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Precision Injection of Dairy Sludge on Crop Yield and N and P Uptake in Juvenile and Mature No-Till Silage Corn

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Abstract: Starter mineral fertilizer is used by famers to provide phosphorus (P) and nitrogen (N) to emerging corn (*Zea mays*) plants. Recent studies have shown that dairy slurry can replace mineral fertilizer provided it is precisely positioned close to the corn rows. This 5-year study examined the multi-year effect of precision injected sludge, the thick fraction separated from dairy slurry, on growth and nutrient uptake at the 6-leaf stage and final harvest of no-till corn. The sludge was first injected 15 cm deep and the corn planted < 10 cm from the sludge furrow at least 3 days later. Sludge provided sufficient P for both early growth and full season growth. At final harvest with equivalent total N and P rates (32P 250N treatments), fertilizer and sludge had similar maximum yields (17.9 and 17.4 t ha^{-1}, respectively) and P uptake (26 and 25 kg ha^{-1}, respectively) but fertilizer had higher N uptake than sludge (200 and 162 kg ha^{-1}). N uptake and recovery N use efficiency was greater for sludge than fertilizer based on equivalent min.-N which suggests crop benefits in the sludge other than min-N and P. The study shows that precisely injected dairy sludge can obviate the need for starter mineral fertilizer, and this may help to alleviate P surpluses on dairy farms. This practice also provides a use on dairy farms for the separated solids fraction remaining after the thin fraction is decanted and applied as the primary N source to grass.

Keywords: phosphorus; nitrogen; corn; *Zea mays*; manure; dairy; sludge; precision; injected; no-till

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1. Introduction

Dairy farms in temperate regions including Canada often handle manure as a dilute liquid (hereafter called slurry). The slurry is collected from housing or hard pads and stored in large covered or uncovered vessels such as tanks or lagoons. The slurry is applied to nearby fields to provide nutrients, especially N and P, to crops and carbon (C) to improve soil quality. Fertilizer replacement value of slurry N is limited by its organic (mainly fecal) fraction which is not completely available to crops and by volatilization of readily available ammonia-N (NH_3-N) in the liquid (mainly urine) fraction soon after application [1]. The inorganic N in stored slurry is mainly ammonia and ammonium (NH_4), referred to as Total Ammoniacal Nitrogen (TAN).

Several innovations and strategies developed to reduce losses of both N and P to the atmosphere and to water bodies improve crop uptake [2,3]. Among the most widely adopted low-cost methods, especially in jurisdictions with regulations that penalize N loss, are low-trajectory, band applicators such as trailing hoses and trailing shoes, or low-disturbance open slot injectors that penetrate the soil only a few cm and leave the manure band exposed. In some situations deep injectors that completely cover the manure channel can be used to more fully reduce NH_3 emissions but these methods are more costly and slow, and often are not well suited for use in standing crops or on stony, steep or hard soils [4]. Furthermore, injection may lead to greater nitrous oxide (N_2O) emissions or possibly increased leaching, which is mitigated by greater crop N uptake [5]. A rolling tine applicator that creates intermittent pockets rather than injection channels can reduce ammonia emissions and runoff by mechanically increasing soil infiltration and reducing surface flow [6]. N volatilization can also be mitigated by rapidly incorporating manure into the soil but this can only be done where tillage is employed.

An alternative approach to reduce emissions and runoff is to facilitate infiltration into the soil by reducing slurry viscosity by adding water or removing solids. The thin liquid fraction after solids removal has more rapid soil infiltration which reduces ammonia losses and improves N use efficiency compared to the raw slurry [1,7]. The remaining thicker fraction contains more solids and has a higher C:N and P:N ratio and DM content; when slurry is undisturbed in vessels, the solids gradually settle to the bottom.

Normal farm practice is to mix the slurry, but the supernatant can be decanted and used for low disturbance application on grassland to improve N use efficiency and reduce ammonia emissions and P loading [1]. Bittman et al. [4,8,9] first proposed that slurry sludge can be precision-placed by injection close to corn rows (<10 cm) in order to completely replace commercial fertilizer which is routinely applied with the corn planter near corn seed at up to 30–40 kg P ha^{-1} and 20 kg N ha^{-1} as mono- or diammonium phosphate. Farmers apply starter to ensure good early growth of corn in cold soils irrespective of soil P status or manure applications. Provision of P and N to corn by precision placement of slurry has now been validated in Netherlands, Denmark and Germany [10–13]. Where slurry incorporation is not possible (e.g., reduced-tillage corn planting), the injected sludge has high availability of P, N and other nutrients such as K and S. The potential effect of injection on N_2O emissions and N leaching is mitigated by increased crop N uptake. Damage to corn by injected slurry has been reported in Denmark [14], but injected sludge did not significantly modify corn yield, root growth or colonization by arbuscular mycorrhizae in British Columbia, Canada [4].

The objective of this multi-year field study was to assess the effect of precision-injected separated dairy sludge relative to starter commercial fertilizer, on yield and nutrient (N and P) uptake by silage corn under no-till management.

2. Materials and Methods

2.1. Site Description

The experiment was carried out in 2010 to 2014 at the Agassiz Research and Development Centre of Agriculture and Agri-Food Canada located near Agassiz in south coastal British Columbia (BC), Canada (49°24′ N, 121°76′ W). The long-term mean daily air temperatures in January and July are 2.5 and 18.2 °C, respectively, and the average annual precipitation is 1680 mm, most of it falling between November and March. Growing conditions over the five growing seasons, measured 100 m from the experimental site, is presented in Table 1 and Figure 1. Mean daily temperature for the growing period which was 128 to 148 days ranged from 16.3 °C in 2011 to 18.3 °C in 2014. Typically, moisture balance during growing periods was slightly positive in May, negative in July and August (50 to 150 mm) and positive or negative in June and September (Figure 2).

Table 1. Management and weather information for trials conducted in 2010–2014 at Agassiz, BC.

	2010	2011	2012	2013	2014
Manure application date	7 May	4 May	10 May	1 May	30 April
Seeding date	13 May	10 May	11 May	6 May	6 May
V6 sampling date	29 June	4 July	3 July	17 June	11 June
Harvest date	6 October	5 October	1 October	11 September	10 September
Growing days (plant to harvest)	146	148	143	128	129
Corn hybrid	Pioneer 38B11RR	Pioneer 38B11RR	Pioneer 38B13RR	Pioneer 39B94RR	Elite MuranoRR
Corn heat units (plant to harvest)	2766	2787	2831	2775	2797
Precipitation (plant to harvest) (mm)	459.9	470	367.6	290.3	287.4
Mean daily temperature (plant to harvest) (°C)	16.5	16.3	17.1	18.2	18.3

The soil in the study belongs to the Monroe series derived from medium textured, stone-free, Fraser River deposits classified as Eutric Eluviated Brunisols [15] with about 50 g kg^{-1} organic matter and a bulk density of 1.26 g cm^{-3}. Soil at 0–15 cm depth contained 277 g kg^{-1} sand, 584 g kg^{-1} silt and 139 g kg^{-1} clay. The experimental plots received the same experimental nutrient treatments since 2008 and no manure had been applied before 2008. The corn was planted with no tillage, with soil disturbance limited to single disk manure-applicator and the planter fitted with a fertilizer side-bander. There was little crop residue on the soil surface after harvest since the corn was harvested as silage at about 15 cm height.

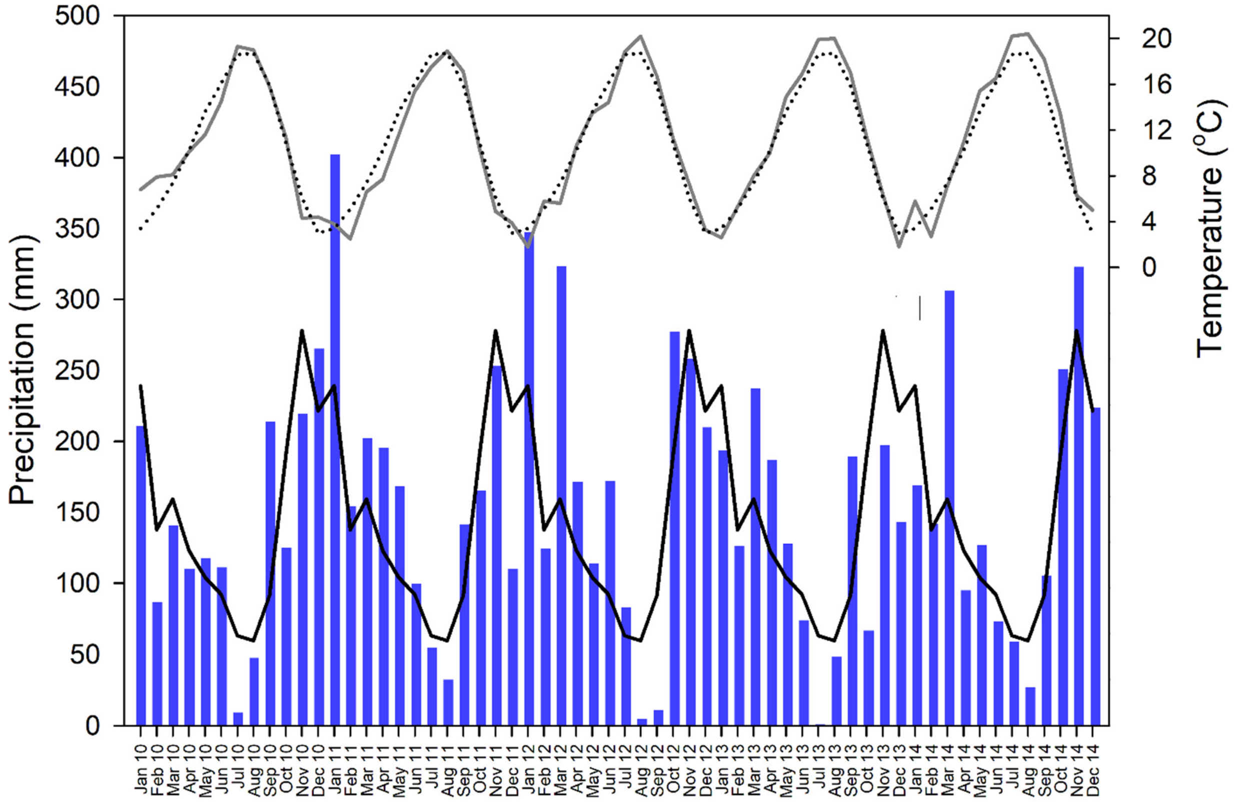

Figure 1. Average monthly air temperature (grey line) and total monthly precipitation (blue bars) for Agassiz B.C. 2010–2014. Climate normals overlaid for 1981–2010 average monthly air temperature (dotted grey line) and total monthly precipitation (solid black line).

2.2. Experimental Design and Plant Cultivation

The trials were conducted in a randomized complete plot design with four blocks and 11 treatments in four-row plots, each measuring 3 × 10 m. The treatments were selected to obtain detailed information about the N and P supplied by the sludge relative to commercial fertilizer. Besides a zero control, there were synthetic fertilizer (hereafter called fertilizer) treatments representing a range of N rates, from 27 to 250 kg N ha^{-1} all at a typical P rate used on farms of 32 kg P ha^{-1}. There was also a fertilizer treatment with 250 kg N ha^{-1} and no P. The synthetic P, along with 27 kg N ha^{-1}, is provided by a typical corn starter fertilizer containing diammonium phosphate (11:52 N:P_2O_5). The starter fertilizer was side-banded with the corn planter (see below) 5 cm beside and 5 cm below the seed furrow. Additional granular N fertilizer was applied by surface broadcasting at planting as is often done on farms. Ammonium nitrate was used because it is has consistently low ammonia volatilization compared to urea, especially after light rains. Fertilizer plots were also treated annually with K, Mg and S (210, 25 and 50 kg ha^{-1}, respectively) according to local recommendations, and lime was added to keep soil pH above 5.8.

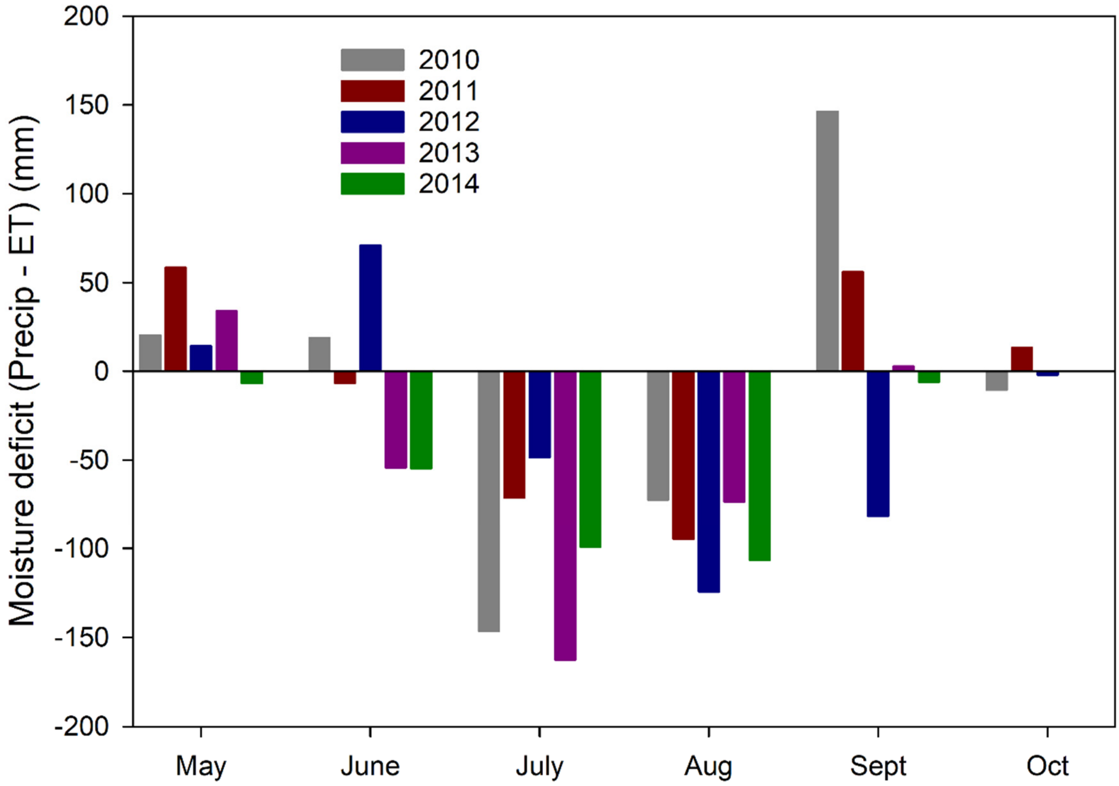

Figure 2. Moisture balance over the five growing seasons (May–October) for Agassiz B.C. (2010–2014).

Dairy slurry was obtained in late fall from high-producing commercial dairy farms feeding mainly corn and grass silage and grain supplements and using sawdust bedding. The slurry was stored over winter (about 3–5 months) in 3-m-deep in-ground concrete tanks furnished with a roof to keep out rain. The slurry was allowed to settle so that a layer of sludge collected in the bottom third below a thinner supernatant. The supernatant was removed by pumping and the sludge was mixed and pumped out. Properties of the settled dairy sludge, hereafter referred to as sludge, are reported in Table 2.

Table 2. Annual properties of dairy cattle sludge based on wet weight in 2010 to 2014 and 5-year mean of whole slurry.

Values	2010	2011	2012	2013	2014
DM (%)	5.80	5.79	7.20	9.50	6.85
P (g kg^{-1})	0.4	0.5	0.6	0.4	0.35
Total N (g kg^{-1})	2.5	2.5	2.2	3.0	2.4
NH_4-N (g kg^{-1})	1.63	1.45	1.20	1.45	0.95
Total N:P	6.25	5.00	3.67	7.50	6.95
Total N:NH_4-N	1.53	1.72	1.83	2.07	2.53
Total C (g kg^{-1}DW)	436	394	406	442	418
pH	7.1	7.3	7.2	7.0	7.2
EC (ms cm^{-1})	12.80	9.66	8.57	15.40	-

Prior to planting the corn, the sludge was injected about 15 cm deep into the untilled soil using single disc injectors producing relatively low soil disturbance [16]. The injectors were set 75 cm apart to match the corn row spacing. To reduce ammonia loss, the 5 cm wide $\times$ 15 cm deep injection furrows were immediately manually covered using the soil loosened by the injector. Since the primary purpose of the sludge was to replace synthetic commercial P fertilizer, the sludge application rate was set to provide the same rate of P used in synthetic starter fertilizers, i.e., 32 kg P ha^{-1}. Treatments were included where the sludge was applied at 50% P (16 kg P ha^{-1}) and 100% P (32 kg P ha^{-1}); a 200% P (64 kg P ha^{-1} rate) included the 100%P sludge plus 32 and 27 kg ha^{-1} of P and N, respectively, as DAP applied with the planter. Total N application of 250 kg N ha^{-1} was set by broadcasting ammonium nitrate at 209 kg N ha^{-1} to the 50% P sludge rate and 167 kg N ha^{-1} to the 100% P sludge rates. The actual rates of applied total-P (tot-P), total-N (tot-N), mineral-N (min-N) and fertilizer-N applied to each treatment are shown in Table 3 and are depicted on the graphs. Additionally, treatments were included where the sludge at full P rate was applied in alternating years starting in either 2010 or 2011. Mineral fertilizer treatments comparable to the sludge rates, as explained more fully above, included N rates from 83 to 250 kg N ha^{-1} at 32 kg P ha^{-1}, 250 kg N ha^{-1} treatment with no P and a zero control.

Table 3. Average application rates of total N, total mineral N, organic N, manure NH_4-N, fertilizer N (broadcast and banded with planter) and total-P for treatments containing only synthetic fertilizer and treatments containing sludge with or without synthetic fertilizer (2010–2014).

Treatment	Total P	Total N	Manure Organic-N	Manure NH_4-N	Fertilizer-N Broadcast	Fertilizer-N Banded	Total Mineral-N *
				------------------------------------- kg ha^{-1} -------------------------------------			
Control	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Synthetic Fertilizer only							
Fert 0P-250N	0.0	249.6	0.0	0.0	223.4	26.2	249.6
Fert 32P-83N	32.1	83.3	0.0	0.0	56.7	26.6	83.3
Fert 32P-167N	32.1	166.6	0.0	0.0	140.1	26.6	166.6
Fert 32P-250N	32.1	250.0	0.0	0.0	223.4	26.6	250.0
Sludge-based							
Sludge 16P-80N	14.7	95.4	45.0	50.5	0.0	0.0	50.5
Sludge 16P-250N	14.7	253.6	45.0	50.5	158.2	0.0	208.6
Sludge 32P-167N	29.3	190.9	90.0	100.9	0.0	0.0	100.9
Sludge 32P-250N	29.3	257.2	90.0	100.9	66.3	0.0	167.3
Sludge 64P-250N **	61.4	257.2	90.0	100.9	39.7	26.6	167.2
Sludge Alt start Yr1 +	17.2	110.3	52.4	57.9	0.0	0.0	57.9
Sludge Alt start Yr2 ++	12.1	80.6	37.6	43.1	0.0	0.0	43.1

* Mineral-N from synthetic fertilizer and/or sludge. ** P 32.1 kg ha^{-1} from fertilizer and 29.3 kg ha^{-1} from sludge. + 28.7 P and 183.7 N applied every other year starting in 2010 (start Yr1). ++ 30.3 P and 201.6 N applied every other year starting in 2011 (start Yr2).

The corn was sown on both fertilizer and sludge plots about 1–6 days after sludge application to allow it time to soak into the soil. Corn was sown in 75 cm rows at 75,000 seeds ha^{-1} using a four-row John Deer MaxEmerge Planter (Deere & Co., Moline, IL, USA) fitted with no-till attachments. On the sludge plots, the seeding rows were positioned at a distance of <10 cm (average of 6 cm) from the middle of the injection furrow which had been marked with stakes; measurements taken immediately after planting confirmed the distance. Table 1 shows corn hybrids and dates for manure application, planting and harvesting of corn over the 5 years of the study. The corn hybrids were glyphosate resistant (RR) and the plots were treated with a non-selective herbicide [glyphosate (*N*-(phosphonomethyl) glycine, 1000 g ha^{-1}; Syngenta Canada, Guelph, ON, Canada], plus AGRAL 90 (nonylphenoxy polyethoxy ethanol, 0.03% [*v*/*v*]) (Syngenta Canada) after emergence at V5-6 so no additional herbicide was used; escaped weeds were hand weeded. Wireworms were controlled by banding Force 3.0G (active ingredient: tefluthrin applied at 150 g ha^{-1}; Syngenta Canada, Guelph, ON, Canada) in the corn rows.

2.3. Sampling and Analyses

Corn shoots were sampled at the V6 stage by harvesting six plants from the middle two rows. To minimize the effect of plant removal on remaining plants, the two middle rows were divided into two zones: a zone for V6 sampling and a larger zone for the final harvest. The corn was harvested at silage maturity by manually cutting (15 cm height) a

3-m section in the two middle rows of each four-row plot. The harvested whole plants were weighed in the field, chopped with a portable shredder/chipper and a 1000 g sample was dried at 60 °C for dry matter (DM) percent then ground through a 2-mm screen (Model 4 Wiley Mill, Thomas Scientific, Swedesboro, NJ, USA) for nutrient determinations. Additionally, ears were removed from ten random plants and these were dried (60 °C), shelled and weighed to determine grain percentage.

Plant N concentration was determined using the dry ash method (LECO™ F-428 Nitrogen analyzer, Saint Joseph, MI, USA). All plant weights and concentrations are reported on oven dry matter basis. The ground samples were analyzed for P colourimetrically after a sulphuric acid-selenium-hydrogen peroxide digestion using a spectrophotometer (Model SP6-350, Pye Unicam) at a wavelength of 660 nm [17] as described in [18]. Aboveground corn N and P uptake were calculated as N or P concentration × above-ground whole plant biomass. Apparent N recovery was calculated as (N recovery of treatment-N recovery of control)/N applied as either tot-N or min-N. Apparent N use efficiency was calculated as (yield of treatment- yield of control)/N applied, as either tot-N or min-N.

Statistical Analysis. Data for each trial were subjected to analysis of variance using PROC GLIMMIX with replicates designated as a random factor and years as a fixed factor (SAS 9.4 SAS Institute, Cary, NC; USA 2012). Statistical significance was determined at the 5% probability level using the protected LSD. Standard error bars are shown on the graphs.

3. Results and Discussion

The sludge analysis for each trial year is shown in Table 2. The P concentration ranged from 0.35 in 2014 to 0.60 g kg^{-1} in 2015 averaging 0.45 g kg^{-1} and the N:P ratio varied from 3.67 in 2012 to 7.50 in 2013 averaging 5.87. Concentration of dry matter (DM) varied from 5.79% in 2011 to 9.5% in 2013 averaging 7.03%. Based on the N:P ratio, more settling separation occurred in 2013 than in 2012. Very efficient separation by settling is observed on farms with two stage lagoon systems connected by a weeping wall [1,19]. Since settling is the least expensive method for solid–liquid separation, protocols to improve consistency would be helpful. In all cases the sludge used in this trial and other studies [1] was fluid enough to pump and would be somewhat cheaper to transport and inject (smaller trenches) than raw slurry due to lower water content.

The growing conditions for the growing periods over the 5-year trial varied between 2766 and 2831 corn heat units and 287 to 470 mm precipitation (Table 1). These ranges represent typical conditions for this location. Annual production is discussed below.

Whole crop biomass averaged over the 5 years responded to broadcast ammonium nitrate fertilizer (at 32 kg ha^{-1} P) reaching maximum yields of 17.9 t DM ha^{-1} at the 250 kg N ha^{-1} rate compared to 5.6 t ha^{-1} for the unfertilized control (Table 4, Figure 3). The maximum yield is consistent with long-term trials conducted at the research center and on local high intensity dairy farms (https://farmwest.com/varieties/pacific-field-corn-association-testing/corn-hybrid-trials/2017-corn-silage-hybrids/late-agassiz-long-term-average/, accessed on 18 February 2021) with farm N inputs from manure and fertilizer likely between the test rates of 167 and 250 kg N ha^{-1} application rates. These results show that the site is moderately responsive to N fertilizer. The yield of the high fertilizer N treatment with no P (15.1 t ha^{-1}) was significantly lower than the respective treatment (17.9 t ha^{-1}) receiving 32 kg ha^{-1} P indicating that the site is also P responsive.

Precision application of sludge into injection furrows positioned 0–10 cm from the corn rows increased whole crop yield significantly compared to control, and the response was related to rate of application. Without commercial fertilizer, crop yields increased significantly from 5.6 for the control, to 10.4 and 14.3 t ha^{-1} with the half and full P sludge rates (14.7 and 29.3 kg P ha^{-1}), respectively (Table 4, Figure 3). The yield was 1.8 t ha^{-1} lower than equivalent rates of fertilizer N and P, but with the sludge having just slightly more than half the N in the form of TAN and the remainder in the less available organic form (Table 3). Based on equivalent rates of min-N (167 kg N ha^{-1}), yields and N uptake with sludge and mineral fertilizer were similar (Table 4, Figure 4). To achieve an acceptable yield of 16.1 t ha^{-1}, the fertilizer treatment received 167 kg N ha^{-1}, whereas sludge, to achieve the same yield, would need an estimated 230 kg tot.-N ha^{-1} or 63 kg ha^{-1} more tot-N than with fertilizer (Figure 3). For equivalent N uptake, the difference is around 73 kg N ha^{-1} (Figure 5). Since the manure was injected and covered, little of this surplus N is likely to have been lost as ammonia, it would probably be lost by leaching and denitrification, or sequestered (along with C) in the soil. The latter may be a positive outcome that warrants further testing.

Table 4. Average whole crop yield, grain yield, percent grain, percent dry matter, N uptake and P uptake for 5 years (2010–2014).

Treatment	Whole Crop Yield		Grain		Dry Matter		N Uptake		P Uptake	
	t ha^{-1}		%		%		kg ha^{-1}		kg ha^{-1}	
Control	5.6	g ‡	34.7	d	28.1	d	41	f	10	f
Synthetic Fertilizer only										
Fert 0P-250N	15.1	cde	40.6	c	32.5	cd	166	bc	22	bc
Fert 32P-83N	13.3	e	41.3	bc	33.5	cd	96	de	17	de
Fert 32P-167N	16.1	bcd	43.0	abc	34.1	bc	151	c	22	bc
Fert 32P-250N	17.9	ab	42.0	bc	31.5	d	200	a	26	a
Sludge-based										
Sludge 16P-80N	10.4	f	43.5	abc	32.7	cd	75	e	14	e
Sludge 16P-250N	17.0	abc	44.0	ab	34.4	abc	180	ab	24	abc
Sludge 32P-167N	14.3	de	43.7	ab	34.5	abc	110	d	20	cd
Sludge 32P-250N	17.4	ab	43.8	ab	36.6	a	162	bc	25	ab
Sludge 64P-250N *	18.3	a	45.2	a	36.1	ab	166	abc	27	a

‡ Values within a column not followed by the same letter are statistically significant at $p < 0.05$. * P 32.1 kg ha^{-1} from fertilizer and 29.3 kg ha^{-1} from sludge.

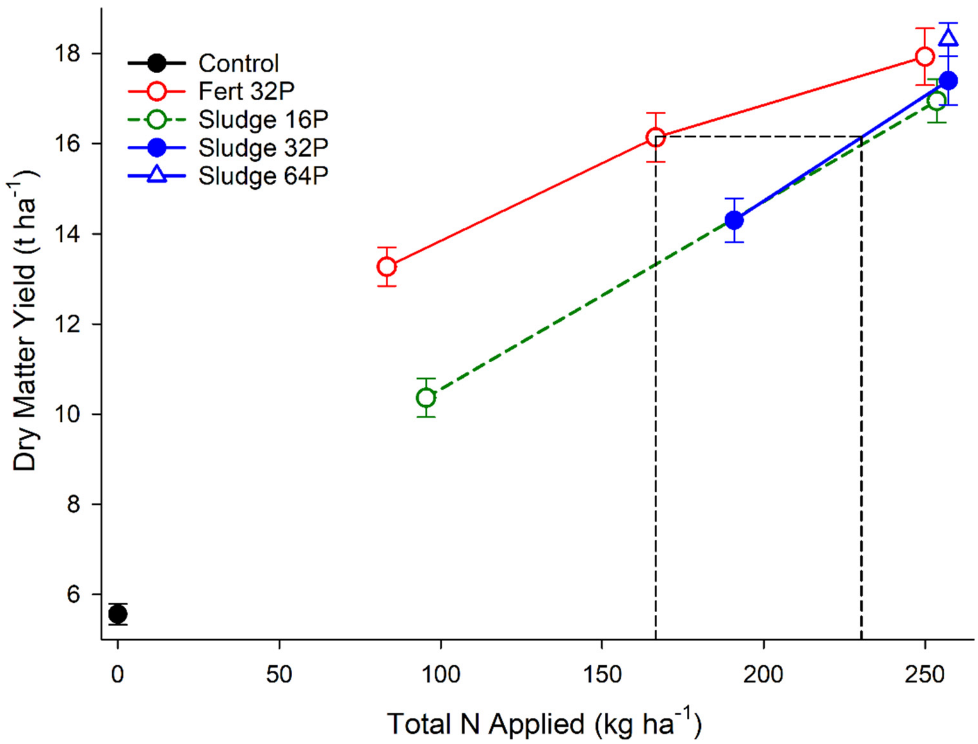

Figure 3. Mean annual corn dry matter yield over 5 years (2010–2014) in relation to annual applications of total N. Please note that vertical lines show estimated N rates at equivalent corn yields.

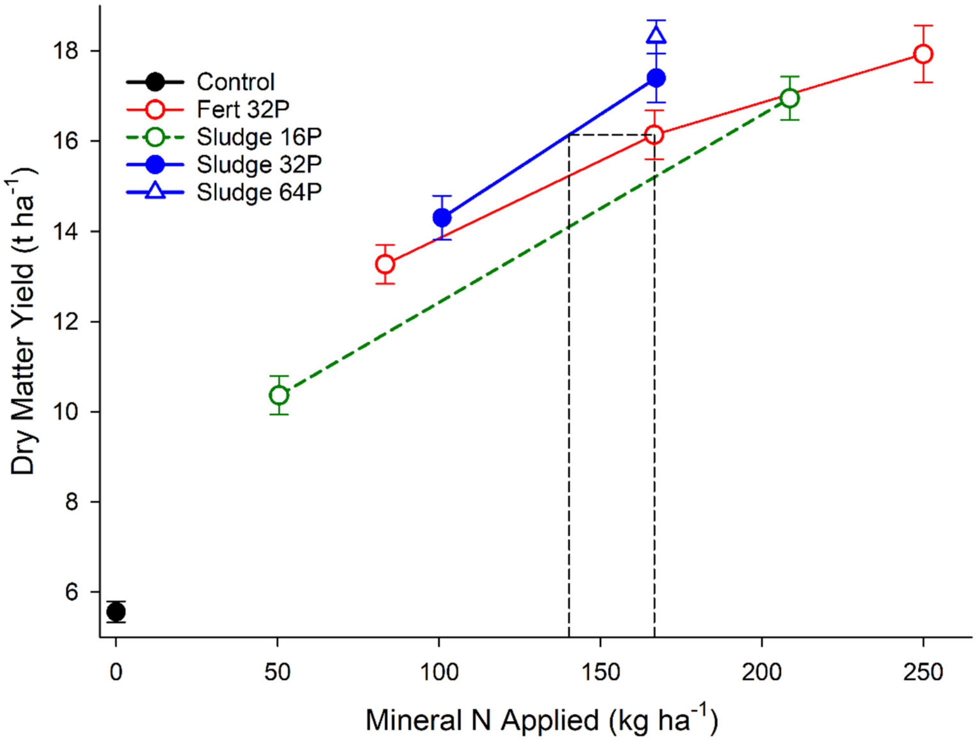

Figure 4. Mean annual corn dry matter yield over 5 years (2010–2014) in relation to annual applications of mineral N. Please note that vertical lines show estimated N rates at equivalent corn yields.

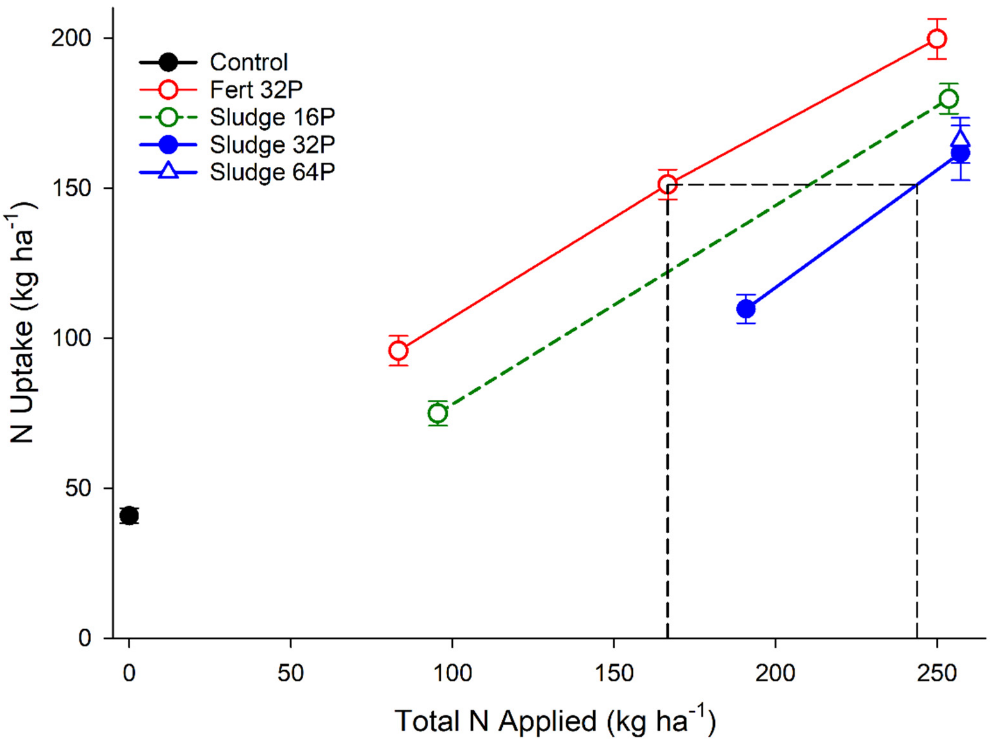

Figure 5. Mean annual N uptake over 5 years (2010–2014) in relation to annual applications of total N. Please note that vertical lines show estimated N rates at equivalent N uptake.

The above comparisons were made with similar target rates of precision placed P, sludge P at 29.3 kg ha^{-1} and fertilizer P at 32.1 kg ha^{-1} (Table 3), repeated annually, and so include both N and P from the current and previous applications, which is further discussed below. Since the injected manure is meant to replace starter mineral fertilizer applied typically at around 32 kg P ha^{-1}, we refer to this as the full sludge rate. At half the P sludge rate and with no additional N, yield was only 10.4 t ha^{-1} (Table 4). This treatment is of potential interest to farmers who have an abundance of land and would like to minimize losses and maximize apparent N use efficiency in corn production. However, to achieve high P recovery to avoid loading on already rich soils, the 50% P with 250N achieved almost complete apparent P recovery (99%) compared to about 50% for mineral and sludge P (Table 5). Therefore, if the sludge is used primarily as a P source, its efficacy is enhanced by the added mineral N fertilizer, which promotes greater root growth and above-ground crop sink, and possibly by priming mineralization of organic matter [20].

Table 5. Average apparent recovery for total N, mineral-N, total P and apparent N use efficiency for Total N and mineral-N for 5 years (2010–2014).

Treatment	Apparent N Recovery (Total N)		Apparent N Recovery (Mineral N) *		Apparent P Recovery		Apparent N Use Efficiency (Total N)		Apparent N Use Efficiency (Mineral N)	
	%		%		%		kg DM kg^{-1} N			
Synthetic Fertilizer only										
Fert 0P-250N	50	c ‡	50	b	-		38	d	38	e
Fert 32P-83N	66	a	66	ab	22	d	93	a	93	ab
Fert 32P-167N	66	a	66	ab	37	c	63	b	63	cd
Fert 32P-250N	64	ab	64	ab	53	b	50	c	50	de
Sludge-based										
Sludge 16P-80N	36	e	68	ab	30	cd	50	c	94	a
Sludge 16P-250N	55	bc	67	ab	99	a	47	cd	55	d
Sludge 32P-167N	37	de	70	a	36	c	45	cd	89	ab
Sludge 32P-250N	47	cd	72	a	52	b	47	cd	72	c
Sludge 64P-250N **	49	c	75	a	28	cd	50	c	77	bc

* Mineral-N from synthetic fertilizer and/or sludge. ** P 32.1 kg ha^{-1} from fertilizer and 29.3 kg ha$^{-1.}$ ‡ Values within a column not followed by the same letter are statistically significant at $p < 0.05$

Nitrogen recovery was not significantly affected by sludge tot-N rate but declined with fertilizer N rate (not shown). Apparent N recovery was much lower for sludge that for fertilizer based on total applied N but similar based on applied mineral N (Table 5). Fertilizer P application increased N uptake by 34 kg ha^{-1} and apparent N uptake from 50 to 64 kg ha^{-1}, while the banded fertilizer P added to sludge did not affect apparent N recovery, although it greatly lowered apparent P recovery (Tables 4 and 5). For the sludge treatment with no supplemental mineral N, uptake was 110 kg N ha^{-1} at 191 kg ha^{-1} or an efficiency of 60% (or 52% assuming 20 kg of atmospheric N deposition, [21], which is a reasonable N recovery rate for sludge with almost 50% organic N. At a relatively similar N application rate for fertilizer (167 kg N ha^{-1}), N uptake was 151 kg N ha^{-1}, which is an uptake efficiency of 91% (81% with accounting for atmospheric deposition). When adjusted for control N uptake, the apparent N recovery was about 66% for mineral fertilizer and 37% from the sludge (Table 5). Apparent N use efficiency for the fertilizer treatments declined with N application rate from 93 to 50 kg DM kg^{-1} N. Most of the sludge treatments had apparent N use efficiency between 50 and 45 kg DM kg^{-1} tot-N. However, based on comparable rates of applied mineral N, sludge treatments had significantly greater apparent N use efficiency than fertilizer (63–50 and 89–72 DM kg^{-1} for fertilizer and sludge, respectively). This indicates that there are yield benefits derived from the non-mineral N constituents of the sludge such as mineralized organic N and other nutrients that might have been deficient in the fertilizer treatments. Sludge C injected into the untilled soil may have improved soil physical properties near the seed. The benefits of sludge warrant further investigation.

Differential responses to nutrient treatments were evident at the 6-leaf stage (V6) of corn. Side-banded P fertilizer significantly increased yield and nutrient uptake (0P vs. 32P at 250N, nominal) but there was no difference among the N rates with the side-banded P (Table 6). However, yield values at V6 were significantly higher for sludge (223 and 242 kg DM ha^{-1}) than for fertilizer (173 and 167 kg DM ha^{-1}) at the 32P-167N and 32P-250N (nominal) rates, respectively. Similarly, uptake values for N were significantly greater for the sludge than for fertilizer treatments (9.1–10.5 vs. 7.5 kg N ha^{-1}) as was uptake of P (0.85–0.90 vs. 0.65–0.66 kg P ha^{-1}), as previously reported by [4]. These results show that precision placed sludge is a more effective source of nutrients than mineral fertilizer N and P at the critical early stage when uptake of nutrients by corn roots, especially P, may be restricted by low soil temperatures, and P deficiencies are most likely to be observed [22]. The increased yield and nutrient uptake responses of sludge plots receiving additional side-banded mineral P are difficult to understand given the very small amount of P uptake (approximately 1 kg ha^{-1}) at this stage, but help to explain the tendency of farmers to sideband mineral P in addition to manure. The effects of the added mineral P did not persist to final harvest, but vigorous early growth is valued by farmers concerned about plant pests and early maturity. The results at V6 suggest that there was no injury to corn roots, as recently reported [14], or mycorrhizal colonization, which is needed for P uptake in corn, so the precision injected sludge can safely replace mineral starter fertilizer even at the highest sludge rate under cool moist conditions of this study.

Table 6. V-6 average plant yield, N uptake and P uptake for 5 years (2010–2014).

Treatment	Plant DM Yield		N Uptake		P Uptake	
	kg ha^{-1}		**kg ha^{-1}**		**kg ha^{-1}**	
Control	58	e ‡	2.0	f	0.29	d
Synthetic Fertilizer only						
Fert 0P-250N	114	d	4.9	e	0.36	d
Fert 32P-83N	168	c	7.0	d	0.67	c
Fert 32P-167N	173	c	7.5	d	0.66	c
Fert 32P-250N	167	c	7.5	d	0.65	c
Sludge-based						
Sludge 16P-80N	173	c	6.5	d	0.64	c
Sludge 16P-250N	178	c	7.9	cd	0.66	c
Sludge 32P-167N	223	b	9.1	bc	0.85	b
Sludge 32P-250N	242	b	10.5	b	0.90	b
Sludge 64P-250N *	299	a	13.0	a	1.17	a

‡ Values within a column not followed by the same letter are statistically significant at $p < 0.05$. * P 32.1 kg ha^{-1} from fertilizer and 29.3 kg ha^{-1}.

The response of corn at V6 helps to explain the effect of nutrient treatments on DM concentrations, which is an indicator of crop development and a useful trait for farmers. At the 32P-250N nominal rate, DM% was significantly greater for sludge than fertilizer (36.6% and 31.5%, respectively, Table 4). Early corn maturation is important for farmers, underlining the importance of early P nutrition provided by the sludge. Higher DM% allows earlier harvests with better ensiling potential, and favors the effective use of cover crops, which is therefore an important co-benefit of early nutrition by sludge.

While sludge P and N enhanced early growth and N and P uptake, nutrient source had no effect on final P uptake. Please note that N rate did affect P uptake from both fertilizer and sludge at both application rates and this was likely in part due to effect on yield. Maximum P uptake was around 25–26 kg ha (27 kg ha^{-1} at very high P application rate of 61 kg ha^{-1}, Table 4). Under similar N regimes, there is no difference in P uptake from mineral fertilizer or sludge and this is consistent with previous reports [4,9,23]. Apparent recovery of applied fertilizer P at 32P increased with N rate from 37% to 53% (Table 5), and apparent recovery rate of sludge P at 32P was similar at 36% to 52%, but at the low sludge P rate of 16P and with abundant N, the P recovery averaged 99% of applied P, which suggests a soil P equilibrium. The actual P recovery of 16P 250N treatment 24 kg ha^{-1}, which is 166% of applied P and suggests a strategy for removing excess P from contaminated soils.

Figures 6 and 7 show the annual N and P uptake for the unfertilized control and the sludge 32P-190N treatments over the 5 trial years. The data shows fairly consistent annual values for both the control and the sludge treatments reflecting overall consistent crop growing conditions over the course of this trial (Table 2, Figure 1). For the sludge treatment, N uptake ranged from 100 to 123 kg ha^{-1}, while control ranged between 34 and 48 kg ha^{-1}, and there was no statistically significant upward or downward trend for these two treatments suggesting little discernable legacy effect from previous applications. The N uptake of treatments receiving sludge in alternating years also showed little effect of sludge treatments in the previous year. N and P uptake were similar in the treatment application year to the continuous treatment. In the non-treatment year, uptake of these nutrients was similar to the continuous control. Annual P uptake ranged from 18.4 to 22.1 for the sludge treatment and from 8.5 and 11.6 for the control. There was no significant annual trend, and like N, the values in the treatment years were similar to the comparable continuous treatment so there is little evidence of a short term legacy effect, except perhaps in the final year. Longer term assessments of legacy nutrient effects are warranted.

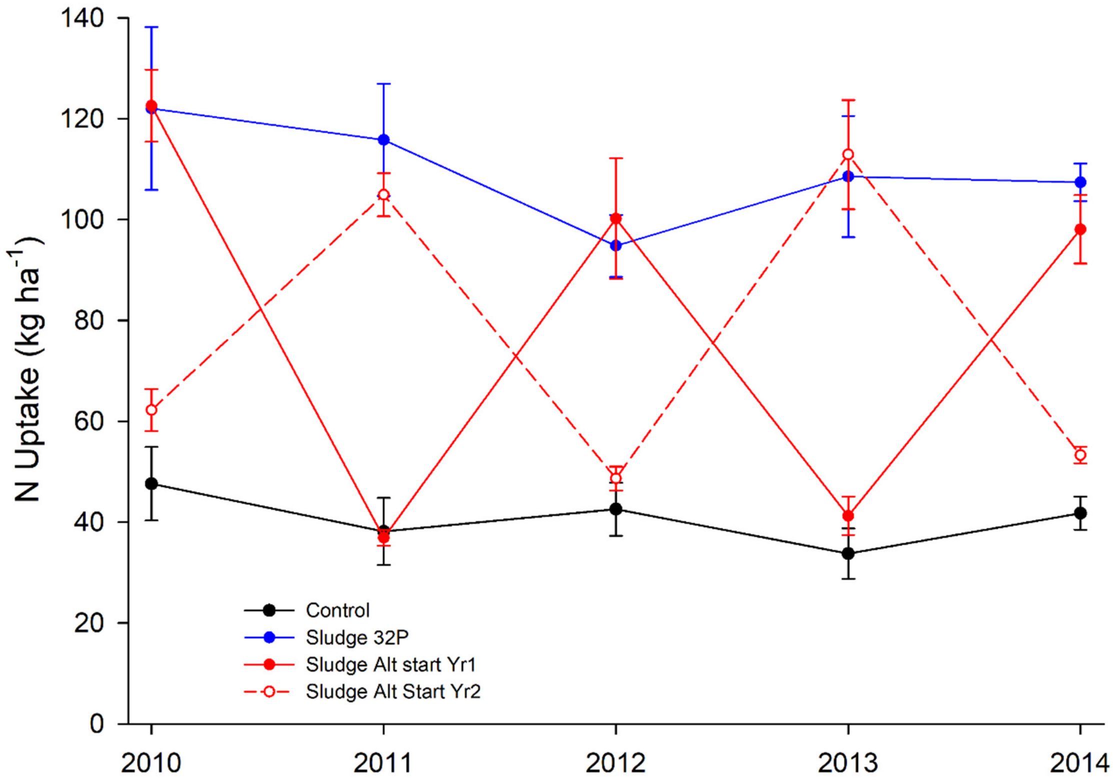

Figure 6. Annual uptake of N by unfertilized corn and corn treated annually or biennially with injected sludge (no fertilizer). Application rates are given on Table 3. SE values are shown on data point.

Corn response to available (inorganic) N from sludge and fertilizer is similar but there seems to be little benefit to the crop derived from the organic N fraction from either the current or from previous applications. There is evidence of greater N_2O emissions from the injected sludge, which is suggestive of denitrification, and some N might be lost by leaching, as it is mineralized over fall and winter [24]. Other possibilities are N (and C) immobilization, which would add to the long-term fertility of the soil, which, as mentioned above, may require longer studies [18,25]. Thus, although injection is known to reduce N loss as ammonia emissions, in this multi-year trial it has not fully resolved the problem of efficient use of sludge N which therefore needs further investigation [26]. Better N use is achieved when manure and fertilizer applications are combined [1]. It is our hypothesis that the organic fraction of manure, including N, should be considered primarily a soil amendment rather than a fertilizer source due to a C:N ratio of 11.8 based on total N but up to 25.4 based on the non-labile organic N fraction mostly remaining in the soil (Table 2).

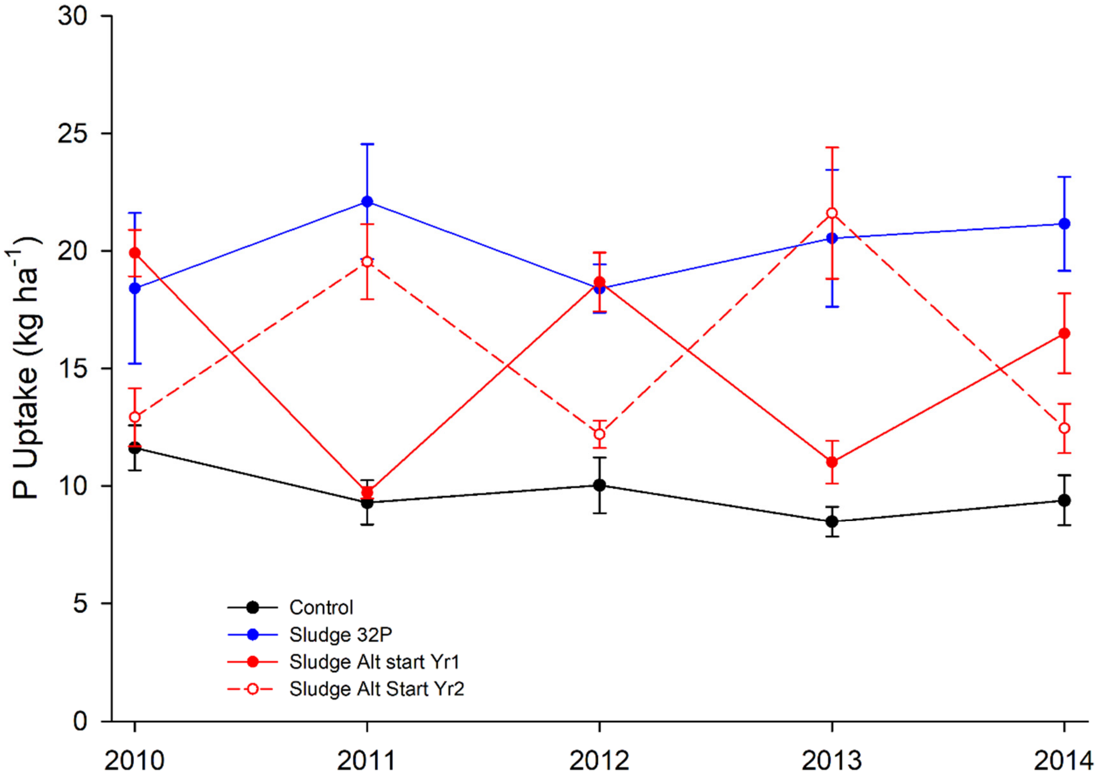

Figure 7. Annual uptake of P by unfertilized corn and corn treated annually or biennially with injected sludge (no fertilizer). Application rates are given on Table 3. SE values are shown on data point.

4. Conclusions

This multi-year field study supports the use of precision-placed dairy sludge for supplying P and N to silage corn, a practice first proposed by [4,9]. This study further demonstrates the effective use of sludge nutrients in the challenging no-till or reduced-till setting (depending on definition of no-till). The study also shows that P uptake from sludge depends greatly on presence of available N and N uptake. When uptake of P is compared at equal rates of available N, there was a substantial advantage for sludge at V6 but no difference in P uptake or recovery between fertilizer and sludge at maturity.

Overall, this study provides a solution for use of separated dairy solids, here in the form of a thick fluid sludge, which are left after the supernatant thin fraction is decanted. As a primary P source for corn, precision injected sludge placed within 10 cm of the corn rows can obviate the need for mineral P, as previously reported also for whole slurry [11,13] and may have additional benefits including supplying multiple nutrients with no cost. Having a beneficial way to use the separated sludge with no additional costs or emissions at storage facilitates administering the rapidly infiltrating thin fraction on grass, which has a higher N requirement and is difficult to inject; rapid infiltration increases N efficiency without requiring additional equipment or draft energy, and potentially minimizes P loading [1]. Injecting sludge for corn will not reduce nutrient loading on corn but by replacing commercial fertilizer will reduce the P surplus on dairy farms. Finally, the 'no-till' planting used in this study reduces economic and environmental costs and risks associated with corn production and helps to preserve colonization by arbuscular mycorrhizae which are important for P nutrition in corn and other crops.

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