Research Article

Nitrogen Availability and Uptake by Sugarbeet in Years Following a Manure Application

Rodrick D. Lentz and Gary A. Lehrsch

North West Irrigation and Soils Research Laboratory, USDA-ARS, 3793 N 3600 W, Kimberly, ID, 83341-5076, USA

Correspondence should be addressed to Rodrick D. Lentz, rick.lentz@ars.usda.gov

The use of solid dairy manure for sugarbeet production is problematic because beet yield and quality are sensitive to deficiencies or excesses in soil N, and soil N availability from manure varies substantially depending on the year of application. Experimental treatments included combinations of two manure rates (0.33 and 0.97 Mg total N ha^{-1}) and three application times, and non-manure treatments (control and urea fertilizer). We measured soil net N mineralization and biomass, N uptake, and yields for sprinkler-irrigated sugarbeet. On average, the 1-year-old, low-rate manure, and 1- and 2-year-old, high-rate manure treatments produced 1.2-fold greater yields, 1.1-fold greater estimated recoverable sugar, and 1.5-fold greater gross margins than that of fertilizer alone. As a group the 1-year-old, low-rate manure, and 2- and 3-year-old, high-rate-manure treatments produced similar cumulative net N mineralization as urea fertilizer; whereas the 1-year-old, high-rate manure treatment provided nearly 1.5-fold more N than either group. With appropriate manure application rates and attention to residual N and timing of sugarbeet planting, growers can best exploit the N mineralized from manure, while simultaneously maximizing sugar yields and profits.

1. Introduction

An estimated 20 million Mg manure is produced annually by the 9-million-cow US dairy herd. The regional dairy center in southern Idaho comprises 5.6% of the US total dairy herd and produces approximately 1.11 million Mg manure annually. In Idaho, much of the dairy manure is soil applied to supply crop nutrients and as a means of rebuilding soil organic carbon. The latter is particularly important for eroded soils, which are common in this historically furrow irrigated region [1]. To maximize their use of manure and minimize losses of nitrogen (N) to the environment, growers need to know how much N becomes available to crops from manure applications [2]. In addition, as competition increases for cropland in the region, farmers who rent acreage can expand the pool of land available to them if they are willing to utilize manured ground.

This is particularly important for sugarbeet (*Beta vulgaris* L.) growers because yield and beet quality parameters, sugar, and brei nitrate concentration are sensitive to both insufficient N [3, 4] and excess soil N [5, 6]. In addition, sugarbeet tends to incorporate soil residual N preferentially over fertilizer N, that is, sugarbeet will utilize more soil residual N and less applied fertilizer N than corn or tomato crops [7]. Applying excess N fertilizer early in the season or applying an optimal N application after June can divert photosynthate sugars normally used for beet root growth and sucrose accumulation to excess top growth [8]. By contrast, multiple small feedings of N to the sugarbeet from May through July can increase sucrose accumulation in roots [9]. Early research showed a positive influence of manure on beet yield and sucrose concentration [3, 5]. Still, planting sugarbeet in recently manured fields is not always recommended because N availability from the manure is not well quantified and is believed to occur too late in the season to improve yield and quality [10]. However, Lentz et al. [11] reported that (1) peak net N mineralization in manure-amended, irrigated soils coincided with maximum N uptake by beet and (2) first-year manure applications ≤20 Mg ha^{-1} (dry wt.) had no significant adverse effect on beet yield or quality.

Much of the N in dairy manure is in the organic form and only becomes available for uptake by crops via the time-dependent microbial-mediated process of mineralization.

Several studies have examined crop N uptake after multiple dairy manure applications, for barley (*Hordeum vulgare* L.) [12–14], corn (*Zea mays* L.) [15], wheat (*Triticum aestivum* L.) [16], and orchard grass (*Dactylis glomerata* L.) [17], or in the first year after a single manure application, for corn [18, 19], sugarbeet [11], and orchard grass (*Dactylis glomerata* L.) [17]. Relative to the total N applied in dairy manure, N recovery by corn, sugarbeet, and orchard grass in the first year after a single application ranged from −5 to 40% and averaged 21% [11, 17–19]. Crop N uptake from dairy manure amendments is influenced by type of crop [15], manure characteristics [20], organic amendment history [21], soil and location factors [18, 22, 23], application timing [12], and cropping management [24].

Far fewer studies have assessed N uptake by crops two and three or more years after a single manure application. For corn, the crop N recovery in the 2nd year after manure application was reported to be 9% by Klausner et al. [25], 8 to 15% by Ma et al. [15], and 15% by Eghball and Power [19], and N recovery for corn in years 3 through 4 was reported by Klausner et al. [25], being 2 or 3%. Similar studies for sugarbeet are lacking. One of the difficulties encountered when measuring crop N recovery from a manure application in successive years is the obfuscation caused by climatic variations between years [11]. Our objective was to (1) determine the effect of a single dairy manure application on sugarbeet yields and quality, N uptake, and N recovery for one, two, and three years after applying manure to a calcareous, irrigated, southern Idaho soil, and (2) employ an experimental approach that would reduce the confounding effects of climate between years.

2. Materials and Methods

We conducted the experiment at a site located 1.7 km southwest of Kimberly, ID (42E 31.12′N, 114E 22.47′W, elevation of 1190 m). The field plots were prepared in Portneuf silt loam soils (coarse silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid). The experimental site had a history of maznure applications, receiving 40 to 75 Mg ha^{-1} dry wt. every 3 yr between 1969 and 1986. In 1991 the uppermost 0.3 m (Ap horizon) of the Portneuf silt loam's profile was removed to expose the underlying Bk horizon and simulate an eroded profile [26]. For noneroded soil, the Ap horizon was left undisturbed. The site last received manure in 1994, 10 yrs before field plot preparations began for the current study. The eroded Portneuf soil profile is deep and calcareous, with textures ranging from silt loam to very fine sandy loam. Its surface soil (0 to 15 cm), that is, the Bk horizon, is a silt loam and contains on average 184 g kg^{-1} clay, 609 g kg^{-1} silt, 207 g kg^{-1} sand, has a pH of 7.8 (H$_2$O saturated paste), electrical conductivity (EC) of 0.08 S m^{-1}, and includes 4.1 mg kg^{-1} organic carbon, and 221 mg kg^{-1} calcium carbonate equivalent. A silica and calcium carbonate-cemented horizon (20–60% cementation) occurs between depths of 33 to 130 cm in the eroded Portneuf. The soil has a mean cation exchange capacity of 190 mmol$_c$ kg^{-1} and exchangeable sodium percentage of 1.5.

2.1. Experimental Design. Comparing sugarbeet yield and N uptake from a soil in years following a one-time manure application is problematic. Comparisons between annual sugarbeet measurements would be influenced not only by the treatment, but also by pest problems related to the continuous beet plantings and by climatic factors, which vary from year to year. To limit the effect of these confounding factors, we applied manure treatments at a 1x rate (average bulk application rate of 21.7 Mg ha^{-1} dry wt. or 0.31 Mg total N ha^{-1}), and a nominal 3x rate (average bulk application of 68.9 Mg ha^{-1} dry wt. or 0.97 Mg total N ha^{-1}) once only to a different set of field plots in the fall of each year 2004, 2005, and 2006. Thus, when sugarbeet was grown in 2007, the field plots included a set of two manure-rate treatments that were 1, 2, or 3 years old and were exposed to the same climatic conditions.

The experimental design was a randomized complete block with nine treatments and 4 replicates (Table 1). The experiment included the six manure treatments, with a manure-1x (m1) and manure-3x (m3) applied once to different plots of "eroded" Portneuf silt loam in 2004, 2005, and 2006. Three no-manure treatments were also included, urea fertilized (Fert) and control (no fertilizer or manure) treatments on eroded Portneuf soil, and a fertilized (urea) treatment on noneroded Portneuf soil (NE-Fert). No inorganic N fertilizer was applied to manure treatments. The Fert and NE-Fert treatments received 135 kg N ha^{-1} as urea-N, based on a sugarbeet yield goal of 63 Mg ha^{-1} [27] and a spring preplant soil test, which determined residual inorganic N present in the root zone (0–90 cm). The manure-1x application rate was a commonly applied rate in the region. At application time, we estimated the m1 manure would provide an average 107 kg N ha^{-1} to crops in the first year after application, based upon earlier reports that 32% of total manure N was available to crops in the first year [28]. Since a soil test indicated that no P or K fertilizer was needed on our site, we applied none. Plots were 9.1 m wide × 21.3 m long and accommodated 16 rows of beets.

For each year that manure treatments were applied, we obtained solid dairy cattle (*Bos* species) manure that had been stockpiled at a local dairy through the summer. The manure's average total C concentration (standard error) was 217 g kg^{-1} (58 g kg^{-1}), total N was 14.1 g kg^{-1} (2.6 g kg^{-1}), and C : N ratio was 15.9 (1.5).

2.2. Field Operations. Manure was applied to designated plots on 18 Nov. 2004, 22 Dec. 2005, and 19 Oct. 2006 using a commercial spreader truck equipped with rooster-comb beaters. Two to four 0.15 m^2 trays were randomly placed in each plot prior to spreading to quantify application rate. The manure collected in each tray was weighed, mixed, subsampled for moisture, C, and N analyses, and then returned to the soil surface from which it had been collected. The field was disked to a depth of 0.1 m within 48 hours of manure application. Plots were not fertilized in 2005 prior to planting spring barley. Barley was harvested in mid-July 2005. In fall 2005 prior to manure application, surface residue was burned to destroy weedy growth that had occurred after harvest.

TABLE 1: Description of treatments.

Treatment name	Treatment ID	Soil type	Added N source	Bulk applic. rate, dry wt. Mg ha^{-1}	Year of application[†]	Treatment age (y) at time of measurement
Noneroded fertilizer	NE-Fert	Noneroded	Urea	0.29	Each year	1
Control	Control	Eroded	None	0	N/A	1
Fertilizer	Fert	Eroded	Urea	0.29	Each year	1
Manure-1x						
2006	m1-y1	Eroded	Dairy manure	17.4	2006	1
2005	m1-y2	Eroded	Dairy manure	32.5	2005	2
2004	m1-y3	Eroded	Dairy manure	23.0	2004	3
Manure-3x						
2006	m3-y1	Eroded	Dairy manure	56.7	2006	1
2005	m3-y2	Eroded	Dairy manure	78.4	2005	2
2004	m3-y3	Eroded	Dairy manure	71.7	2004	3

[†] All fertilizer was applied in spring 2007 while all manure was applied in fall of the year shown.

In March 2006 soil samples were taken from plots at 0-to-30 cm and 30-to-60 cm depths and analyzed for soil N, P, and K (described below). Levels of P and K in the soils were adequate for small grain. On 13 Apr. 2006 the Fert and NE-Fert treatments received 134 kg N ha^{-1} as urea via hand-held spreader, while the control and manure plots received none. The field was disked to 0.1 m depth and roller-harrowed prior to planting barley in late April 2006. Barley residue and volunteer growth was burned on 13 Oct. 2006 before manure was applied to the designated plots.

On 15 Mar. 2007 soil samples were collected from plots in 30 cm increments down to 90 cm. We applied urea to the Fert and NE-Fert treatments and immediately incorporated the material with a roller harrow. Sugarbeet seed was planted (cv. BETA 4023R) on 20 Apr. 2007 in rows 0.56 m apart, with an in-row spacing of 55 mm and later thinned (30 May 2007) to a population of 117,000 plants ha^{-1} (manufacturer or trade names are included for the readers' benefit. The USDA-ARS neither endorses nor recommends such products). Insect control was accomplished using a Poncho seed treatment (CropScience LP, Research Triangle Park, NC, USA). Standard commercial procedures were used to control weeds and diseases. A single cultivation was performed on 26 June 2007. Irrigation through the growing season was supplied via sprinkler to meet the crop's evapotranspiration requirements. The beet crop was harvested on 10 Oct. 2007. Meteorological data required to calculate crop evapotranspiration (ET) were acquired from a weather station located 5.6 km northeast of the experimental plots. A rain gauge located near the field plot measured growing season precipitation. Crop ET was estimated from the maximum reference ET calculated using the Kimberly-Penman ET model [29], adjusted with the appropriate daily crop coefficient. Mean monthly air temperature, and total monthly precipitation, and irrigation during the 36-month study (including the plot preparation period, Fall, 2004 through 2006, and 2007 growing season) are reported in Figure 1.
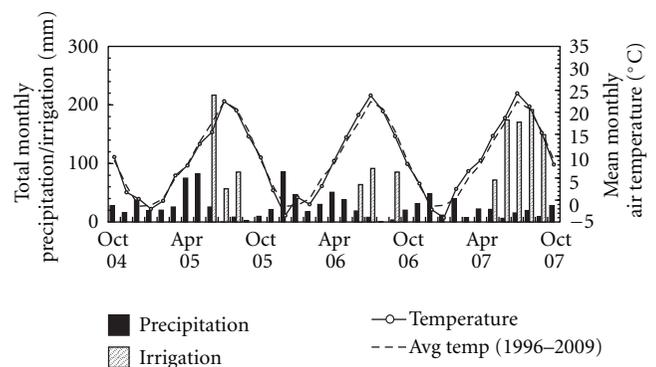

FIGURE 1: Total monthly precipitation and irrigation amounts, and mean monthly air temperature at the study site from fall 2004, when the first manure treatment was applied, through the 2007 growing season, when sugarbeet was planted on the experimental plots.

2.3. Sampling and Analyses. We measured N uptake in sugarbeet four times (1 June, 13 July, 20 Aug., and 27 Sep.) during the 2007 growing season by sampling total biomass of plant tops (aboveground tissue) and roots from 2 m of two adjacent rows (4 m total). The shredded sugarbeet roots and other aboveground plant tissue were dried at 65°C for dry matter determination. After grinding the dried tissue in a Thomas Wiley mill (Swedesboro, NJ) to pass an 865 μm screen, its total-N concentration was determined on a Thermo-Finnigan FlashEA1112 CNS analyzer (CE Elantech Inc., Lakewood, NJ, USA).

Sugarbeet yields were determined on 10 Oct. 2007 from two samples in each plot, each consisting of two adjacent 7.6 m long rows. Beet root subsamples collected for each of the two plot samples were analyzed for soil tare, as well as quality factors such as brei nitrate, brei conductivity, and sugar concentration, by the Amalgamated Sugar Company laboratory (Paul, ID, USA). Plot values were computed as

the arithmetic mean of the two samples. The projected gross margin for each plot was computed as gross revenue minus operating costs. The gross revenue was calculated as the product of beet yield (tons, wet wt.) and the 2007 grower beet payment, which varied from \$33.47 to \$39.23 per ton of beets (wet wt.) depending on beet sugar percentage. Operating costs [30] were assumed equal for all treatments except for differences related to fertilizer and manure application. Manure costs included only transport and spreading fees based on a 3.2 km one-way haul distance. Manure application costs were amortized across two years, hence the manure cost in the 3rd year after application was zero. Costs associated with annual fertilizer treatments included the price of product and its application.

A buried bag technique [31] was used to measure net N mineralization in plot soils during the 2007 growing season. Briefly, three 5.7 cm diameter soil cores, 0-to-30 cm deep were collected on 25 Apr. 2007 in each plot (one from three of the plot's four quadrants), composited, and passed through a 0.4 cm screen. A subsample of the composited soil was collected to determine baseline (or initial) inorganic N and soil water content. The remaining soil was placed in 10 μm thick, 5 cm diam. polyethylene tubes sealed on one end. After being filled, the tubes were sealed on the remaining end, resulting in three 30 cm long soil columns that were inserted into the sample holes created previously. The bag's polyethylene film was only slightly permeable to water vapor but allowed good gas exchange between the enclosed soil and that surrounding it [31, 32]. A single bag was pulled from each plot on 15 June, 1 Aug., and 2 Oct. 2007. The net N mineralization during the period between burial and retrieval was calculated by subtracting the baseline inorganic N concentration (NO_3-N + NH_4-N) of the initial soil (collected 25 Apr.) from that of the retrieved bag. A positive difference indicated net N mineralization, while a negative value indicated net N immobilization during the period. We measured net N mineralization using buried bags for 25 Apr. to 15 June, 15 June to 1 Aug., and 1 Aug. to 2 Oct. The latter two period values were computed by difference relative to the previously retrieved buried bag sample. In addition, we estimated the net N mineralization in the not-yet-planted plots from 15 Mar. to 25 Apr. as the difference in soil inorganic N concentration (0–30 cm) between the two dates. We reported the net N mineralized as mg N kg^{-1} soil. Cumulative available soil N (0-to-30 cm depth) during the growing season was computed as the sum of the initial soil inorganic N present on 15 Mar., added fertilizer N (if any), and net N mineralized across the four periods.

The March 2006 and 2007 field soil samples and buried bag soil samples were air dried at 35°C and ground to pass a 2 mm screen. Soil N was extracted using a 2 M KCl solution. Within 6 h of extraction, the NO_3-N concentration in each extract was determined using an automated flow injection analyzer (Lachat Instruments, Loveland, CO, USA) after cadmium reduction (Method 12-107-04-1-B) while NH_4-N concentration was determined using a salicylate-hypochlorite method (Method 12-107-06-2-A). The soil's inorganic N concentration was calculated as the sum of the NO_3-N and NH_4-N concentrations (mg N kg^{-1} of dry soil). Bicarbonate extractable P [33] and exchangeable K [34] (except without

the addition of charcoal) were determined on field soil samples using ICP-OES. Manure C and N concentrations were determined on a freeze-dried sample with the CNS analyzer described above.

2.4. Statistical Analysis. Crop yield, biomass, N uptake, and quality factors for sugarbeet (brei nitrate, brei conductivity) were examined separately for each reporting interval via analysis of variance (ANOVA), PROC Mixed [35]. The statistical model included treatment as the fixed effect and block as the random effect. Treatment means were separated using the Tukey option [35]. We also included several single-degree-of-freedom orthogonal contrasts in the analysis. These included up to five class comparisons, where a class represents a combination of treatments: (1) no-manure versus manure treatments, where the no-manure class is control + Fert + NE-Fert and manure is m1 + m3; (2) manure-1x versus manure-3x treatments, averaged across all years; (3) manure-1x versus manure-3x treatments for years 2 and 3 only; (4) manure only treatments (m1 + m3) in year-1 versus years 2 and 3; (5) m1-y1 + m3-y1 + m3-y2 versus NE-Fert + Fert. The last contrast (number 5) tested the hypothesis that, relative to fertilizer applications, the effect of manure on the crop was influenced by the interaction between the factors, manure rate and age of application. Since the manure-1x added less C and N to the soil, its influence on the crop would diminish more rapidly than the manure-3x applications. All analyses were conducted using a $P = 0.05$ significance level. An identical statistical approach was used to analyze treatment effects on cumulative available soil N.

Since the experiment was conducted at a single location, findings pertain principally to that location. With judicious foresight, however, inferences made and conclusions drawn may apply to other locations with similar climatic conditions and crop management practices.

3. Results and Discussion

Meteorological data presented in Figure 1 portray the climatic conditions that prevailed during the years when the experimental plots were being developed and for 2007, the year that sugarbeet was grown on the site. The 2007 growing season was warmer than average, specifically during the February–July period, which was on average 1.5°C warmer than the 1996-to-2009 mean. The plots received 175 mm of annual rainfall in 2007, or 70% of the 1996-to-2009 mean value. The increased early-summer heat units coupled with abundant irrigation water supplies and the delay of hard frost until after October (instead of late September) contributed to near optimal 2007 sugarbeet yields in southern Idaho [36].

3.1. Sugarbeet Biomass and N Uptake. Several treatment effects were significant for the sugarbeet cumulative biomass (Table 2) and N uptake (Table 3) within each measurement period. The contrast tests identified several relationships with respect to treatment classes. First, the no-manure and manure treatments on the whole produced similar cumulative biomass and N uptake in sugarbeet tops, roots, and whole

TABLE 2: The influence of treatment on the total cumulative biomass for 2007 sugarbeet plant components. Table gives P values for treatment effects, and single-degree-of-freedom orthogonal comparisons derived from an analysis of variance.

Source of variation	Accumulated sugarbeet biomass											
	Tops				Roots				Whole plant			
	1 June	13 July	20 Aug	27 Sept	1 June	13 July	20 Aug	27 Sept	1 June	13 July	20 Aug	27 Sept
							P values					
Treatment (TRT)	**	***	***	**	0.36	**	***	**	0.02	***	***	***
Orthogonal contrasts[†]												
No manure versus manure	0.64	0.26	0.7	0.5	0.9	0.6	0.8	0.25	0.7	0.4	0.9	0.23
Man: m1 versus m3	**	**	***	0.06	**	0.07	***	0.13	**	*	***	*
Man: y1 versus y2 & y3	0.9	***	**	0.29	0.82	**	**	*	0.9	***	**	*
Man y2 & y3: m1 versus m3	**	**	***	*	**	*	***	*	**	**	***	**

[†] No manure: NEFert + control + Fert; Man: manure = m1 + m3 where m1: manure-1x; m3: manure-3x; y1, y2, y3: fall manure applied 1, 2, and 3 years in the past, respectively.
*$P < 0.05$,**$P < 0.01$,***$P < 0.001$.

TABLE 3: The influence of treatment on N uptake in 2007 sugarbeet plant components. Table gives P values for treatment effects, and single-degree-of-freedom orthogonal comparisons derived from an analysis of variance.

Source of variation	N uptake by beet biomass components											
	Tops				Roots				Whole plant			
	1 June	13 July	20 Aug	27 Sept	1 June	13 July	20 Aug	27 Sept	1 June	13 July	20 Aug	27 Sept
							P values					
Treatment (TRT)	*	***	***	***	*	**	***	***	*	***	***	***
Orthogonal contrasts[†]												
No manure versus manure	0.26	0.25	0.78	0.52	0.38	0.35	0.75	0.7	0.65	0.26	0.9	0.6
Man-1x versus Man-3x	***	*	***	*	**	0.08	***	**	***	*	***	*
Man: y1 versus y2 & y3	0.9	***	*	0.15	0.87	***	**	0.11	0.9	***	*	0.09
Man y2 & y3: m1 versus m3	**	**	***	*	*	0.06	***	**	**	**	***	**

[†] No manure: NEFert + control + Fert; Man: manure = m1 + m3 where m1: manure-1x; m3: manure-3x; y1, y2, y3: fall manure applied 1, 2, and 3 years in the past, respectively.
*$P < 0.05$, **$P < 0.01$,***$P < 0.001$.

plants. This result was partly due to substantial variability among treatment responses within each class, for example, the control treatment values were about half those of other no-manure treatments, and the m1-y3 values were about half that of other manure treatments (Table 4). However, the result shown in Table 3 suggests that no-manure treatments provided similar quantities of soil N to sugarbeet on average as did the manure treatments. As a consequence, season-long, total biomass production, and N uptake were similar between the groups (Table 4). See the discussion later in this section.

Second, compared to the manure-1x treatments, the manure-3x in general resulted in 1.12x greater season-long cumulative biomass production and 1.37x greater N uptake (Table 4). In addition, the relative difference between manure-3x and manure-1x responses was greater in the 2nd and 3rd years after manure application (i.e., comparing results of the m1 versus m3 contrast in y2, y3 with that of the m1 versus m3 contrast averaged across all years in Table 4). The disproportionately smaller increase in both

biomass and N uptake in response to a tripling of the manure rate indicated that the manure-3x treatment supplied excess N, and/or crop utilization of manure N decreased with increasing manure application [37]. As time since application increased (comparing the m1 versus m3 contrast in y2, y3), the N supplied by manure-1x apparently was less able to support beet growth than the manure-3x, causing a greater difference in biomass production and N uptake between the manure rate classes.

Third, the year of manure application affected total sugarbeet biomass and N uptake more during the early-June to mid-July period than at season's end (Tables 2 and 3). By 13 July 2007 the y1 manure treatments produced 1.4x greater sugarbeet biomass with 1.7x greater N uptake than the average for y2 and y3 manure treatments (Table 4). These disparities declined from that date onward. Thus by season's end, the sugarbeet in 2-year-old and 3-year-old manure plots had largely caught up to those of the 1-year-old manure treatments, such that differences were no longer significant. Thus y1 manure treatments generally provided greater

TABLE 4: Accumulated total biomass and N uptake in sugarbeet (tops and roots) at four times during the 2007 growing season.

Treatment[†]	Biomass				N uptake			
	1 June	13 July	20 Aug	27 Sept	1 June	13 July	20 Aug	27 Sept
	Mg ha^{-1} (dry wt.)				Kg ha^{-1}			
No manure								
NE-Fert	0.15a[‡]	7.3ab	17.5a	25.0bc	6.57a	124.6ab	183.8ab	257.4ab
Control	0.06b	4.2b	10.4c	17.1c	2.81b	52.7b	103.1b	152.5b
Fert	0.10ab	8.4a	20.9a	30.6a	4.85ab	164.6a	288.4a	383.3a
Manure-1x								
m1-y1	0.07ab	8.0a	18.2ab	25.3ab	3.18ab	140.3a	201.6ab	268.4ab
m1-y2	0.08ab	4.8b	12.1bc	21.8ab	3.6ab	62.6b	119.4b	211.0b
m1-y3	0.07b	4.1b	11.7bc	17.3c	2.98ab	56.4ab	123.2b	151.4b
Manure-3x								
m3-y1	0.13ab	7.6a	19.6a	24.8abc	5.89ab	140.5a	251.8a	300.2ab
m3-y2	0.13ab	7.0ab	18.4a	25.3ab	5.86ab	118.6ab	236.8a	315.4ab
m3-y3	0.13ab	6.0ab	17.3a	22.7b	5.44ab	92.4ab	211.4a	252.6ab
Treatment classes for orthogonal contrasts								
No manure	0.10	6.6	16.2	24.1	4.7	114.0	189.4	262.9
Manure	0.10	6.3	16.2	22.8	4.5	101.8	191.1	246.2
Manure-1x	0.07b	5.6b	14.0b	21.5b	3.3b	86.4b	146.9b	207.6b
Manure-3x	0.13a	6.9a	18.4a	24.1a	5.7a	117.2a	235.2a	284.8a
Manure Year-1	0.10	7.8a	18.9a	24.8	4.5	140.4	227.8a	273.4
Manure Year 2 & 3	0.10	5.5b	14.9b	21.8	4.5	82.5	172.7b	232.6
Year 2 & 3: m1	0.08b	4.5b	11.9b	19.6b	3.3b	59.5b	121.3b	181.2b
Year 2 & 3: m3	0.13a	6.5a	17.85a	24.0a	5.65a	105.5a	224.1a	284.0a

[†] NE-Fert: noneroded fertilizer (all other treatments on eroded soil); m1: manure-1x; m3: Manure-3x; y1, y2, y3: fall manure applied 1, 2, and 3 years in the past, respectively; manure: m1 + m3; no manure: NEFert + Control + Fert.
[‡] Within a given plant component and sample date, treatment means followed by the same lower case letter are not significantly different ($P < 0.05$). Not displayed if effect was not significant in the ANOVA (Table 5).

available soil N than y2 and y3 manure during the June-July sugarbeet growth period, but in later months, either soil N availability declined or some factor interfered with the growth and N uptake in y1 manure beets. We hypothesize that the former was the case, resulting from increased N immobilization for y1 beets during the June and July. The release of abundant, readily metabolized C from manure in y1 may have stimulated microbial growth [38, 39]. Lentz et al. [11] showed that immobilization in manure-amended soils was greater in y1 after application compared to y2 and y3 (see later discussion).

Fourth, when y1 manure treatments as a class were compared with y2 and y3 manure treatments, y1 had 1.14x greater season-long total biomass production and 1.18x greater total N uptake (Table 4). Within a manure treatment and measurement period, however, the magnitude and significance of the differences between y1 manure treatments and y2 or y3 manure treatments were greater and more common for manure-1x than for manure-3x treatments (Table 4). This suggests that manure-3x treatments, regardless of age, provided adequate N for the crop. Furthermore, the m1-y1 treatment resulted in similar sugarbeet biomass production and N uptake as any manure-3x treatment no

matter the year applied. This indicates that the m1-y1 treatment also provided adequate N for the sugarbeet.

The Fert and NE-Fert treatments consistently produced greater season-long crop biomass and N uptake than the control, although the difference was significant only for Fert after 1 June (Table 4, Figure 2), reflecting the greater N availability in the two fertilized treatments compared to the control. The NE-Fert produced greater sugarbeet biomass and N uptake than Fert on 1 June, day of year (DOY) 152, whereas the opposite tendency was observed at later dates. This likely resulted because seedlings emerged later and stand counts were 15% smaller (after thinning) in Fert plots relative to NE-Fert (data not presented). Later in the season, the lesser plant density for Fert compared to NE-Fert and other treatments (after thinning) may have rendered it less susceptible to a powdery mildew outbreak [40], which was identified in the field in midsummer and subsequently treated with fungicide and sulfur.

3.2. Sugarbeet Yield, Quality, and Profitability. Clean beet yields for all treatments ranged from 56.4 to 101.1 Mg ha^{-1} and averaged 83.0 Mg ha^{-1} (Table 5). These yields compare favorably with the average 2007 sugarbeet yield for southern
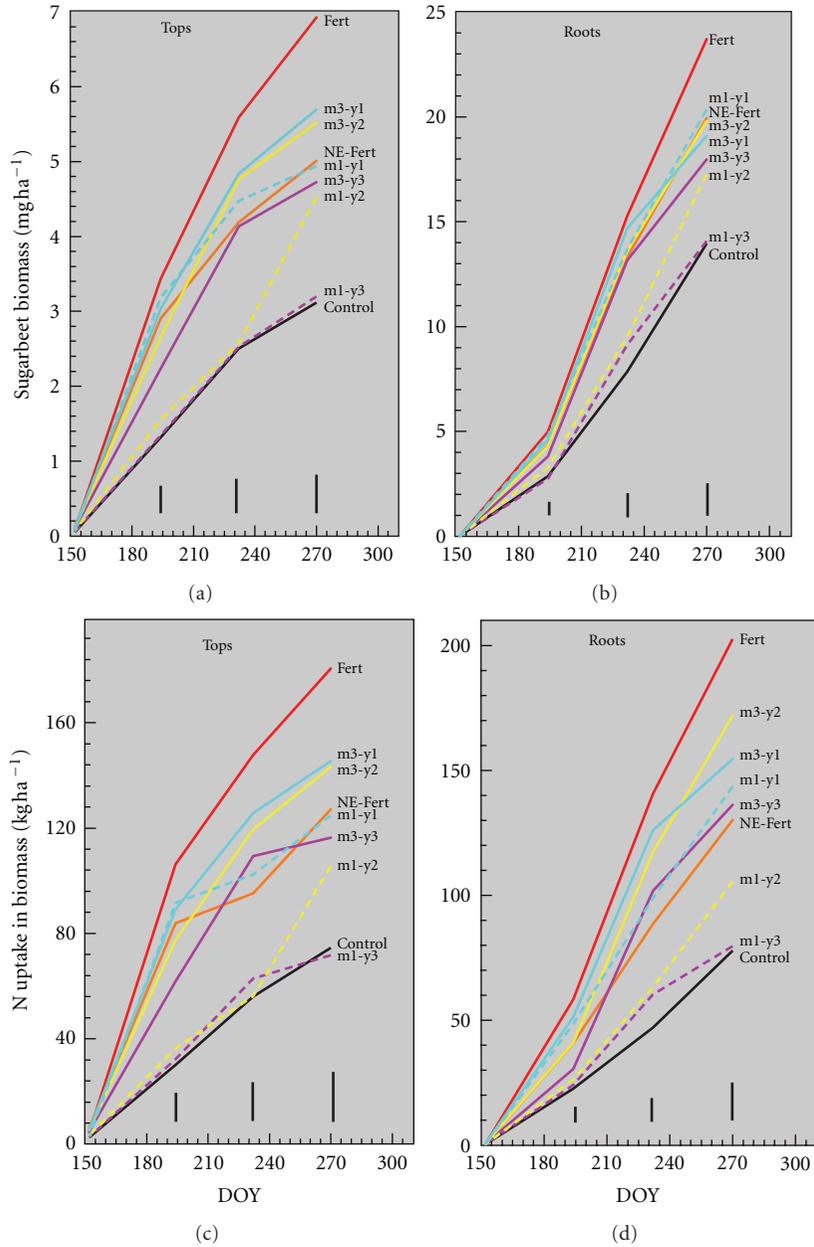
Figure 2: The effect of treatments on biomass accumulation in sugarbeet tops, that is, aboveground tissue (a) and root (b) components, and on N uptake in sugarbeet tops (c) and roots (d) in 2007. (Measured on dates (DOY) 1 June (152), 13 July (194), 20 Aug. (232), and 27 Sep. (270). Bar length represents the mean standard error ($n = 4$) for the 9 treatments at the given measurement date.

Idaho growers, 76.6 Mg ha^{-1} [36]. Sugarbeet yield and quality were affected by treatments, whether considered individually or when compared as classes (contrasts). The m1-y1, m3-y1, and m3-y2 treatments produced 1.3 to 1.8 times greater root yields than NE-Fert, control, m1-y2, and m1-y3 treatments (Table 5). Contrast tests showed that yields increased about 1.2-fold when (1) manure instead of fertilizer or no amendment was added to soil; (2) the manure amendment rate was increased from 1x to 3x; (3) sugarbeet was planted in the first year after fall manure application instead of waiting until the 2nd or 3rd year after application (Table 5).

Sugar concentration in beets ranged from 15.6 to 17.7% and averaged 16.7% (Table 5) with concentrations being generally greater in lower-yielding treatments, as expected. Our study's mean sugar concentration was nearly equivalent to the average sugar concentration obtained by southern Idaho growers in 2007, that is, 16.8% [36]. The NE-Fert and control treatments produced greater beet sugar concentrations than Fert, m3-y2, and m3-y3 treatments (mean 17.6 versus 16.0). Beet sugar concentrations decreased slightly (3–6% on average) when (1) manure was applied instead of fertilizer or no amendment; (2) manure application was

TABLE 5: Treatment and orthogonal contrast mean values for sugarbeet yield, quality, and gross margin parameters.

Treatment[†]	Clean beet root yield[‡]	Sugar	Est. Recov. sugar[‡]	Brei nitrate	Brei conductivity	Gross margin[§]
	Mg ha^{-1}	%	Mg ha^{-1}	mg kg^{-1}	dS m^{-1}	$US ha^{-1}
No manure						
NE-Fert	75.2c[§]	17.7a	11.6ab	59.8c	0.58d	979bc
Control	56.4c	17.6a	8.5b	106.8c	0.68cd	292 d
Fert	90.2ab	16.4b	12.3ab	187.3bc	0.88bc	1272ab
Manure-1x						
m1-y1	101.0a	16.7ab	14.0a	147.1bc	0.91b	1884a
m1-y2	72.8bc	16.8ab	10.4ab	143.6bc	0.77bcd	731bcd
m1-y3	64.5c	16.8ab	9.1b	185.4bc	0.81bc	484cd
Manure-3x						
m3-y1	97.7a	16.8ab	13.6a	149.1bc	0.95b	1676a
m3-y2	101.1a	16.0b	13.2a	259.6ab	0.96b	1510ab
m3-y3	88.5ab	15.6b	11.2ab	308.5a	1.02a	1138b
Treatment classes for contrasts						
No manure	73.9b	17.2a	10.8	118.0b	0.71a	848b
Manure	87.6a	16.5b	11.9	198.9a	0.90b	1237a
Manure-1x	79.4b	16.8a	11.2b	158.7b	0.83b	1033b
Manure-3x	95.8a	16.1b	12.7a	239.1a	0.98a	1441a
Manure y1	99.4a	16.8a	13.8a	148.1b	0.93	1780a
Manure y2 & y3	81.7b	16.3b	11.0b	224.3a	0.89	966b
Year 2 & 3: m1	68.7b	16.8a	9.8b	164.5b	0.79b	607b
Year 2 & 3: m3	94.8a	15.8b	12.2a	284.1a	0.99a	1324a
m1-y1, m3-y1, m3-y2	99.9a	16.5b	13.6a	185.3	0.9a	1690a
NE-Fert, Fert	82.7b	17.1a	12.0b	123.6	0.7b	1126b

[†] NE-Fert: noneroded fertilizer (all other treatments on eroded soil); m1: manure-1x; m3: manure-3x; y1, y2, y3: fall manure applied 1, 2, and 3 years in the past, respectively; manure: m1 + m3; no manure: NEFert + Control + Fert.
[‡] Clean yield: yield minus soil tare; Est. Recov. Sugar: estimated amount of sugar extractable from beets per unit area.
[§] Gross margin: gross revenue minus operating costs.
[¶] For a given yield or quality parameter, treatment means or means for individual orthogonal contrasts followed by the same lower case letter are not significantly different ($P < 0.05$). Not displayed if effect was not significant in the ANOVA.

increased from 1x to 3x; or (3) sugarbeet was planted in the first year after fall manure application instead of waiting until the 2nd or 3rd year after application. These results are consistent with the concept that increasing N availability decreases beet root sugar concentration [8, 9].

Increased nitrate and soluble impurity (conductivity) concentrations in sugarbeet brei (fresh macerated beet root) are associated with a decrease in the quantity of sugar recovered from the sugarbeet and increased sugar extraction costs [4, 27]. When the manure application rate increased from 1x to 3x, brei nitrate increased an average 1.6-fold (from 158.7 to 239 mg kg^{-1}) and conductivity increased 1.2-fold on average. Brei conductivity of manure treatments in year 1 did not differ from the mean value for year 2 and year 3. The m3-y3 treatment produced the greatest brei nitrate concentrations in beet roots, 309 mg kg^{-1}. While this value exceeded the 250 mg kg^{-1} target level recommended for southern Idaho [27], it was still well below the mean value for the 2007, southcentral Idaho sugarbeet crop, 351 mg kg^{-1} (S. Camp, Amalgamated Sugar Co., personal communication, 2010).

The control produced the least estimated recoverable sugar, 8.5 Mg ha^{-1} (Table 5). The treatments m1-y1, m3-y1, and m3-y2 produced the greatest estimated recoverable sugar values (mean 13.6 Mg ha^{-1}), which were 1.5x greater than that of the two least performing treatments, m1-y3 and control (mean 8.8 Mg ha^{-1}), and 1.1x that of the two fertilizer treatments (mean 12.0 Mg ha^{-1}). In addition, the estimated recoverable sugar in beets increased 1.22-fold, on average, when manure application was increased from the 1x to 3x rate or sugarbeet was planted in the first year after fall manure application instead of waiting until the 2nd or 3rd year after application.

The gross margins listed in Table 5 integrate treatment effects on beet yield and quality and fertilizer or manure costs, and provide a measure of treatment effects on profitability. An examination of individual manure treatments revealed that all except m1-y3 produced similar or greater gross margins than either the Fert or NE-Fert. Contrast tests showed that 1) the average gross margin for m1-y1, m3-y1, and m3-y2 manure treatments was 1.5-fold greater

TABLE 6: Treatment and contrast class mean values for soil (0–30 cm) inorganic N concentrations in spring (before and after planting), cumulative net N mineralization, and cumulative available N during the growing season.

Treatment[†]	Soil N 15 Mar.	Soil N 25 Apr.	Cum. net N mineralized 25 Apr.–27 Sept.	Cum. available N 15 Mar.–27 Sept.
			mg kg^{-1}	
No manure				
NE-Fert	8.3b[‡]	39.0a	18.0bc	57.0bc
Control	10.9b	12.6b	14.6c	27.1d
Fert	8.9b	33.6a	19.6bc	62.8bc
Manure-1x				
m1-y1	13.5b	31.8a	32.8ab	64.6b
m1-y2	10.0b	17.9b	23.7bc	41.6c
m1-y3	8.3b	14.1b	22.5bc	36.7cd
Manure-3x				
m3-y1	24.1a	45.9a	41.4a	87.3a
m3-y2	12.7b	27.8ab	28.5bc	56.3bc
m3-y3	13.7b	28.7ab	29.1b	57.8bc
Treatment classes for contrasts				
No manure	9.4	28.4	17.1b	49.0b
Manure	13.7	27.7	29.7a	57.4a
Manure-1x	10.6	21.3b	26.3b	47.6b
Manure-3x	16.8	34.1a	32.9a	67.1a
Manure y1	18.8	38.9a	37.1a	76.0a
Manure y2 & y3	11.2	22.1b	26.0b	48.1b
Year 2 & 3: m1	9.2b	16.0b	23.1b	39.2b
Year 2 & 3: m3	13.2a	28.3a	28.8a	57.1a

[†]NE-Fert: noneroded fertilizer (all other treatments on eroded soil); m1: manure-1x; m3: manure-3x; y1, y2, y3: fall manure applied 1, 2, and 3 years in the past, respectively; manure: m1 + m3; No manure: NEFert + Control + Fert.

[‡]For a given yield or quality parameter, treatment means or means for individual orthogonal contrasts followed by the same lower case letter are not significantly different ($P < 0.05$). Not displayed if effect was not significant in the ANOVA.

than that for NE-fert and Fert treatments; 2) manure-3x treatments as a whole produced 1.4-fold greater gross margin than manure-1x treatments; 3) the mean gross margin for y1 manure treatment class was 1.8-fold greater than the y2 and y3 manure mean value; and 4) in the 2nd and 3rd year after manure application the manure-3x treatments on average resulted in a 2.2-fold greater gross margin than the manure-1x treatments.

Thus, fall manure applications 1 or 2 years prior to growing sugarbeet can potentially widen profit margins relative to conventional fertilizers applied preplant in the spring. While the m1-y1 manure treatment produced the greatest mean gross margin, use of greater manure application rates might be advisable. Manure quality often varies and the 1x rate leaves less margin for error. A greater application rate every two years, rather than one, halves application costs. Moreover, a high N-demand crop such as corn could be grown the year before sugarbeet to efficiently and profitably use the N mineralized in the first 12 months after the manure was applied [11]. On the other hand, mineralized N (as NO_3^-) could be leached below the sugarbeet's root zone before or during the beet growing season. Note that our

margin analysis does not account for extra costs that may arise due to manure use, for example, additional management costs associated with increased weed pressure.

The influence of increasing manure applications on sugarbeet yields and estimated recoverable sugar in year 1 were also investigated by Lentz et al. [11] in 2003 for similar soils in southern Idaho. Lentz et al. [11] reported that, in contrast to the results of this study, sugarbeet root yields and recoverable sugar decreased as manure application rates increased. This difference was likely due to less initial residual soil N and less C and total N in the manure used in the current study relative to those in 2003. In sum, these factors decreased the N available in the 2007 soils which in turn reduced the possibility that excessive N mineralized from manure amendments would limit beet yields and recoverable sugar values [2, 8].

3.3. N Mineralization and Availability. The contrast tests for the season-long (25 Apr. to 27 Sept.) cumulative net N mineralization (Table 6) established that (1) manure treatments taken as a class produced 1.7x greater N than no-manure treatments; (2) manure-3x treatments on average produced 1.3x greater N than manure-1x treatments; (3) N
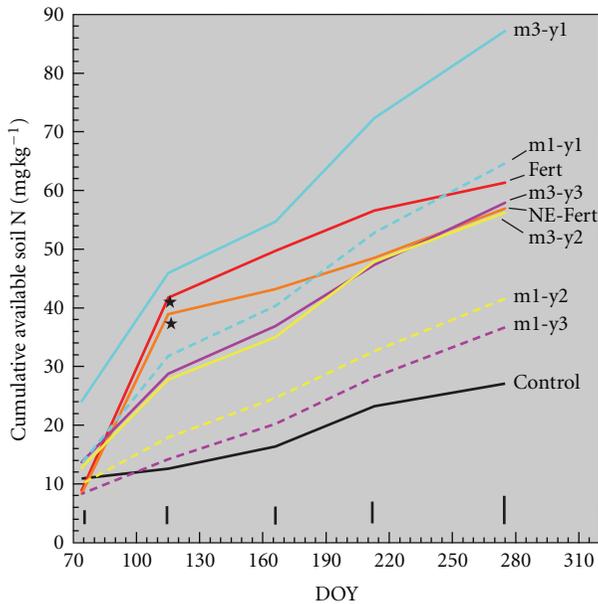
★ Includes added fertilizer N

FIGURE 3: Cumulative net soil N available through mineralization and any fertilizer addition in the 0-to-30 cm soil during the 2007 sugarbeet growing season (measured on dates (DOY) 15 Mar. (74), 25 Apr. (115), 15 June (166), 1 Aug. (213), and 2 Oct. (275). Bar length represents the mean standard error ($n = 4$) for the 9 treatments at the given measurement date.

mineralized from y1 manure treatments as a class was 1.4x greater than that for the y2 and y3 manure treatment class mean. Hence, the cumulative available soil N from manure amendments generally declined as application rate decreased and time since application increased (Table 6, Figure 3).

The net N mineralized in the uppermost 0.3 m soil profile during the growing season (25 Apr. to 27 Sept.) for year-1 manure treatments was 32.8 mg kg^{-1} for manure-1x, or 2.2 times the control value, and 41.4 mg kg^{-1} for manure-3x, or 2.8 times that of the control (Table 6). These net N mineralization values for the year-1 treatments were similar to those reported by Lentz et al. [11] for comparable treatments in 2003, that is, 32.6 (manure-1x) and 48.7 mg kg^{-1} (manure-3x). Net N mineralized during the growing season for year-2 and year-3 manure treatments was reduced an average 30% in comparison to year-1 manure (Table 6). Findings from the 2007 growing season showed that fertilizer and the m1-y1, m3-y2, and m3-y3 treatments supplied similar amounts of cumulative N. In contrast m3-y1 provided nearly 1.5x more N ($P < 0.0001$), and m1-y2 and m1-y3 provided 37% less N ($P < 0.0001$) than the mean fertilizer treatment value (Table 6, Figure 3). The control and m1-y3 treatments provided the least cumulative available soil N, produced the least biomass, and led to the least N being incorporated into crop tissue (Figures 2 and 3).

For manure treatments, mineralized N accumulated at a slower rate in the interval from 25 Apr. to 15 June (DOY 115 to 166) than for other intervals (revealed as a decrease

in slope in Figure 3). This slowing of the rate was most pronounced for the larger and more recent manure applications. This corroborates observations made by Lentz et al. [11], who described an identical phenomenon in their experiment conducted on similar soils at Kimberly, ID. The slowing rate of net N mineralization was likely due to immobilization of manure N that occurred after soils warmed during this early summer period. Mean soil temperatures at the 10 cm depth exceeded 21°C by mid-June (data not shown). Seasonal N mineralization data from an Ontario, Canada, experiment also showed a subtle dip in mineralization rate during this period, but the researchers described a more substantial decrease in N mineralization rate after DOY 227 [15]. The researchers attributed the substantial decreases to the release of carbonaceous root exudates and subsequent N immobilization [15]. Similar declines in N mineralization during the early summer period were reported for coastal Alabama soils amended with composted dairy manure [41].

The pattern of crop biomass accumulation and N-uptake in sugarbeet tops and roots (Figure 2) generally followed that of soil N availability (Figure 3). There were two exceptions. First, while Fert and NE-Fert treatments provided similar soil N, Fert produced substantially greater season-long crop biomass and N uptake than the NE-Fert (Figure 2, Table 4). This may be related to the differences in stand density and mildew pathology, as discussed previously. Second, though the net N mineralized for the m3 treatment was greater in y1 than for y2 or y3 (Figure 3), the extra N mineralized in y1 did not result in greater season-long crop N uptake (Figure 2, Table 4). This reveals that the N derived from the 3x manure (applied in the previous fall) was not utilized efficiently, presumably because it exceeded crop needs. Moreover, the excess soil mineral N in the 3x treatments was subject to leaching losses.

4. Conclusions

This study quantifies the effects of stock-piled dairy manure applications made 1, 2, or 3 years previously on sugarbeet. Results of this and a previous, related study [11] on calcareous, southern Idaho soil indicate that the influence of manure N applications on soil N availability, N uptake, and sugarbeet yield and quality was a function of residual inorganic soil N at the start of the growing season, the amount of Fall-applied manure added, and the year in which the manure was applied. A Fall manure application alone, when applied at an appropriate rate and planted to sugarbeet in either the first or second year after application provided adequate N nutrition for the production of a high quality sugarbeet crop. Furthermore, these manure treatments (m1-y1, m3-y1, and m3-y2) increased estimated recoverable sugar yields an average of 1.1-fold and increased gross margins an average of 1.5-fold relative to conventional fertilizer treatments. The increases in recoverable sugar and gross margins documented in this study are likely to vary from one site to another as a function of soil type, climate, and growing conditions. Our results illustrate nonetheless how proper manure management can increase sugarbeet yields and producer profit margins.

Abbreviations

Fert: Fertilizer on eroded soil
NE-Fert: Fertilizer on noneroded soils
EC: Electrical conductivity
y1, y2, y3: Fall manure applied 1, 2, and 3 years in the past, respectively.

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