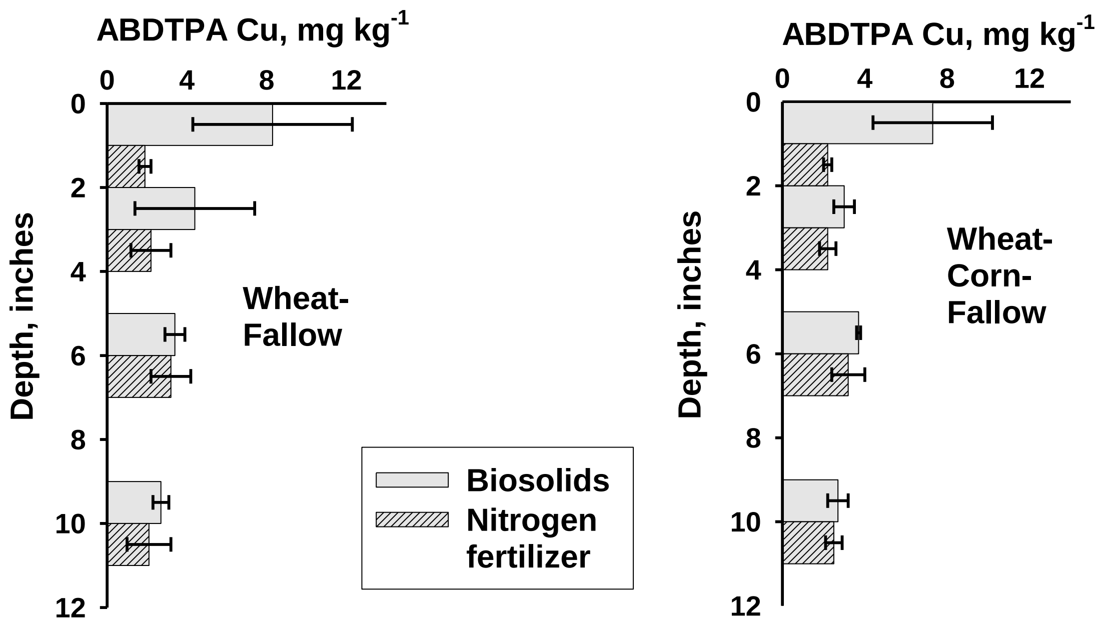
0-2 inches
$LSD_{0.10}$
Rotations NS
Treatment 1.7
Rot. X Treat. NS

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

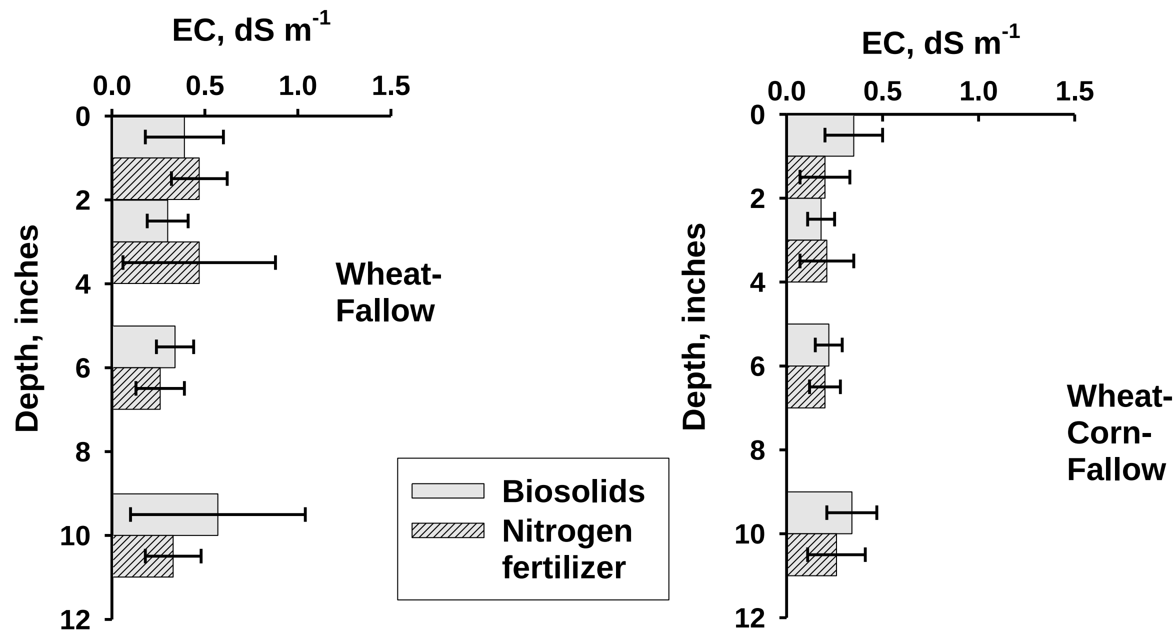
Figure 18. Soil ABDTPA-extractable Cu concentration following 2011 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.



Statistical summary by soil depth:

0-2 inches	2-4 inches	4-8 inches	8-12 inches
$LSD_{0.10}$	$LSD_{0.10}$	$LSD_{0.10}$	$LSD_{0.10}$
Rotations NS	Rotations NS	Rotations NS	Rotations NS
Treatment 3.5	Treatment NS	Treatment NS	Treatment NS
Rot. X Treat. NS	Rot. X Treat. NS	Rot. X Treat. NS	Rot. X Treat. NS

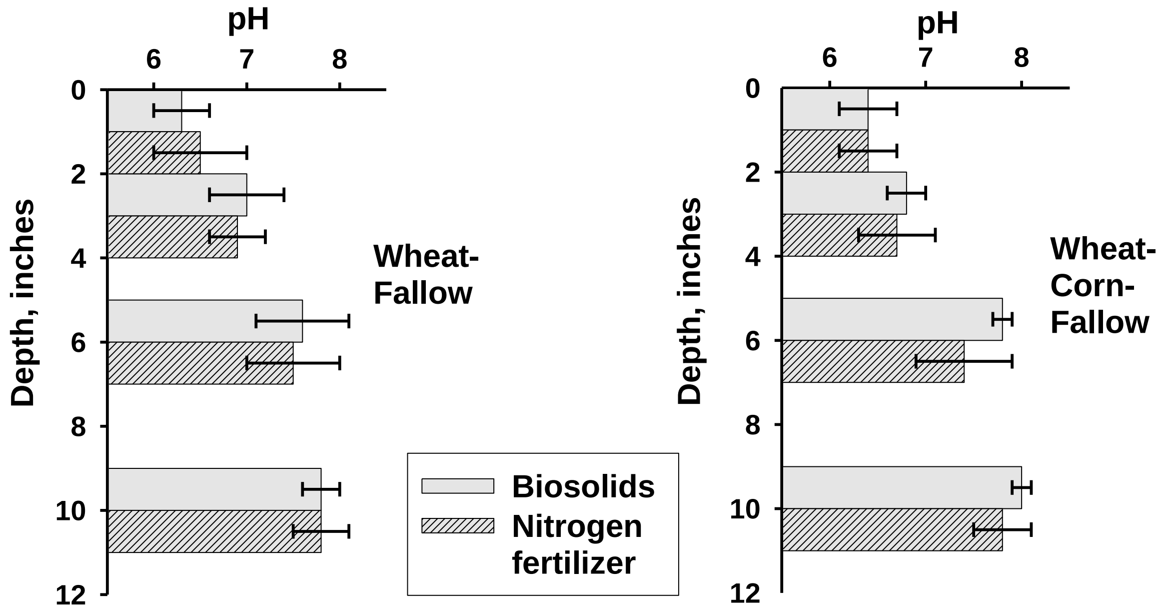
Figure 19. Soil saturated-paste electrical conductivity (EC) following 2011 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant 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 NS	*Rotations 0.19*	Rotations NS	Rotations NS
Treatment NS	Treatment NS	*Treatment 0.04*	Treatment NS
Rot. X Treat. NS	Rot. X Treat. NS	Rot. X Treat. NS	Rot. X Treat. NS

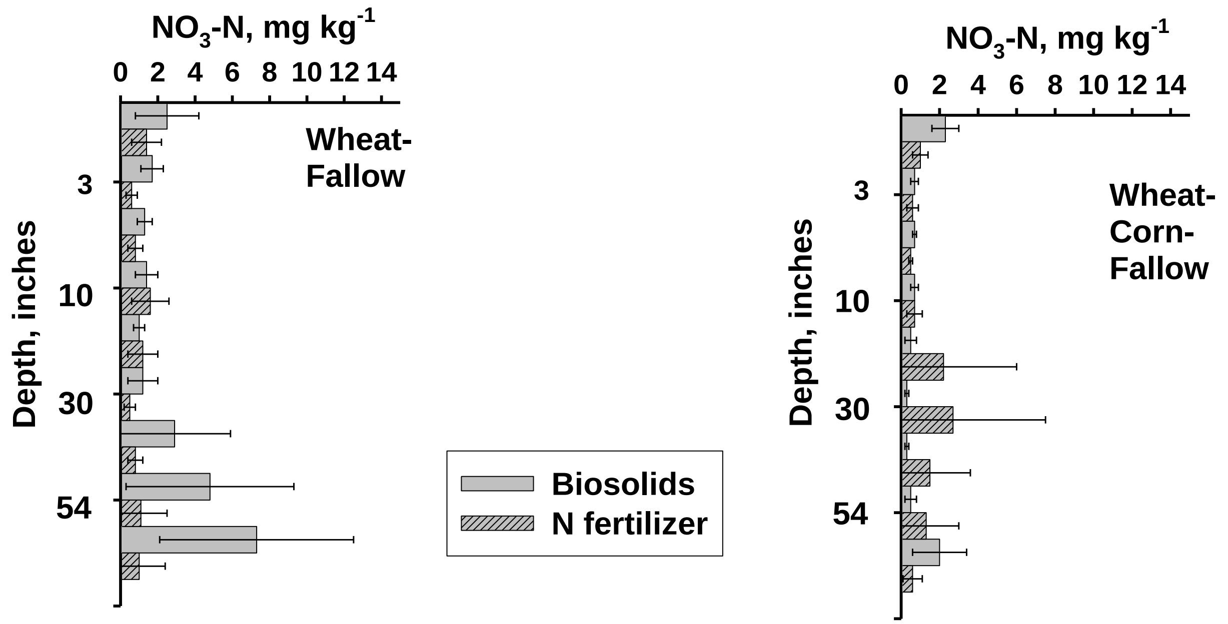
Figure 20. Soil saturated-paste pH following 2011 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 0.10 probability level and NS indicates non-significant differences.



Statistical summary by soil depth:

0-2 inches	2-4 inches	4-8 inches	8-12 inches
$LSD_{0.10}$	$LSD_{0.10}$	$LSD_{0.10}$	$LSD_{0.10}$
Rotations NS	Rotations NS	Rotations NS	Rotations NS
Treatment NS	Treatment NS	Treatment NS	Treatment NS
Rot. X Treat. NS	Rot. X Treat. NS	Rot. X Treat. NS	Rot. X Treat. NS

Figure 21. Soil NO_3-N concentrations following 2011 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>
$LSD_{0.10}$
Rotations NS
Treatment 1.0
Rot. X Treat. NS

<u>2-4 inches</u>
$LSD_{0.10}$
Rotations NS
Treatment 0.2
Rot. X Treat. 0.1

<u>4-8 inches</u>
$LSD_{0.10}$
Rotations 0.3
Treatment 0.3
Rot. X Treat. NS

<u>8-12 inches</u>
$LSD_{0.10}$
Rotations 0.6
Treatment NS
Rot. X Treat. NS

<u>12-24 inches</u>
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

<u>24-36 inches</u>
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

<u>36-48 inches</u>
$LSD_{0.10}$
Rotations 2.4
Treatment NS
Rot. X Treat. NS

<u>48-60 inches</u>
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS

<u>60-72 inches</u>
$LSD_{0.10}$
Rotations NS
Treatment NS
Rot. X Treat. NS