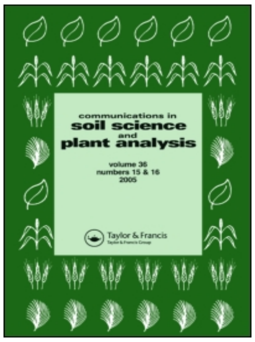

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Winter Wheat Yield, Quality, and Nitrogen Removal Following Compost- or Manure-Fertilized Sugarbeet

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ABSTRACT

To efficiently use nitrogen (N) while protecting water quality, one must know how a second-year crop, without further N fertilization, responds in years following a manure application. In an Idaho field study of winter wheat (*Triticum aestivum* L.) following organically fertilized sugarbeet (*Beta vulgaris* L.), we determined the residual (second-year) effects of fall-applied solid dairy manure, either stockpiled or composted, on wheat yield, biomass N, protein, and grain N removal. Along with a no-N control and urea (202 kg N ha^{-1}), first-year treatments included compost (218 and 435 kg estimated available N ha^{-1}) and manure (140 and 280 kg available N ha^{-1}). All materials were incorporated into a Greenleaf silt loam (Xeric Calciargid) at Parma in fall 2002 and 2003 prior to planting first-year sugarbeet. Second-year wheat grain yield was similar among urea and organic N sources that applied optimal amounts of plant-available N to the preceding year's sugarbeet, thus revealing no measurable second-year advantage for organic over conventional N sources. Both organic amendments applied at high rates to the preceding year's sugarbeet produced greater wheat yields (compost in 2004 and manure in 2005) than urea applied at optimal N rates. On average, second-year wheat biomass took up 49% of the inorganic N remaining in organically fertilized soil after sugarbeet harvest. Applying compost or manure at greater than optimum rates for sugarbeet may increase second-year wheat yield but increase N losses as well.

Abbreviations CNS, carbon–nitrogen–sulfur

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Dairy manure; grain yield; nitrogen uptake; nutrient management; organic fertilizer; protein; small grain; urea

Introduction

Worldwide, nitrogen (N) is the plant nutrient most limiting agricultural production (Fageria and Baligar 2005). In addition, N is often the most or among the most expensive inputs needed to produce crops in developed countries (Thomason et al. 2002). One organic amendment that can potentially decrease the N costs for a farmer is solid manure, either stockpiled or composted. Organic amendments provide (i) carbon that restores, sustains, or improves soil physical properties (Powlson et al. 2011), and (ii) macro- and micronutrients for crop uptake. The effective use of organic amendments is often limited by our ability to accurately predict the N mineralization rate of the organic-N to inorganic-N (Goss, Tubeileh, and Goorahoo 2013). Properly crediting the value of organic amendments as fertilizer in the years following their application will improve manure's nitrogen use efficiency (NUE) (Carter, Westermann, and Jensen 1976; Webb et al. 2013). This will, in turn, provide farmers with more effective manure management options and reduce N losses to the environment. If manure is not well managed, however, impairments can occur in the quality of both groundwater and surface water, being the two environmental parameters often considered most at

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risk (Schmitt 1999). Compared to inorganic N fertilizers, manure is far more difficult to manage and apply (Schröder 2005).

Depending upon crop, soil, and site characteristics, nitrate leaching can occur after organic or inorganic N is applied. Nitrate leaching is typically greater under a cereal than sugarbeet, *Beta vulgaris* L. (Webb et al. 2004), since sugarbeet is a very efficient scavenger of inorganic N (Shepherd and Lord 1996; Tarkalson, Bjorneberg, and Moore 2012). Under sugarbeet, nitrate leaching can be minimized (i) with a late, rather than early harvest since a late harvest allows for better utilization of N mineralized in autumn; (ii) if harvested sugarbeet fields are left fallow over winter, thereby delaying beet residue incorporation, N mineralization, and leaching, rather than being plowed in the fall and sown with a winter cereal (Shepherd and Lord 1996); and (iii) if manure is applied in winter or early spring rather than fall (Thomsen 2005). Thomsen (2005) demonstrated that spring barley (*Hordeum vulgare* L.) planted the first year after amendment application (hereafter termed first-year barley) recovered twice as much of the manure's total N when the manure was applied in either winter or spring than fall.

In some irrigated areas of the Inland Pacific Northwest, water may be in short supply late in the growing season. In those areas, a winter small grain such as wheat (*Triticum aestivum* L.) or barley is often sown soon after sugarbeet harvest. Once the short-season grain matures in mid-summer, some of the water that had been allocated to the wheat then becomes available for longer-season crops such as corn (*Zea mays* L.), potato (*Solanum tuberosum* L.), or sugarbeet growing in fields nearby. Winter wheat following sugarbeet yields well (Montemurro 2009) and indirectly lessens disease buildup and aids weed control (Wilson 2001). In a sugarbeet, wheat, or other rotation, about 70% of the N taken up by sugarbeet remains in the field as above-ground biomass residue after the harvested roots are removed (Mengel and Kirkby 1987; cited by Moraghan and Smith 1996). Sugarbeet tops, typically not removed from production fields, provide organic N that can be mineralized to supply a portion of the N needs of subsequent crops (Franzen 2004; Groves and Bailey 1997; Moraghan and Smith 1996).

Nitrogen uptake, translocation, and transformations in wheat are complex. As the wheat's growing season progresses, a progressively larger proportion of its N uptake comes from mineralized organic N (Harper et al. 1987). Half of the N in grain at harvest had come directly from the soil after anthesis, whereas the remainder had been translocated from the wheat plant's own tissue (Harper et al. 1987). If a suboptimal N fertilizer rate is applied to small grain, the grain N concentration can decrease if tillering increases, resulting in N dilution (Moraghan and Smith 1996).

Where manure or other organic amendments have been applied for one or more years, managing N efficiently with time is challenging (Lentz and Lehrsch 2012a; Mallory and Griffin 2007). In the near term, manures with high carbon:nitrogen (C:N) ratios can lead to N being immobilized instead of mineralized (Calderón et al. 2004). Those same high C:N ratio organic amendments in the long term, however, may provide more mineralized N late in the second year for wheat (Wen et al. 2003). In this and other ways, organic amendments typically benefit soil N fertility in the long term (Gutser et al. 2005; Lentz and Lehrsch 2012b). Since split N fertilizer applications that supply N later in the growing season increase grain N concentrations (Menezes, Gascho, and Hanna 1999), slow but sustained N mineralization from residual cattle manure may provide an extended supply of N to second-year wheat in its later growth stages (Wen et al. 2003). This additional N from mineralization potentially could increase both wheat grain protein and the quality of breadmaking wheat (Montemurro, Convertini, and Ferri 2007), but decrease the quality of soft wheat classes (Brown et al. 2005). Much of the N needed by second-year spring wheat was supplied by the mineralization of organic N from manure applied to first-year canola, *Brassica napus* L. (Wen et al. 2003).

Residual effects on crop performance likely differ between stockpiled manure and composted manure because composting may reduce N availability (Gutser et al. 2005; Larney et al. 2006). Relative to manure, compost typically contains less readily available residual N and more stable organic compounds which (i) resist microbial decomposition that, in turn, limits N mineralization

(Larney et al. 2006; Muñoz et al. 2008) and (ii) immobilize fertilizer N sufficiently to reduce N recovery by crops in some cases (Chalk, Magalhaes, and Inacio 2013). Thus, more N can often be mineralized from the organic fraction of manure (Chalk, Magalhaes, and Inacio 2013). Indeed, Muñoz et al. (2008) reported greater second-year N availability for fresh rather than composted cattle manure.

While researchers have reported second-year wheat recoveries and responses to N from conventional fertilizer (e.g., MacDonald et al. 2002; Shepherd and Sylvester-Bradley 1996; Zapata and Van Cleemput 1986), fewer have reported second-year wheat responses to N from manure. In a companion study to the current one, Lentz et al. (2011) studied winter wheat following manure- and compost-fertilized sugarbeet. They reported grain yield, averaged across amendment rates and eroded and non-eroded soil, of 6.2 Mg ha^{-1} where manure was applied, 1.55-fold greater than the control and 1.32-fold greater than where compost was applied. They did not report a comparison of a urea-fertilized treatment with either a manure or compost treatment average. Stumpe, Wittenmayer, and Merbach (2000) and Mooleki et al. (2004) also reported that subsequent wheat crops can benefit from the residual effects of manure applied in earlier years.

As Webb et al. (2013) advised, we need to measure N availability and uptake for more than 1 year after manure is applied if we are to most efficiently use the manure's N. Thus, with a goal of more efficient, long-term use of the N mineralized from solid manures, particularly under irrigated conditions, we conducted this multiyear field study. Our study's objective was to determine the residual (second-year) effects of fall-applied dairy manure, either stockpiled or composted, on winter wheat yield, biomass N, protein, and grain N removal.

Materials and methods

Soils and amendments

The experiment was conducted at the University of Idaho Research and Extension Center in Parma, Idaho, with a Greenleaf silt loam (fine silty, mixed, superactive, mesic Xeric Calciargid; Soil Survey Staff 2014) at Field A, planted to sugarbeet in 2003 followed by winter wheat in 2003–2004, and at Field B, planted to sugarbeet in 2004 then wheat in 2004–2005. Soil properties are given in Table 1. The soil micronutrient

Table 1. Soil properties of the Greenleaf silt loam in fall prior to amendment application (after Lehrsch et al. 2015a).

Soil properties (0 to 0.3 m depth, or as noted)	Field A 2002–2004[a]	Field B 2003–2005[a]
Particle size distribution, g kg^{-1}		
Sand (0.05 to 2 mm)	330	300
Silt (0.002 to 0.05 mm)	600	550
Clay (< 0.002 mm)	70	150
Bulk density, g cm^{-3}		
0 to 0.3 m	1.47	1.47
0.3 to 0.6 m	1.37	1.37
Organic C, g kg^{-1}	6.4	5.5
pH (aqueous sat. paste)	7.8	7.6
Electrical conductivity, dS m^{-1}	0.56	0.54
$CaCO_3$ equivalent, g kg^{-1}	67	42
Residual inorganic N[b]		
0 to 0.3 m, mg kg^{-1}	8.1	15.2
0.3 to 0.6 m, mg kg^{-1}	7.0	8.8
0 to 0.6 m, kg ha^{-1}	66	105
P, mg kg^{-1}	10	14
K, mg kg^{-1}	110	180
B, mg kg^{-1}	0.13	0.24

[a] Amendments were applied in fall of the first year, sugarbeet grown in second year, and winter wheat grown from the fall of the second year through the third year.
[b] NO_3-N + NH_4-N.

concentrations of iron, manganese, zinc, and copper (not reported) were sufficient to produce a crop of sugarbeet (Gallian et al. 1984) and a succeeding crop of winter wheat (Brown 2001). Prior to the current study, neither field had received any organic N source within the preceding 10 years.

We determined the manure and compost application rates each year by assuming that the portion of their total N mineralized in the 12 months following application would be 200 g N (kg total N)$^{-1}$ from compost and 400 g N (kg total N)$^{-1}$ from manure (Eghball and Power 1999; Richard 2005). After collection in fall 2002, dried samples of each amendment were ground to pass a 1-mm screen and their total carbon (C) and N concentrations determined by dry combustion (Tabatabai and Bremner 1991) of a ca. 400-mg sample in a Vario MAX carbon–nitrogen–sulfur (CNS) analyzer (*Elementar, Hanau, Germany*). The total N content of each amendment sample collected the following year was determined via a micro-Kjeldahl analysis using a block digester (Watson, Wolf, and Wolf 2003). Amendment dry matter content was determined by weighing a fresh, 1-kg sample before and after drying at 60°C (Hoskins, Wolf, and Wolf 2003). Compost and manure properties are given in Table 2.

Experimental design and treatments

The experiment, described in detail by Lehrsch et al. (2015a), was a randomized complete block with eight treatments and four replications. The current study reports findings for the six treatments on which wheat yield and grain quality were monitored (Table 3). The six treatments were a control (that received no N fertilizer), conventional N fertilizer (urea) applied at 202 kg N ha^{-1}, the optimum rate recommended for sugarbeet (Gallian et al. 1984), two first-year rates of stockpiled solid manure (21.9 and 43.8 Mg ha^{-1}, dry wt.) from dairy cattle replacement heifers, and two first-year rates (53.1 and 106.1 Mg ha^{-1}, dry wt.) of composted dairy cattle manure (hereafter simply termed compost). The 202-kg N ha^{-1} rate was chosen based upon a sugarbeet yield goal of 67.2 Mg ha^{-1}, after accounting for inorganic N present in the 0.6-m-deep soil profile (66 kg ha^{-1}, Table 1) in fall 2002. The low and high rates of each organic N source were chosen so as to apply plant-available N at the optimum and twice the optimum N rate for sugarbeet, respectively. None of the manure- or compost-treated plots received any additional N fertilizer.

Table 2. Properties of the compost and manure applied in fall of the year shown. Other than dry matter content, all measurements are on a dry-weight basis.

	Compost		Manure	
Property	2002	2003	2002	2003
Total C, g kg^{-1}	282	ND[a]	162	ND
Total N, g kg^{-1}	20.5	15.7	16.0	22.1
C:N ratio	13.8	ND	10.1	ND
Dry matter content, kg kg^{-1}	0.65	0.65	0.65	0.40

[a] ND = Not determined.

Table 3. Treatment descriptions and application rates of bulk amendments (moisture-free basis) and amendment total N for sugarbeet grown in the year shown.

		Bulk appl. rate (Mg ha^{-1})		Total N appl. rate (kg ha^{-1})	
Treatment[a]	Amendment	2003	2004	2003	2004
Ctrl	None	0	0	0	0
Fert	Urea	0.44	0.44	202	202
Com1	Compost	53.1	64.2	1089	1008
Com2	Compost	106.1	128.4	2175	2016
Man1	Manure	21.9	22.8	350	504
Man2	Manure	43.8	45.6	701	1008

[a] Ctrl, Fert, Com, Man = Control, Fertilizer (urea), Compost, or Manure, respectively; 1, 2 = Rate 1 or Rate 2, respectively.

Due to discrepancies in manure analyses among laboratories (discussed by Lehrsch et al. 2015a), the estimated available N applied in the 2003 manure treatments was about 31% less than our two targeted rates, 202 and 403 kg N ha^{-1}. As a consequence, in 2003 the two compost treatments supplied about 1.55-fold more estimated available N than their corresponding manure treatments, on average. Each of the organic source treatments did, however, supply estimated available N either at or within ca. 70% of its targeted rate. Bulk amendment application rates (dry wt. basis) can be as great as 28 Mg ha^{-1} for compost and 55 Mg ha^{-1} for manure in southern Idaho.

Field operations for sugarbeet

Field activities are listed in Table 4. After disking to incorporate wheat crop residue, we collected eight soil samples (four 0 to 0.3 and four 0.3 to 0.6 m) from each field and then composited them by depth to determine each field's initial physical and chemical properties along with baseline contents of inorganic N [calculated as nitrate-N (NO_3-N) + ammonium-N (NH_4-N)], phosphorus (P), potassium (K), and boron (B) (Table 1). In the fall, after applying organic amendments by hand to our 12-row, 6.7-m-wide × 15.2-m-long plots, we incorporated them to a depth of 0.1 m with a rototiller and then, using toolbar-mounted shovels, formed beds for the sugarbeet. Amendments were incorporated within 31 h of application (i) to minimize N loss via ammonia volatilization (Eghball et al. 2002), and (ii) to increase crop N recovery (Schoenau and Davis 2006). Mooleki et al. (2004) reported that manure applied in the fall, as we did, or preplant in the spring was similar in their effects on second-year crops, the focus of the current study.

Based upon the analyses of the initial soil test samples collected the previous fall, Field A was uniformly fertilized in spring with P (as triple superphosphate at a rate of 13.2 kg P ha^{-1}), K [as potassium chloride (KCl) at 33.5 kg K ha^{-1}], and B (as Solubor at 1.15 kg B ha^{-1}). Pretreatment soil tests indicated that in Field B, all nutrients other than N were present in adequate amounts. All nutrients applied to Field A in spring

Table 4. Schedule of field activities.

Activity	Date (day of year, DOY)	
	Field A (2002–2004)	Field B (2003–2005)
Sugarbeet		
Disked to incorporate wheat residue	4, 9, 24 September 2002 (247, 252, 267)	28 August 2003 (240) (three times)
Soil sampled (pretreatment)	16 October 2002 (289)	24 November 2003 (328)
Amendments applied, then rototilled	8 November 2002 (312)	28 November 2003 (332)
Beds formed	8 November 2002 (312)	2 December 2003 (336)
Fertilized (topdressed) with P, K, and B	1 April 2003 (91)	NA[a]
Bed tops removed	3 April 2003 (93)	29 March 2004 (89)
Sugarbeet planted	4 April 2003 (94)	1 April 2004 (92)
Buried bags placed in spring	14 April 2003 (104)	2 April 2004 (93)
Sugarbeet stands thinned	17[b] May 2003 (137)	14 May 2004 (135)
Cultivated	22 May 2003 (142)	27 April 2004 (118)
Cultivated	18 June 2003 (169)	21 May 2004 (142)
Cultivated	9 July 2003 (190)	8 June 2004 (160)
Sugarbeet harvested	27 October 2003 (300)	22 November 2004 (327)
Winter wheat		
Disked to incorporate sugarbeet residue	28 October 2003 (301)	23 November 2004 (328)
Subsoiled to the 0.46 m depth	31 October 2003 (304)	24 November 2004 (329)
Roller harrowed	5 November 2003 (309)	16 December 2004 (351)
Wheat planted	7 November 2003 (311)	20 December 2004 (355)
Buried bags placed	15 December 2003 (349)	14 February 2005 (45)
Buried bags removed	NA	6 June 2005 (157)
Buried bags removed	NA	12 July 2005 (193)
Wheat biomass sampled	23 June 2004 (175)	12 July 2005 (193)
Wheat harvested	13 July 2004 (195)	29 July 2005 (210)
Buried bags removed	8 September 2004 (252)	15 September 2005 (258)

[a] NA = Not applicable.
[b] Day is approximate.

were immediately incorporated with surface tillage that simultaneously reformed planting beds and reestablished furrows (Table 4). Sugarbeet was planted to a depth of 25 mm in a row centered atop each bed. Emergence did not differ among treatments within years, and the final plant population each year was 111,850 plants ha^{-1} after thinning (Lehrsch et al. 2015a). Urea was applied to the conventionally fertilized treatment (Fert) of Field A as a split application: 56 kg N ha^{-1} as a topdressing on 5 May 2003, 67 kg N ha^{-1} as a sidedressing on 4 June and 78 kg N ha^{-1} as a second sidedressing on 17 June. Of the 202 kg N ha^{-1} as urea applied to the Fert treatment of Field B in 2004, half was sidedressed on 14 May and half on 2 June.

Thereafter, in-season net N mineralization was measured (described later) by installing seven buried bags in bed centers in each plot and periodically retrieving one set of bags on each of seven subsequent dates. The net N mineralization determined during the sugarbeet growing season has been reported by Lehrsch et al. (2016) and will not be discussed hereafter.

We furrow irrigated all plots 15 times in 2003 and 14 times in 2004, using furrows spaced 1.12 m apart and separated by two beds. The sugarbeet crop was managed using standard production practices for the area (Panella et al. 2014). As the season progressed, we cultivated the field three times (Table 4) and periodically removed buried bags. The sugarbeet was harvested after being mechanically topped. Sugarbeet yield, quality, N uptake, and N use efficiency were reported earlier (Lehrsch et al. 2015a, 2015b).

Field operations for winter wheat

Beginning 1 day after sugarbeet harvest, the trial areas were disked, subsoiled to a depth of 0.46 m, and roller-harrowed to prepare a seedbed for wheat (Table 4). 'Stephens' soft white winter wheat was planted in 0.18-m rows at a rate of 151 kg seed ha^{-1} in 2003. No additional N, either inorganic or organic, was applied to the wheat in either year so that differences in its yield, biomass N, protein, and grain N would be due primarily to residual and mineralized N from previous treatments. All other macro- and micronutrients were present in adequate amounts, based upon soil tests the previous fall or having been added before growing sugarbeet. Whereas sugarbeet harvest and subsequent wheat planting were timely in 2003, rainfall and excessively wet soil delayed the fall 2004 sugarbeet harvest and, as a consequence, subsequent seedbed preparation and wheat planting, completed on 20 December 2004. Due to the late planting, wheat was seeded at 168 kg ha^{-1}, 1.11-fold greater than in 2003. Also due to wet soil, all postharvest soil sampling and buried bag installation (described later) planned for fall 2004 were delayed until the following February when soils had thawed and adequately dried.

We estimated net N mineralization during and after the wheat's growing season from all but the conventionally fertilized treatment using the buried bag method of Lentz and Lehrsch (2012a) that was adapted from ones described by Westermann and Crothers (1980) and Meek et al. (1994). In brief, the method utilizes polyethylene film, permeable to oxygen (O_2) and carbon dioxide (CO_2) but nearly impermeable to water vapor, to encase moist soil collected from and then replaced within a few hours into the soil profile from whence it came. Once placed, the native microbial population either decomposes the nitrogenous organic compounds in the soil or utilizes any inorganic N present, or both, as the encased soil undergoes the same diurnal and seasonal temperature changes as the soil surrounding it, but none of the N losses due to leaching or plant uptake, as roots do not penetrate the film. Changes in the bagged soil's inorganic N concentration between placement and subsequent removal accurately reflect microbial activity in the interim. After wheat was planted, from each plot 57-mm-diameter soil cores (one in December 2003 and three in February 2005), 0 to 0.3 m deep, were collected with a bucket auger, composited, and passed through a 4-mm screen. If necessary, distilled water was added to attain a water content of ca. 0.20 kg kg^{-1}, equivalent to a matric potential of ca. −86 kPa. After a subsample was taken to determine residual NO_3-N and NH_4-N (described later), soil was vertically shaken into a 10-μm-thick, 50-mm-diameter polyethylene tube that had been sealed on one end, resulting in a water-filled pore space of ca. 39%. The remaining open end was then sealed, with the resulting 0.3-m-long soil column placed into one of the sampling cavities created earlier. Then, sieved soil was (i) added around the tube to fill the cavity and (ii) mounded atop the tube to eliminate sidewall flow and to shed water. In the control only, N mineralization was monitored in a similar manner in soil from the 0.3 to 0.6 m depth. We installed one set of bags in Field A and three in Field B. On selected dates each year (Table 4), a set of buried bags was removed (i.e., destructively sampled) and its soil was analyzed to monitor net N mineralization with time. Soil from the initial postplant sampling and each retrieved buried bag was air-dried and ground to pass a 2-mm sieve. After soil inorganic N was extracted with a 2-mol L^{-1} KCl solution, each sample's NO_3-N concentration after cadmium reduction was determined colorimetrically (Mulvaney 1996). In addition, a standard colorimetric procedure was used to measure the concentration of NH_4-N after reacting with salicylate and hypochlorite (Mulvaney 1996) for the samples collected at bag installation each year. Net N mineralized was calculated as the bagged soil's NO_3-N concentration at removal less that at installation. Buried bags were installed 49 days after sugarbeet harvest in 2003. In 2004, wet soils that had frozen solid delayed buried bag installation until 83 days after sugarbeet harvest.

The wheat was furrow-irrigated ca. five times from April through June, typically for 18 h each time, using furrows 0.76 m apart. The wheat was grown using recommended cultural practices to control weeds, diseases, and pests (Miles et al. 2009). Wheat biomass (whole plant above-ground) samples were collected at the hard dough growth stage by clipping plants about 10 mm above the soil surface by hand from two adjacent 0.61-m-long rows, totaling 0.22 m^2 in area. After weighing the freshly clipped biomass, a subsample was weighed, oven-dried, reweighed, ground to pass a 1-mm screen, and analyzed for total N by dry combustion as were the organic amendments applied prior to planting sugarbeet. The wheat's biomass N was determined by multiplying the total N content of the biomass by the dry biomass. Wheat matured, at which time biomass was sampled, nearly 3 weeks later in 2005 than 2004 (Table 4).

Grain yield was measured using a Kincaid Model 8-XP small plot combine (Kincaid Equip. Mfg., Haven, Kansas) to harvest wheat from an area 1.52 m wide (ca. 8 rows) × 12.6 m long, on average. Subsamples of harvested grain were used for a moisture determination (Multi-Grain Moisture Tester, Dickey-John, Auburn, Illinois). Grain crude protein was subsequently determined at the University of Idaho Wheat Quality Laboratory, Aberdeen, using near-infrared spectroscopy (Perten Instruments, Chatham, Illinois), and calibrated with total N analyzed by combustion (Leco Corporation, St. Joseph, Michigan). The grain's total N content was calculated by dividing the grain's crude protein content by 5.7. Wheat grain N removal per unit area for each plot was determined by multiplying grain N content by dry-weight yield. Reported grain protein content and grain yield have been adjusted to a moisture content of 12%.

Statistical analysis

To test for stable variances, we first regressed the logs of each response variable's within-treatment standard deviations on the logs of its corresponding treatment means. A resulting nonsignificant linear regression indicated stable error variances for that variable (Box, Hunter, and Hunter 1978; Lehrsch and Sojka 2011). Where needed, we used a common log or, at times, an arcsine square root or reciprocal transformation to stabilize a variable's error variance. Thereafter, we analyzed the data by year using a mixed-model analysis of variance (ANOVA) using the PROC Mixed procedure in SAS (SAS Institute Inc., 2014) with a significance probability (P) of 0.05, unless otherwise noted. The model had treatment as a fixed effect and block as the random effect. When needed, ANOVA grouping options accounted for heterogeneous variances among treatments for each response variable. For all significant fixed effects, we separated least-squares means using the Tukey–Kramer multiple comparison test with letter groupings assigned using software written by Saxton (1998). Any mean that was analyzed on a transformed scale was back-transformed into original units for presentation.

Results and discussion

Residual soil N

The 2005 wheat crop was planted in soil with a mean residual soil N of 12.3 mg kg^{-1}, nearly 1.6-fold greater (significant at P = 0.007) than the 7.8 mg kg^{-1} in the soil of the 2004 wheat crop (Table 5). The relatively low residual N in the uppermost 0.3 m for the 2004 crop (measured on 15 December 2003) may reflect the N-scavenging ability of the preceding sugarbeet, whose root system was likely concentrated above 0.3 m, hindered from exploiting lower depths for N by compacted soil at the 0.24 m depth (Lehrsch et al. 2015a). Also, in 2005 more so than the year before, residual N tended to increase with amendment rates. While the 2005 values in part reflect the residual N remaining after sugarbeet, the results may reflect N mineralized, including from incorporated sugarbeet tops (Groves and Bailey 1997; Moraghan and Smith 1996), during an 11-week period between sugarbeet harvest and buried bag placement (Table 4). Wet, then frozen soil caused the nearly three-month delay in installing the buried bags in the field sown with winter wheat for the 2004–2005 season. This additional N mineralization could have occurred in unfrozen soil beneath the profile's frozen surface (not measured). The residual N at the 0.3 to 0.6 m depth was low, 4.2 mg kg^{-1} in 2004 and 3.4 mg kg^{-1} in 2005 for the control, the only treatment monitored (data not shown).

Cumulative net N mineralized

Net N mineralized values are reported for the period from late fall (planting) through 8 September in 2004 and for the periods from winter through 6 June, 12 July, and 15 September in 2005 (Table 5). Additional resources in 2005 permitted us to more frequently estimate cumulative net N mineralization. In control plots, at the 0 to 0.3 m depth the cumulative net N mineralized through September averaged 22.5 mg NO_3-N kg^{-1} for 2004 and 30.2 mg kg^{-1} for 2005 (Table 5). The range of net N mineralized among treatments within dates was smaller in 2005 than 2004. Indeed, in 2005 the net N mineralized through 15 September was similar among treatments, with values ranging only from 45.2 to 47.0 mg NO_3-N kg^{-1}. The current study's two-year average, cumulative net N mineralized to September for the Man1 treatment, 38.2 mg kg^{-1} (Table 5), can be compared to the second-year mineralization value of 21.1 mg kg^{-1} reported by Lentz and Lehrsch (2012a) and the 27.7 mg kg^{-1} reported by Lentz et al. (2011). Similarly, this study's two-year cumulative average for Man2, 54.4 mg kg^{-1} (Table 5), can be compared to the second-year mineralization value of 34.2 mg kg^{-1} reported by Lentz et al. (2011).

Table 5. Residual N in soil at wheat planting and cumulative net N mineralized (0 to 0.3 m depth) in buried bags on the dates shown in each wheat growing season. Soil residual N was measured when the buried bags were placed in the soil profile. The treatment × year interaction for residual N was not significant (P = 0.203).

	2003–2004		2004–2005				
	Residual N[b]	Cum. net N mineralized[c] to	Residual N	Cumulative net N mineralized to			Residual N
Treatment[a]	15 December 2003 (mg N kg^{-1})	8 September 2004 (mg N kg^{-1})	14 February 2005 (mg N kg^{-1})	6 June 2005 (mg N kg^{-1})	12 July 2005 (mg N kg^{-1})	15 September 2005 (mg N kg^{-1})	(two-year avg.) (mg N kg^{-1})
Ctrl	6.8	22.5 b[d]	9.6	11.2 b	15.6 b	30.2	8.2 b
Com1	6.8	24.5 ab	8.6	13.0 ab	22.8 ab	45.2	7.7 b
Com2	8.3	35.5 ab	14.5	17.5 ab	27.5 a	47.0	11.4 ab
Man1	8.2	30.9 ab	11.5	20.9 a	28.9 a	45.5	9.8 ab
Man2	9.0	61.8 a	17.1	20.2 ab	31.8 a	47.0	13.1 a

[a] Ctrl, Com, Man = Control, Compost, or Manure, respectively; 1, 2 = Rate 1 or Rate 2, respectively.
[b] Residual N was the inorganic N (NO_3-N + NH_4-N) measured when the buried bags were placed.
[c] Cumulative net N mineralized was calculated as the NO_3-N concentration in the soil at bag removal less that at bag placement.
[d] Within a column, means followed by a common letter were not significantly different at $P \le 0.05$. No letters are shown if the effect was not significant in the ANOVA.

The through-September cumulative net N mineralization values reflect long-season mineralization, that is, mineralization that extended well past the winter wheat's potential N utilization period. The N uptake period for wheat is completed by physiologic maturity, the hard dough growth stage (Large 1954), which in our area typically occurs in late June or early July. In 2005, the average cumulative net N mineralization on 6 June at flowering was 16.6 mg NO_3-N kg^{-1}, 38.5% of the mean total long-season net N mineralization. Similarly, the 12 July sampling at physiologic maturity yielded cumulative net N mineralization of 25.3 mg NO_3-N kg^{-1}, 59% of the total long-season net N mineralization. Thus, even in the second growing season after organic amendments were applied, more than 40% of the N mineralized through September in this mostly organically fertilized soil occurred after wheat N uptake ceased. In addition, the increase in mineralization from June to July in soil amended with high rates of compost and manure was more than twice that of the control. As a consequence, by 12 July both high rate means exceeded the control at $P \leq 0.05$ (Table 5).

In the control, the cumulative net N mineralized in the 0.3 to 0.6 m depth to September was 3.3 mg NO_3-N kg^{-1} in 2004 and 7.1 mg kg^{-1} in 2005 (data not shown), representing 13% and 19%, respectively, of the total N mineralized to 0.6 m each year (Table 5). The current study's two-year average of 16% compares favorably with the 13% for a similar untreated soil reported by Lentz et al. (2011). Lentz et al. (2011) and Lentz and Lehrsch (2012a) also documented substantial N mineralization in the 0.3 to 0.6 m depth in a similar soil, wherein compost and manure were incorporated to a depth of 0.1 m, as in the current study. In the Greenleaf profiles of the current study, residual inorganic N may also have been available even deeper, that is, below 0.6 m, depths which were not sampled.

Wheat biomass N uptake

Nitrogen uptake by winter wheat biomass and sugarbeet roots in relation to the inorganic N available each year are shown in Table 6. The N available was an estimate of each treatment's total N that was mineralized in the year ending at sugarbeet harvest. The available N was calculated using each treatment's total N application rate (Table 3) assuming a first-year mineralization of 200 g N (kg total N)$^{-1}$ from compost and 400 g N (kg total N)$^{-1}$ from manure (Eghball and Power 1999; Richard 2005). The sugarbeet root N uptake data in Table 6 were reported by Lehrsch et al. (2015b), though as two-year averages, but are given here to facilitate comparison with the N taken up

Table 6. Nitrogen uptake in the two cropping seasons after amendment application relative to the inorganic N available in each field. Nitrogen uptake by sugarbeet root was measured at harvest and by winter wheat biomass at physiologic maturity.

	Field A			Field B		
	Input N	2003	2004	Input N	2004	2005
Treatment[a]	Total available[b] (kg ha^{-1})	Sugarbeet root N uptake[c] (kg ha^{-1})	Wheat biomass N uptake (kg ha^{-1})	Total available[b] (kg ha^{-1})	Sugarbeet root N uptake[c] (kg ha^{-1})	Wheat biomass N uptake (kg ha^{-1})
Ctrl	0	61 d[d]	37	0	65 b	58
Fert	202	102 ab	51	202	145 a	ND[e]
Com1	218	78 cd	49	202	99 ab	72
Com2	435	125 a	57	403	141 a	101
Man1	140	71 d	45	202	114 ab	79
Man2	280	99 bc	59	403	147 a	104

[a] Ctrl, Fert, Com, Man = Control, Fertilizer (urea), Compost, or Manure, respectively; 1, 2 = Rate 1 or Rate 2, respectively.
[b] Calculated using each treatment's total N application rate (Table 3) assuming a first-year mineralization of 200 g N (kg total N)$^{-1}$ from compost and 400 g N (kg total N)$^{-1}$ from manure (Eghball and Power 1999; Richard 2005).
[c] Adapted from Lehrsch et al. (2015b).
[d] Within a column, means followed by a common letter were not significantly different at $P \leq 0.05$. No letters are shown if the effect was not significant in the ANOVA.
[e] ND = Not determined.

by the winter wheat that followed the sugarbeet in rotation each year. The root N uptake is the mass per unit area of mineralized N that was removed from each treatment in the harvested sugarbeet.

Nitrogen uptake by sugarbeet roots differed among treatments each year but N uptake by wheat biomass did not (Table 6). While the sugarbeet removed from 29% to 51% of the available N in the treated plots in Field A in 2003 and from 35% to 72% in Field B in 2004, that removal had no effect on the N taken up in wheat biomass in either field (Table 6). Even where high rates of compost and manure were applied to sugarbeet, the wheat biomass took up no more N than it did from the non-N-fertilized control. While variability in the data precluded us from declaring differences significant at $P = 0.05$, N uptake by the four organic N treatments averaged 42% more than the control in 2004 and 53% more in 2005. Nitrogen uptake by wheat biomass from organically fertilized soil did not vary among treatments despite the fact that, of the inorganic N remaining after sugarbeet harvest, wheat biomass took up 18% to 65% (38% on average) of the N in 2004 and 39% to 90% (60% on average) in 2005 (Table 6). Thus, under our experimental conditions, winter wheat following organically fertilized sugarbeet does not appear to be a good choice to scavenge inorganic N remaining after sugarbeet harvest. A cover crop grown as a N trap crop, however, may capture more of the inorganic N for use by subsequent crops. While wheat's N uptake potential might not be best, it is commonly grown in rotation with sugarbeet to, for example, decrease disease pressure (Panella et al. 2014). The great potential for N mineralization in irrigated, silt loam soils in southern Idaho can be seen in the fact that, even in the control soil that received neither organic nor inorganic N, a total of 98 to 123 kg N ha^{-1} was mineralized in two consecutive growing seasons (Table 6).

Following sugarbeet with no additional N fertilizer applied, wheat biomass N uptake averaged across all treatments save Fert was 83 kg ha^{-1} in Field B in 2005, 1.7-fold greater than in Field A in 2004 (Table 6). This result is consistent with greater available N in 2005 as indicated by the greater initial residual N (Table 5). Besides the greater available N in 2005, it is not clear why such differences occurred in annual biomass N. The seeding rate was 1.11-fold greater in 2005, but the later planting normally would reduce vegetative growth. Air temperatures, however, were cooler in 2005 than 2004. In fact, from March through June, monthly mean air temperatures averaged 1.5°C lower in 2005 than 2004 (data not shown), which may have stimulated wheat growth in early spring, reduced early season heat stress, or both. In this limited-N study, differences in N availability may greatly affect early-season vegetative growth in unusual ways.

Grain yield, grain protein, and grain N removal

Grain yield following sugarbeet, with no preplant or in-season N application for wheat, averaged only 3.20 Mg ha^{-1} in 2004 but 5.37 Mg ha^{-1} in 2005, a 1.68-fold increase. Grain yield was significantly higher in 2005 than 2004 for every treatment except Com1, the treatment responsible for the significant ($P = 0.012$) treatment × year interaction (Figure 1). Higher yield for most treatments in 2005 relative to 2004 is due in part to greater average residual soil N, as noted earlier. In addition, the growing season (to physiologic maturity) was nearly 3 weeks longer in 2005 than 2004 (Table 4), enabling the wheat to utilize more of the N that is typically mineralized later in the season from both the control and organically amended treatments. Due principally to limited available N, grain yield each year was well below the region's typical irrigated winter wheat yield, which in southern Idaho averaged 6.05 Mg ha^{-1} in 2004 and 6.11 Mg ha^{-1} in 2005 (NASS 2012).

Grain yield was similar among the conventional fertilizer, and both low-rate organic sources in Field A in 2004 and in Field B in 2005 (Figure 1), all of which provided optimum N rates for first-year sugarbeet, save the Man1 treatment in Field A (Table 6). Thus, there were no measurable second-year advantages for wheat in using organic N sources rather than conventional fertilizer applied at optimum rates for sugarbeet. Yield from the low rates of compost and manure exceeded that from the unfertilized control in Fields A and B. Often greater yield, relative to the control, from the low-rate organic N sources than fertilizer is likely due to more N being mineralized from the

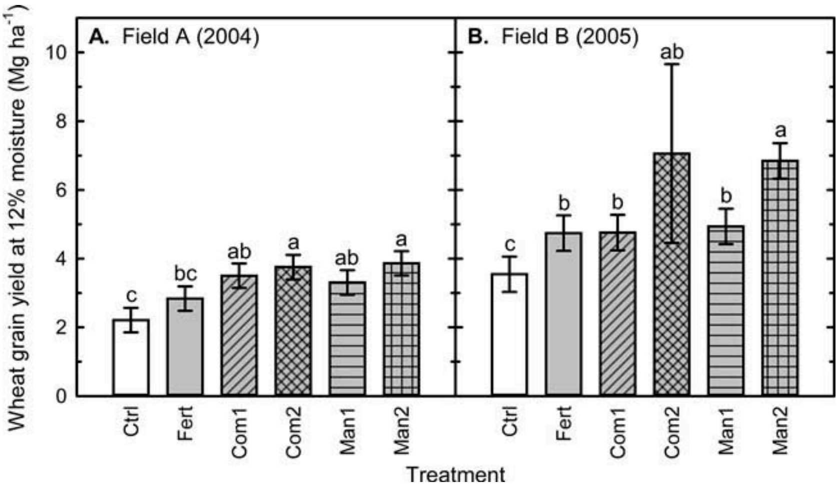

Figure 1. Winter wheat grain yield by treatment following sugarbeet in each field. Within a field, means (n = 4, shown with 95% confidence limits) with a common letter were not significantly different at $P \leq 0.05$. Grain yield is reported at 12% moisture.

1.73- to 5.4-fold more total N they applied (Table 6). Yield did not differ between organic sources at comparable N rates in 2005 (Figure 1).

Grain yields were greater for the high-rate organic N treatments than for the conventional fertilizer treatment in three of four cases (Figure 1), demonstrating a greater abundance of inorganic N in the soils amended with high rates of organic sources rather than conventional fertilizer. Since all treatments had similar biomass N uptake (Table 6), this raises the question of potential N losses from large, one-time applications of organic N sources to crops, especially those that may be over-irrigated. Organic amendments should be applied judiciously and at optimum rates to minimize losses and protect water quality. Annual or biennial applications of smaller rather than larger organic N rates are recommended.

Grain protein, in contrast to biomass N and yield, was greater in 2004 than 2005, on average (Table 7). The protein in 2005 was well below the N sufficiency range for soft white winter wheat (Brown 1988). Even though the protein was greater in 2004, it too was likely insufficient. These protein values reveal that, to maximize yield and protein for second-year 'Stephens' wheat, producers should apply supplemental N, though at rates that account for the organic N applied previously. Montemurro (2009) reported that, where organic N had been applied earlier, an in-season topdressing of inorganic N to winter wheat maximized yield and kept protein high.

Though the protein range among treatments was narrow, 0.5% in 2004 and 0.42% in 2005, the protein of Com2 exceeded that of Man1 each year and Fert in 2004 (Table 7). The greater protein for

Table 7. Treatment effects on winter wheat grain protein and grain N removal following sugarbeet each year.

	Protein[b] (%)		Grain N removal (kg ha^{-1})	
Treatment[a]	2004	2005	2004	2005
Ctrl	9.48 ab[c]	7.85 ab	37 c	49 c
Fert	9.35 b	ND[d]	46 bc	ND
Com1	9.63 ab	8.15 ab	59 a	68 b
Com2	9.85 a	8.25 a	65 a	102 ab
Man1	9.35 b	7.83 b	54 ab	68 b
Man2	9.73 ab	7.88 ab	66 a	95 a

[a] Ctrl, Fert, Com, Man = Control, Fertilizer (urea), Compost, or Manure, respectively; 1, 2 = Rate 1 or Rate 2, respectively.
[b] Protein is reported at 12% moisture.
[c] Within a column, means followed by a common letter were not significantly different at $P \leq 0.05$.
[d] ND = Not determined.

Com2 than Man1 and Fert may be a consequence of the former treatment supplying twice (or more) the N as the other treatments (Table 6). Greater protein for one but not another N source does not necessarily suggest more available N from the former source, however. The protein of marginally N-deficient wheat may be lower than the protein of severely N-deficient wheat (Brown et al. 2005). Indeed, even for non-fertilized controls, grain protein can be great at times due to poor biomass production coupled with high N concentrations in the relatively few grain kernels produced (Dr. O. Walsh 2014, personal communication).

The N removed in the grain at harvest was greater in 2005 than 2004, on average (Table 7), primarily due to higher yield in 2005 (Figure 1). Again, the results are consistent with the significant, 1.6-fold greater initial residual N in 2005 than 2004, when averaged across treatments (Table 5), and the ca. 3-week longer growing season in 2005 than 2004. While organic amendments may not consistently increase wheat yield relative to urea (Figure 1), they may increase grain N removal (Table 7). In three of four cases in 2004, grain N removal was greater where wheat was fertilized with organic rather than inorganic N sources, possibly due to greater N mineralization postanthesis during grain filling where organically fertilized. Grain N removal was higher for all organic N sources, regardless of N rate, than for the control each year (Table 7). Also, grain N removal in 2005 increased linearly with the N supplied by the five treatments (Table 6), as expected (data not shown).

Summary and recommendations

Where the organic N sources and urea each provided the recommended optimum first-year available N to sugarbeet, second-year wheat yield was similar whether compost, manure, or urea was applied. Where organic sources provided twice the optimum, in contrast, wheat yield was greater from compost in 2004 and from manure in 2005, relative to conventional N fertilizer applied at the optimum N rate for sugarbeet.

Applying organic N sources rather than conventional fertilizer at optimum rates for sugarbeet had no measurable effect on the grain yield of second-year wheat.

Of the inorganic N remaining in organically fertilized soil after sugarbeet harvest, second-year wheat biomass took up only 38% in 2004 and 60% in 2005, on average. Thus, small grains are not recommended as a crop to follow organic N-fertilized sugarbeet.

Applying compost or manure at optimum rather than greater rates should minimize N losses when second-year crops are grown without supplemental N fertilizer. Annual or biennial applications of smaller rather than larger organic rates are recommended.

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Declaration of Interest

Manufacturer or trade names are included for the readers' benefit. By including names, the USDA-ARS implies no endorsement, recommendation, or exclusion.

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