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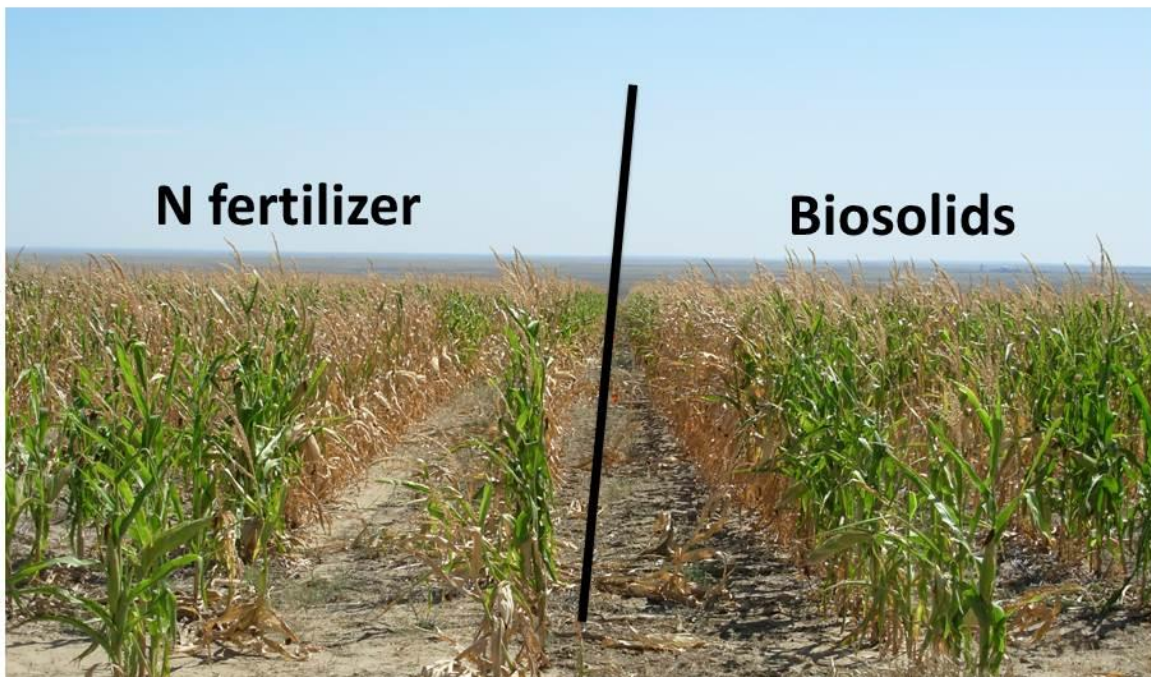
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Biosolids Application to No-Till Dryland Rotations: 2013 Results



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Dryland Crop Rotations:
2013 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 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 ($\text{NO}_3\text{-N}$).

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 latitude longitude for the plot corners are $39^\circ 45'47''/103^\circ 47'50''$ (southwest), $39^\circ 45'47''/103^\circ 47'17''$ (southeast), $39^\circ 46'7''/103^\circ 47'50''$ (northwest), $39^\circ 46'7''/103^\circ 47'17''$ (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 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.

The first biosolids application occurred in August 1999. Planting sequences are given in Table 3. 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 3), 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 4. 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, and 2012 for the summer crops in March 2000, 2001, 2002, 2003, 2004, 2005, 2012, and 2013. We planted the first corn crop in May 2000. We also established wheat rotations in September 2000 through 2013 and corn rotations in May 2001 through 2013, and sunflower plantings in June 2001, 2002, and 2003. Soil moisture was inadequate in June 2004 to plant sunflowers (see Table 1). The sunflower portion of the study was abandoned in 2004.

At 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. 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 NO₃-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.

In the wheat phase of each rotation, 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

Tables 1 and 2 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, 2007, 2008, 2009 and 2011, between 5 and 6 inches in 2002 and 2012, about 12 inches in 2003, 10 inches in 2004, 2005, and 2010, 9 inches in 2006, and about 8 inches in 2013. 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, and 1.3 inches of precipitation in July and August 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, and 2013 respectively.

2013 Crop Grain Data

The rotation by nutrient source interaction was significant for wheat yields with the biosolids treatment in WF producing the largest yields (Figure 1). The treatments did not significantly affect corn yields (Table 5). Average wheat yield for our treatments was 22 bushels/acre while the Colorado state average was 47 bushels/acre (USDA NASS Colorado Field Office, 2014). The corn yields averaged 42 bushels/acre; eight inches of rain were received during the corn growing season (Table 2).

Biosolids produced 1% greater wheat protein content than N fertilizer treatments (Figures 2). The nutrient source and the rotation by nutrient source interaction significantly affected wheat grain P and Zn with the biosolids treatment in the WCF rotation producing the largest concentration of both nutrients (Figure 3 and 4). Wheat grain Cu and corn grain protein, P, Zn, and Cu were not affected by any of the treatments (Figure 5 and Table 5).

2013 Soil Data

In the wheat phase of each rotation, biosolids addition resulted in higher ABDTPA P, Zn, and Cu down to the 4 inch depth while results for EC, pH, and NO₃-N (Figures 6-11) did not show consistent trends. In the CFW rotation, we found that the biosolids produced higher ABDTPA P in the 2 to 4 inch depth and larger NO₃-N in the 36 to 48 and 48 to 60 inch depths (Table 6). The increased nutrient concentration in the top two depths for both crops is expected since the biosolids were not incorporated.

CONCLUSIONS

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

1. In the 2013 wheat and corn plots, we observed that biosolids did not significantly increase yields but we found higher grain concentrations of protein and P with biosolids in the WF rotation compared to N fertilizer.
2. For dryland wheat in 2013, we observed that biosolids additions did increase soil levels of ABDTPA-extractable P, Zn, and Cu in the top 4 inches of soil.
3. No consistent trends were found for soil EC and pH.
4. The results discussed in items 1 through 3 are similar to a majority of our past findings.
5. We applied biosolids to the 2013-14 wheat plots in September 2013.

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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. The tipping bucket rain gauge may not accurately measure precipitation received as snow.

Table 1 (continued). Monthly mean maximum (Max) and minimum (Min) temperatures and precipitation (Precip) in inches at the Byers research site, 2000-2013. (Weather station was installed in April, 2000).

| Month | 2010 | | | 2011 | | | 2012 | | | 2013 | | |
|-----------|--------|--------|---------------|--------|--------|---------------|--------|--------|---------------|--------|--------|---------------|
| | 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 |
| 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 |
| 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 |
| 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 |
| 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 |
| 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 |
| 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 |
| 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 |
| 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 |
| 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 |
| 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 |
| 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 |
| Total | | | 10.4 | | | 13.2 | | | 5.8 | | | 8.4 |

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

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 vegetative | September 2011 - March 2012 | 2.7 |
| Wheat reproductive | April 2006 - June 2006 | 1.3 | Wheat reproductive | April 2012 - June 2012 | 2.4 |
| Corn preplant | July 2005 – April 2006 | 6.4 | Corn preplant | July 2011 – April 2012 | 7.4 |
| Corn growing season | May 2006 – October 2006 | 7.9 | Corn growing season | May 2012 – October 2012 | 3.8 |

Table 2 (continued).

Growing season precipitation.

| Stage | Dates | Precipitation, inches |
|---------------------|-----------------------------|-----------------------|
| Wheat vegetative | September 2012 - March 2013 | 1.9 |
| Wheat reproductive | April 2013 - June 2013 | 1.7 |
| Corn preplant | July 2012 – April 2013 | 3.3 |
| Corn growing season | May 2013 – October 2013 | 8.0 |

Table 3. Biosolids and fertilizer applications and crop varieties used at the Byers research site, 1999-2013.

| 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 ₂ O 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 3. (continued) Biosolids and fertilizer applications and crop varieties used at the Byers research site, 1999-2013.

| 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 ₂ O 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 4. Littleton/Englewood biosolids composition used at the Byers research site, 1999-2013.

| Parameter | 1999 Wheat | 2000 Corn, Sunflowers | 2001 Corn, Sunflowers | 2001 Wheat | 2003 Corn, sunflowers | 2003 Wheat | 2004 Wheat | 2005 Corn |
|--|---------------|--------------------------|--------------------------|---------------|--------------------------|---------------|---------------|--------------|
| Solids, g kg ⁻¹ | 217 | --- | 210 | 220 | 254 | 192 | 197 | 211 |
| pH | 7.6 | 7.8 | 8.4 | 8.1 | 8.5 | 8.2 | 8.8 | 8.2 |
| EC, dS m ⁻¹ | 6.2 | 11.2 | 10.6 | 8.7 | 7.6 | 7.4 | 4.5 | 5.1 |
| Org. N, g kg ⁻¹ | 50 | 47 | 58 | 39 | 54 | 46 | 43 | 38 |
| NH ₄ -N, g kg ⁻¹ | 12 | 7 | 14 | 16 | 9 | 13 | 14 | 14 |
| NO ₃ -N, g kg ⁻¹ | 0.023 | 0.068 | 0.020 | 0.021 | 0.027 | 0.016 | 0.010 | 0 |
| K, g kg ⁻¹ | 5.1 | 2.6 | 1.6 | 1.9 | 2.2 | 2.6 | 2.1 | 1.7 |
| P, g kg ⁻¹ | 29 | 18 | 34 | 32 | 26 | 28 | 29 | 13 |
| Al, g kg ⁻¹ | 28 | 18 | 15 | 18 | 14 | 15 | 17 | 10 |
| Fe, g kg ⁻¹ | 31 | 22 | 34 | 33 | 23 | 24 | 20 | 20 |
| Cu, mg kg ⁻¹ | 560 | 820 | 650 | 750 | 596 | 689 | 696 | 611 |
| Zn, mg kg ⁻¹ | 410 | 543 | 710 | 770 | 506 | 629 | 676 | 716 |
| Ni, mg kg ⁻¹ | 22 | 6 | 11 | 9 | 11 | 12 | 16 | 4 |
| Mo, mg kg ⁻¹ | 19 | 22 | 36 | 17 | 21 | 34 | 21 | 13 |
| Cd, mg kg ⁻¹ | 6.2 | 2.6 | 1.6 | 1.5 | 1.5 | 2.2 | 4.2 | 2.0 |
| Cr, mg kg ⁻¹ | 44 | 17 | 17 | 13 | 9 | 14 | 18 | 14 |
| Pb, mg kg ⁻¹ | 43 | 17 | 16 | 18 | 15 | 21 | 26 | 16 |
| As, mg kg ⁻¹ | 5.5 | 2.6 | 1.4 | 3.8 | 1.4 | 1.6 | 0.5 | 0.05 |
| Se, mg kg ⁻¹ | 20 | 16 | 7 | 6 | 17 | 1 | 3 | 0.07 |
| Hg, mg kg ⁻¹ | 3.4 | 0.5 | 2.6 | 2.0 | 1.1 | 0.4 | 0.9 | 0.1 |
| Ag, mg kg ⁻¹ | --- | --- | --- | --- | 15 | 7 | 0.5 | 1.2 |
| Ba, mg kg ⁻¹ | --- | --- | --- | --- | --- | --- | 533 | 7 |
| Be, mg kg ⁻¹ | --- | --- | --- | --- | --- | --- | 0.05 | <0.001 |
| Mn, mg kg ⁻¹ | --- | --- | --- | --- | --- | --- | 239 | 199 |

Table 4 (continued).

Littleton/Englewood biosolids composition used at the Byers research site, 1999-2013.

| Parameter | 2012 Corn | 2012 Wheat | 2013 Corn | Avg. | Range |
|--|-----------|------------|-----------|-------|----------|
| Solids, g kg ⁻¹ | 170 | 488 | 205 | 236 | 170-488 |
| pH | 8.7 | 8.2 | 8.4 | 8.2 | 7.6-8.8 |
| EC, dS m ⁻¹ | 3.5 | 2.9 | 5.0 | 7.7 | 2.9-11.2 |
| Org. N, g kg ⁻¹ | 12 | 27 | 10 | 45 | 10-54 |
| NH ₄ -N, g kg ⁻¹ | 2 | 2 | 2 | 12 | 2-16 |
| NO ₃ -N, g kg ⁻¹ | 0.003 | 0.002 | 0.002 | 0.023 | 0-0.068 |
| K, g kg ⁻¹ | 0.3 | 0.5 | 0.3 | 2.5 | 0.3-5.1 |
| P, g kg ⁻¹ | 5 | 11 | 5 | 26 | 5-34 |
| Al, g kg ⁻¹ | 1 | 2 | 1 | 17 | 1-28 |
| Fe, g kg ⁻¹ | 4 | 8 | 4 | 26 | 4-34 |
| Cu, mg kg ⁻¹ | 138 | 294 | 128 | 672 | 128-820 |
| Zn, mg kg ⁻¹ | 140 | 325 | 142 | 620 | 140-770 |
| Ni, mg kg ⁻¹ | 4 | 6 | 3 | 11 | 3-22 |
| Mo, mg kg ⁻¹ | 2 | 4.5 | <0.01 | 23 | <0.01-36 |
| Cd, mg kg ⁻¹ | 0.2 | 0.2 | 0.3 | 2.7 | 0.2-6.2 |
| Cr, mg kg ⁻¹ | 2 | 7 | 1 | 18 | 1-44 |
| Pb, mg kg ⁻¹ | 6 | 9 | 1 | 22 | 1-43 |
| As, mg kg ⁻¹ | 2.0 | 5.0 | 1.2 | 2.1 | 0.1-5.5 |
| Se, mg kg ⁻¹ | 12 | 2.7 | 3.3 | 8.8 | 0.1-20 |
| Hg, mg kg ⁻¹ | 0.01 | 0.02 | 0.004 | 1.4 | 0-3.4 |
| Ag, mg kg ⁻¹ | 3.5 | --- | 0.3 | 5.9 | 0.3-15 |
| Ba, mg kg ⁻¹ | 76 | 145 | 64 | 270 | 7-533 |
| Be, mg kg ⁻¹ | <0.01 | <0.01 | <0.01 | <0.05 | <0.05 |
| Mn, mg kg ⁻¹ | 73 | 114 | 70 | 219 | 70-239 |

Table 5. Corn grain characteristics for the corn rotation (CFW) at the Byers research site for 2013. **Highlighted parameters** are significantly different at the 0.10 probability level according to the t-test.

| Parameter, units | Biosolids | Nitrogen | Probability level |
|---------------------|-----------|----------|-------------------|
| Yield, bushels/acre | 39 | 45 | 0.415 |
| Protein, % | 10.6 | 10.0 | 0.889 |
| P, g/kg | 3.3 | 3.2 | 0.997 |
| Zn, mg/kg | 22 | 20 | 0.652 |
| Cu, mg/kg | 2.1 | 1.9 | 0.964 |

Table 6. Soil characteristics for the corn rotation (CFW) at the Byers research site for 2013. **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 | 53 | 30 | 0.129 |
| | 2-4 | 20 | 12 | 0.075 |
| | 4-8 | 3.0 | 3.7 | 0.793 |
| | 8-12 | 1.6 | 2.4 | 0.226 |
| ABDTPA Zn, mg kg ⁻¹ | 0-2 | 4.5 | 2.6 | 0.540 |
| | 2-4 | 0.5 | 0.6 | 0.646 |
| | 4-8 | 0.0 | 0.0 | ----- |
| | 8-12 | 0.0 | 0.0 | ----- |
| ABDTPA Cu, mg kg ⁻¹ | 0-2 | 9.3 | 5.4 | 0.601 |
| | 2-4 | 3.2 | 3.4 | 0.277 |
| | 4-8 | 3.9 | 3.5 | 0.277 |
| | 8-12 | 3.4 | 3.9 | 0.738 |
| pH | 0-2 | 6.8 | 7.0 | 0.537 |
| | 2-4 | 6.8 | 7.3 | 0.318 |
| | 4-8 | 7.6 | 7.6 | 0.792 |
| | 8-12 | 8.1 | 8.0 | 0.965 |
| ECe, dS m ⁻¹ | 0-2 | 0.73 | 0.75 | 0.289 |
| | 2-4 | 0.42 | 0.54 | 0.992 |
| | 4-8 | 0.52 | 0.42 | 0.994 |
| | 8-12 | 0.31 | 0.33 | 0.560 |
| NO ₃ -N, mg kg ⁻¹ | 0-2 | 4.5 | 3.4 | 0.809 |
| | 2-4 | 2.7 | 2.6 | 0.143 |
| | 4-8 | 2.4 | 2.3 | 0.116 |
| | 8-12 | 1.6 | 1.6 | 0.481 |
| | 12-24 | 0.9 | 1.1 | 0.406 |
| | 24-36 | 1.1 | 0.6 | 0.534 |
| | 36-48 | 4.9 | 1.0 | 0.015 |
| | 48-60 | 5.3 | 1.6 | 0.030 |
| 60-72 | 0.8 | 1.0 | 0.160 | |

Figure 1. Wheat grain yields for 2013 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).

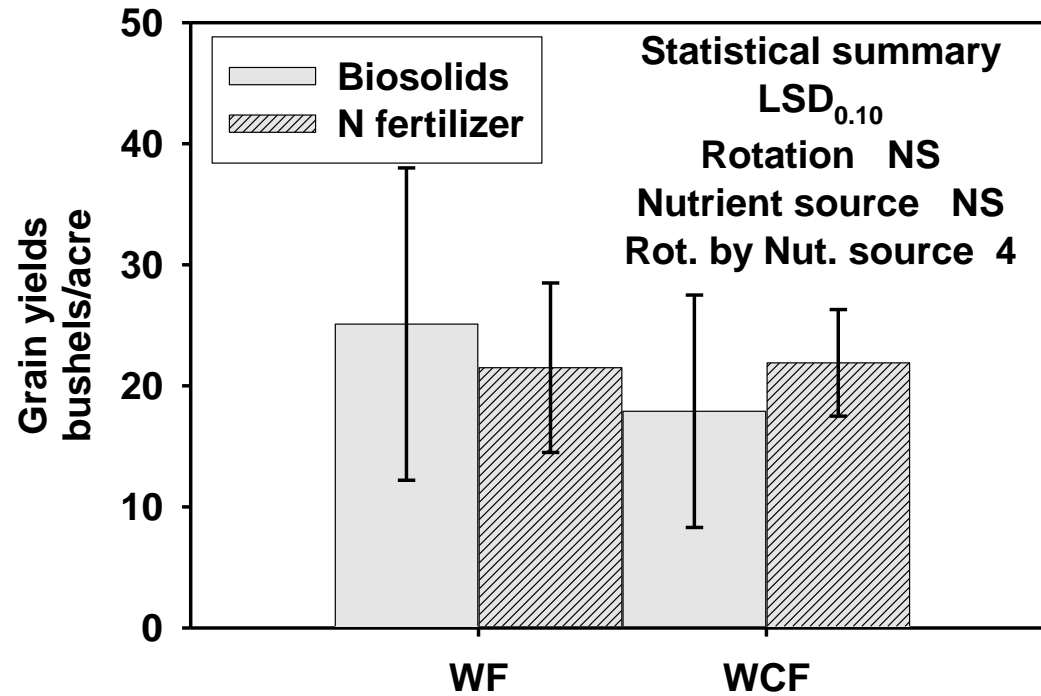


Figure 2. Wheat grain protein contents for 2013 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).

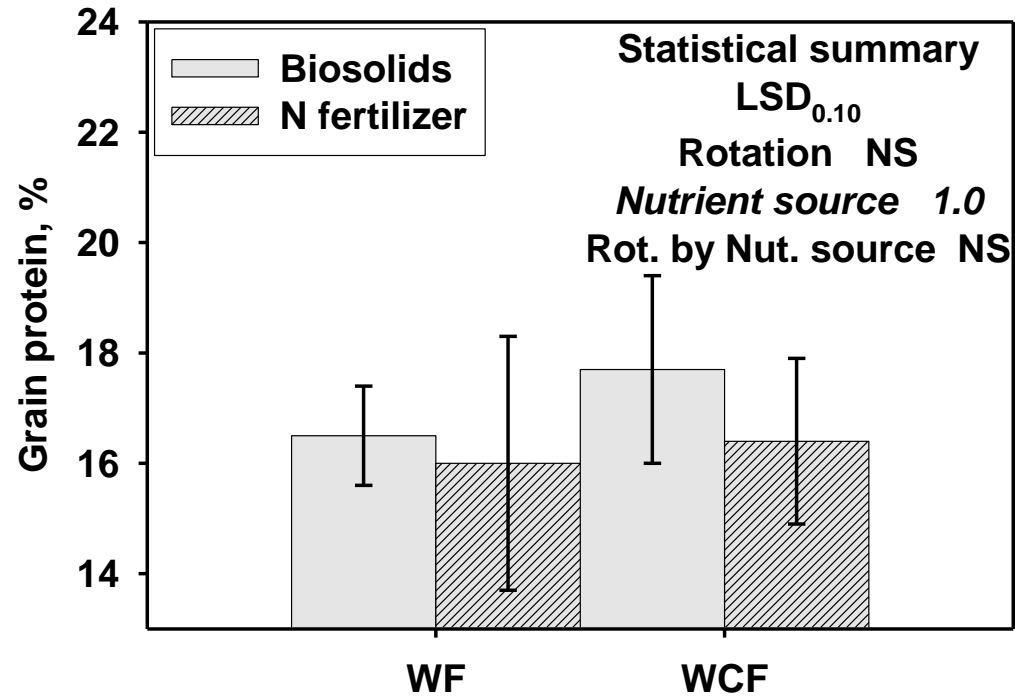


Figure 3. Wheat grain P concentrations for 2013 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).

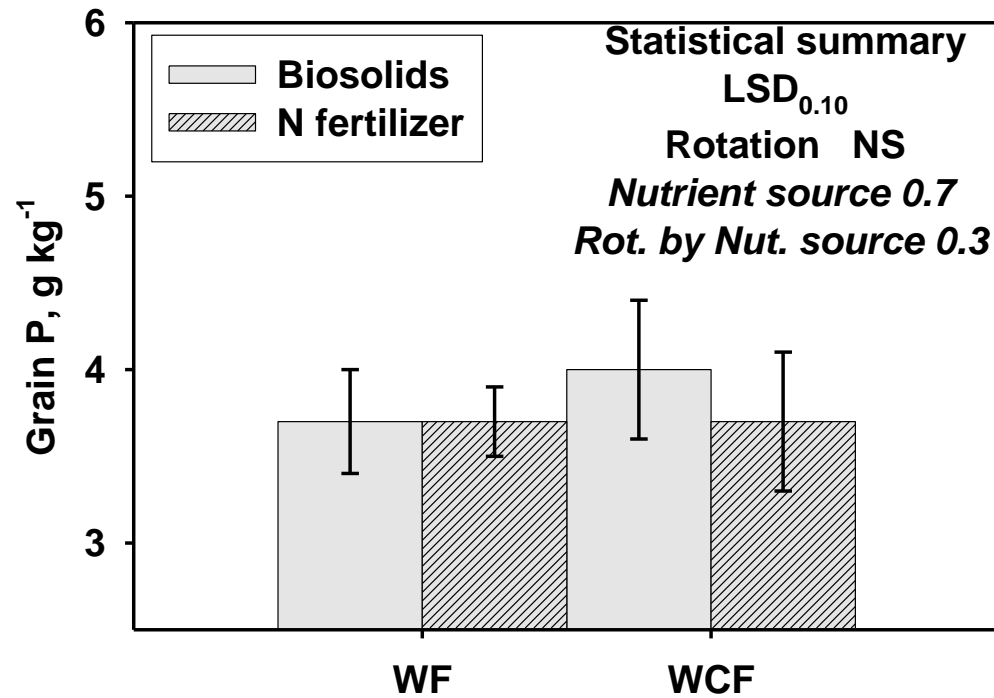


Figure 4. Wheat grain Zn concentrations for 2013 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences. (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).

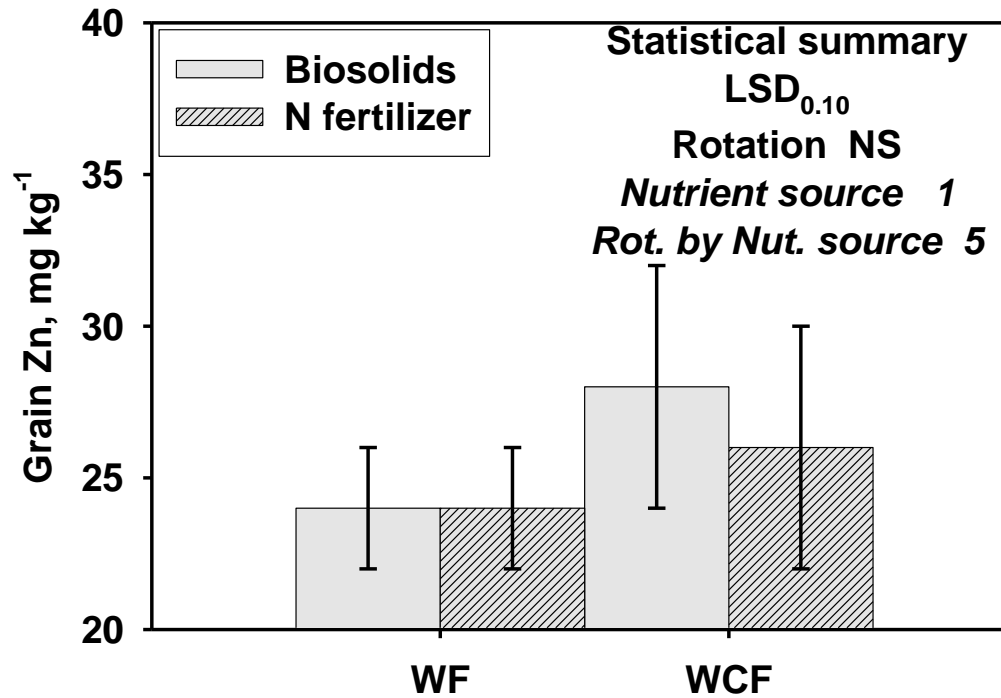


Figure 5. Wheat grain Cu concentrations for 2013 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 10% probability level and NS indicates non-significant differences (WF = wheat-fallow and WCF = wheat-corn-fallow rotations).

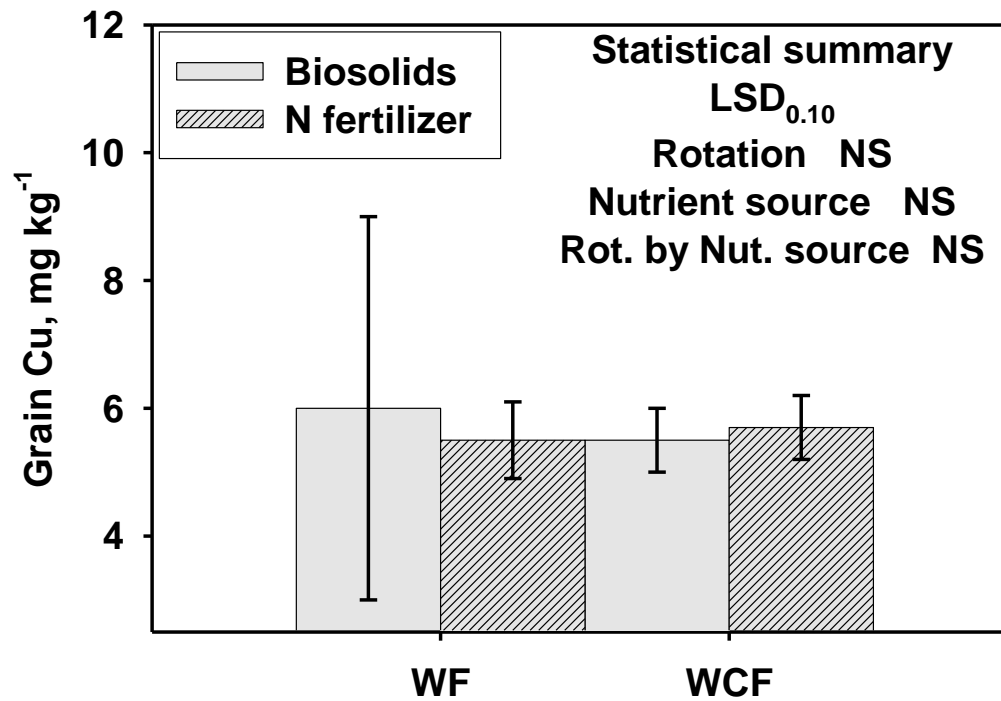
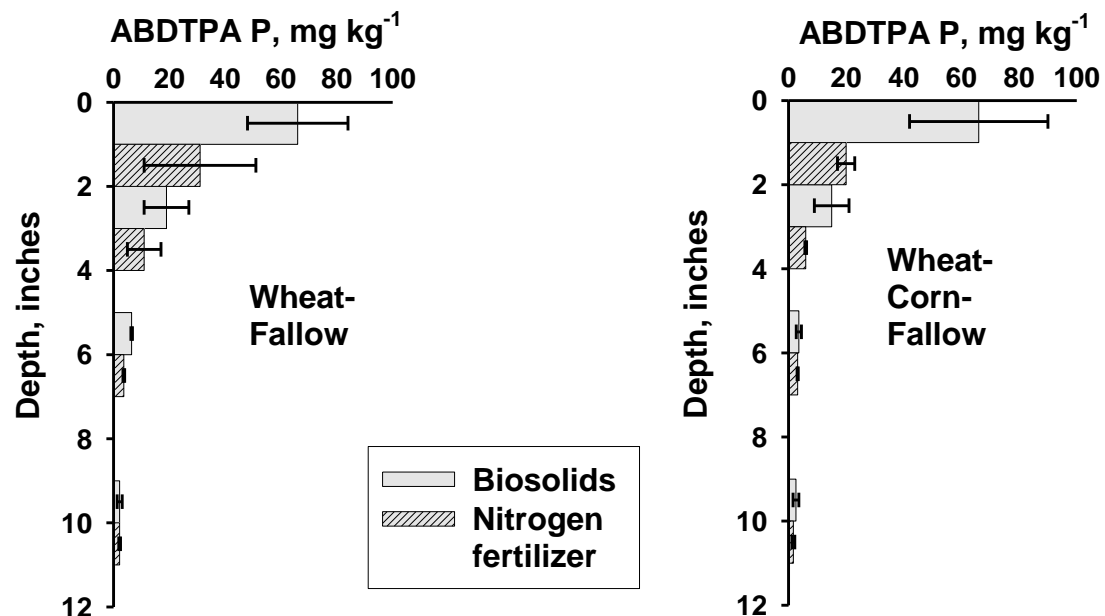


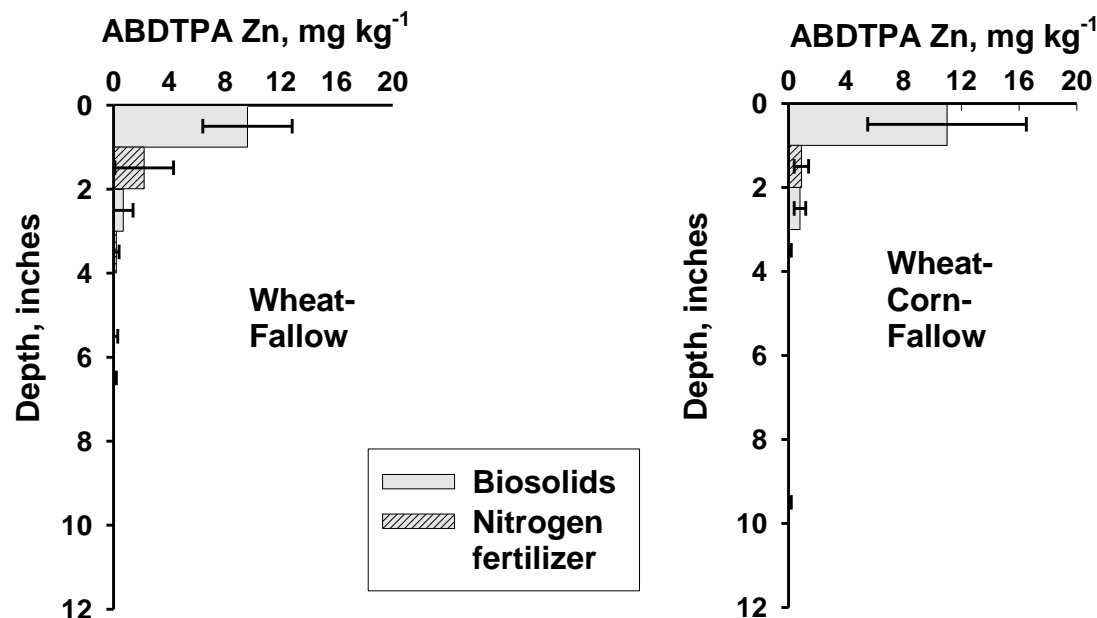
Figure 6. Soil ABDTPA-extractable P concentration following 2013 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference 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 NS | Rotations NS | Rotations NS |
| Treatment 13 | Treatment 4 | Treatment NS | Treatment NS |
| Rot. X Treat. NS | Rot. X Treat. NS | Rot. X Treat. NS | Rot. X Treat. NS |

Figure 7. Soil ABDTPA-extractable Zn concentration following 2013 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:

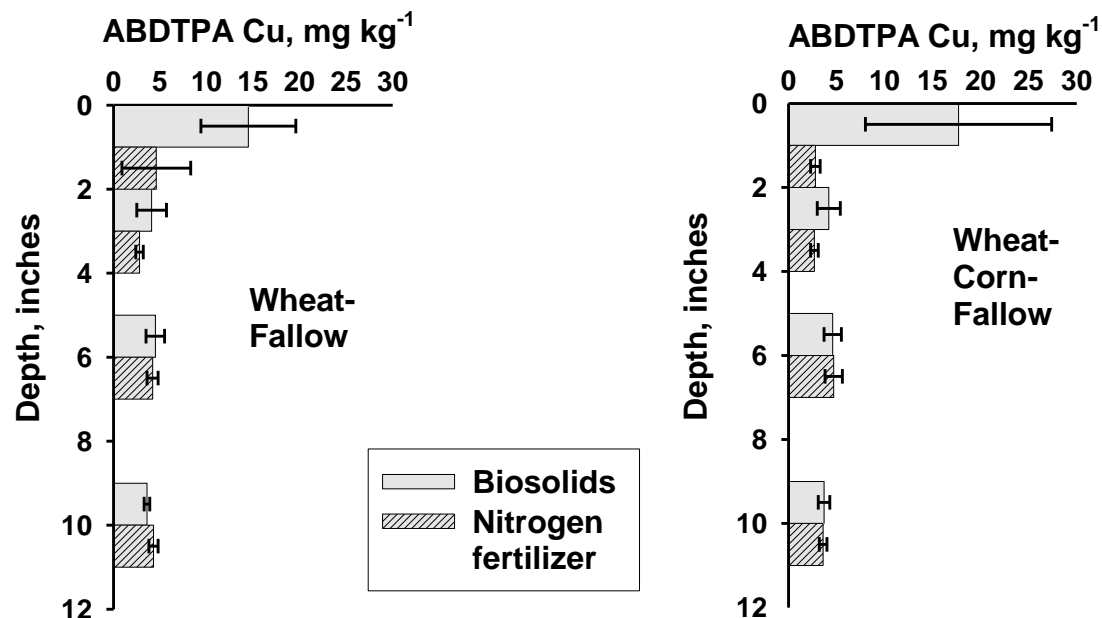
0-2 inches
 $LSD_{0.10}$
 Rotations NS
 Treatment 1.5
 Rot. X Treat. NS

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 8. Soil ABDTPA-extractable Cu concentration following 2013 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:

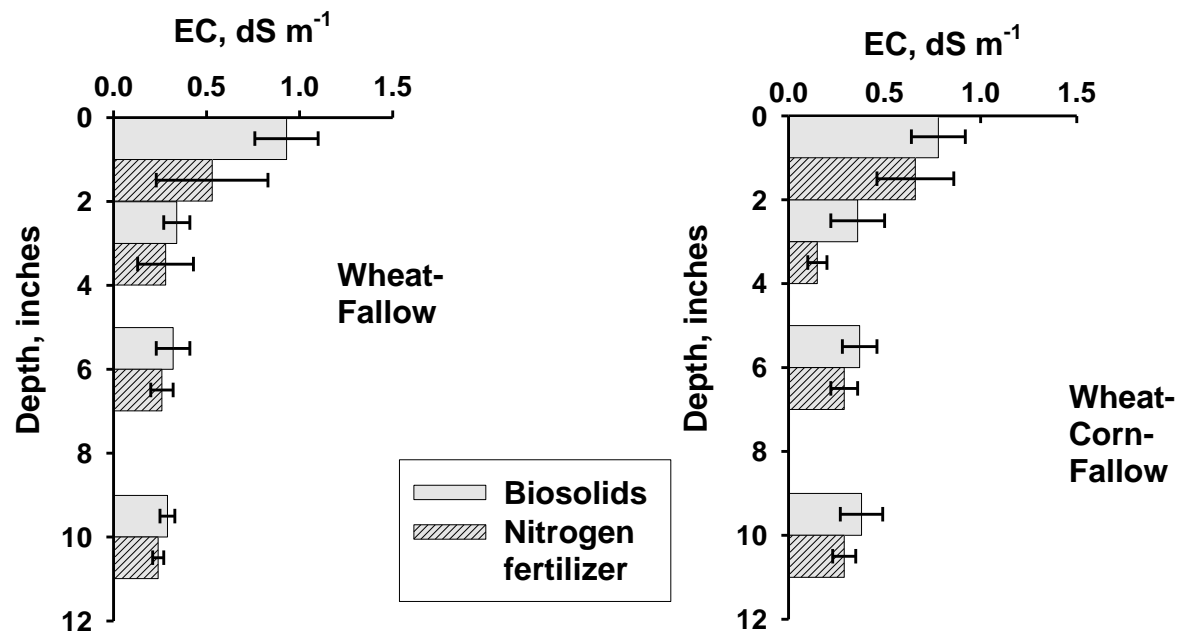
0-2 inches
 $LSD_{0.10}$
 Rotations NS
 Treatment 3.0
 Rot. X Treat. NS

2-4 inches
 $LSD_{0.10}$
 Rotations NS
 Treatment 1.1
 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

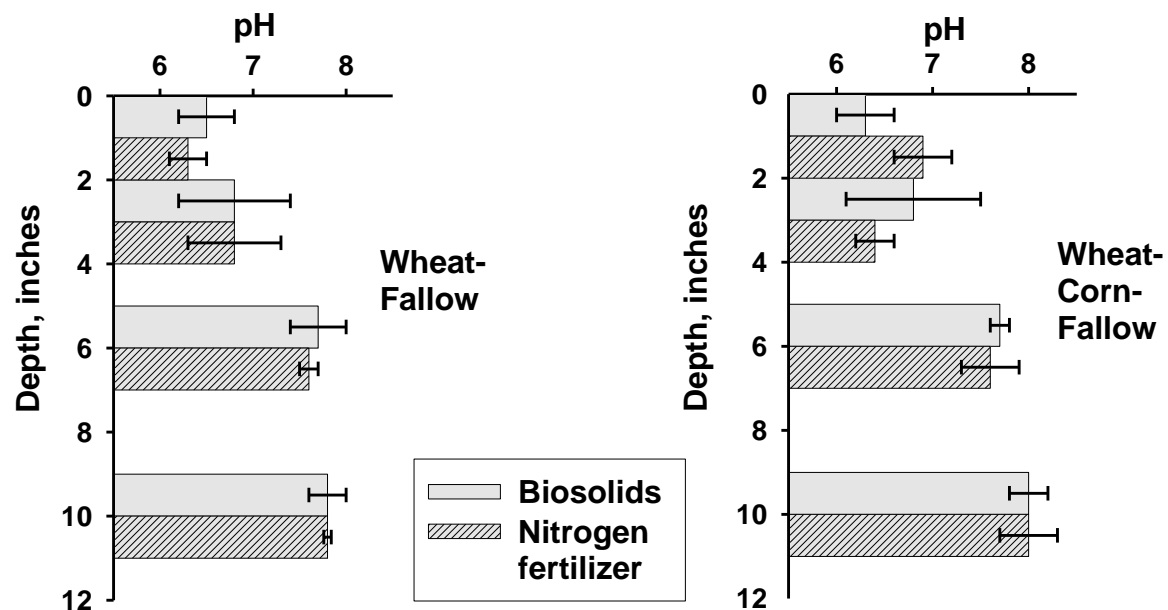
Figure 9. Soil saturated-paste electrical conductivity (EC) following 2013 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant 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 NS | Rotations NS | Rotations NS |
| Treatment NS | Treatment NS | Treatment 0.02 | Treatment 0.05 |
| Rot. X Treat. NS | Rot. X Treat. NS | Rot. X Treat. NS | Rot. X Treat. NS |

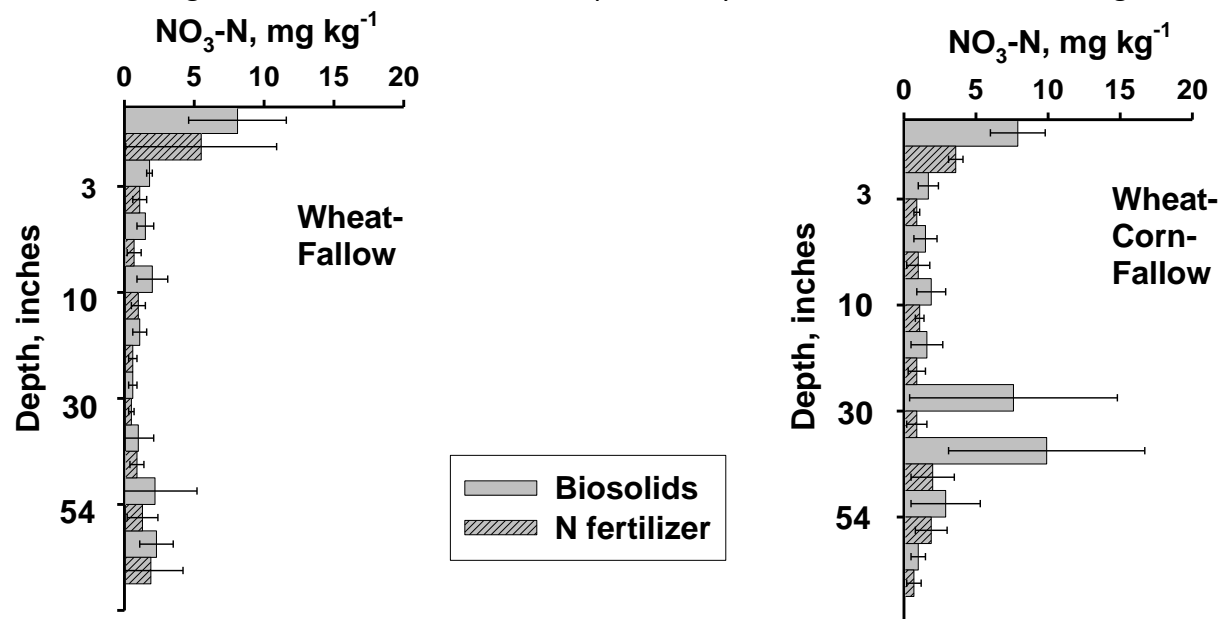
Figure 10. Soil saturated-paste pH following 2013 dryland-wheat-rotation harvests comparing Littleton/Englewood biosolids to commercial N fertilizer. Error bars represent the standard error of the mean. In the statistical summary, $LSD_{0.10}$ represents the least significant difference at the 0.10 probability 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 NS | Rotations NS | Rotations 0.1 |
| Treatment NS | Treatment NS | Treatment NS | Treatment NS |
| Rot. X Treat. 0.6 | Rot. X Treat. NS | Rot. X Treat. NS | Rot. X Treat. NS |

Figure 11. Soil NO₃-N concentrations following 2013 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 0.5 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 | <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 2.8 Treatment 3.5 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 | |