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Nitrogen and Weed Management for Organic Sweet Corn Production on Loamy Sand

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ABSTRACT

Irrigated vegetable production dominates the landscape of the Central Sands region of Wisconsin, where sandy soil limits its nutrient and water retention. Sweet corn (*Zea mays* L. var. rugosa) was managed organically in 2011 and 2012 growing seasons to evaluate effects of organic N input and weed management with respect to sweet corn yield and soil N content. The first treatment factor was early season manure, including spring-seeded field pea (*Pisum sativum* L.) incorporated as a green manure cover crop, pelletized poultry manure, and no manure. The second treatment factor was weed management intensity. The last factor was varying N application rate, split applied as feather meal during the growing season. There was a positive yield response to feather meal in both years with yields reaching 18.6 and 21.5 Mg ha^{-1} in 2011 and 2012, respectively, with 224 and 112 kg N ha^{-1} feather meal application, respectively. Early season manure treatments did not clearly affect yields despite 90 kg N ha^{-1} applied as both manure types in 2012, and lower rates of 33 and 75 kg N ha^{-1} applied in 2011 as field pea and poultry manure, respectively. These results underscore the well-known potential for rapid nutrient loss on coarse soil and management challenges associated with asynchrony between organic N release and crop uptake. Weed management contributed to an interaction effect on yield, with early tillage potentially controlling weeds in both treatments. This study demonstrated benefits of in-season organic amendment use, though limited potential for early season application on loamy sand.

Core Ideas

- Feather meal is a viable organic nitrogen fertilizer for sweet corn on loamy sand.
- Pre-plant application of manures did not reduce optimum in-season N application rate.
- Irrigated organic sweet corn can produce yields comparable to those of conventional methods.

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Inconsistent timing of organic nutrient mineralization can make N availability a limiting factor in organically managed systems (Berry et al., 2002; Cassman et al., 2002; Dawson et al., 2008). Ideally, the mineralization of organic amendments would synchronize with crop demand for N over time (Diacono and Montemurro, 2010) as asynchronous N release and N uptake patterns will result in nitrate leaching, inefficiency, and yield loss (Gaskell and Smith, 2007; Cherr et al., 2006a). The challenge of N release timing is further exacerbated on sandy soil, which has poor nutrient and water retention (Olesen et al., 2009; Berntsen et al., 2006). Nitrate not recovered by crops can rapidly leach through the soil profile at a rate of 15 cm downward movement per day in sandy soil given 2.5 cm of total water (Endelman et al., 1974; Wolkowski et al., 1995). Bundy and Andraski (2005) calculated leaching losses to vary from 38 to 100 kg N ha^{-1} with a mineral fertilizer application rate of 190 kg N ha^{-1} with sweet corn grown at this study location. However, there is potential for organic amendment use on sandy soils because of slower mineralization or lower initial soil concentrations of ammonium or nitrate available to leach, as compared to mineral fertilizers. Improved understanding of organic amendment nutrient availability is required for organic production on sandy soils.

Animal manure is a viable organic amendment option for improved yields on sandy soil (Bitzer and Sims, 1988; Olesen et al., 2007; Wild et al., 2011). Pelletizing poultry manure increases ease of handling and application, and results in a product with more readily mineralizable N as compared to raw application, and a low C/N ratio, likely between 4 and 6 (Hadas et al., 1983). To further increase crop benefit, application of manure in combination with N fertilizer has been shown to reduce short-term leaching of mineral-N fertilizer and improve nitrogen use efficiency (NUE) in corn, due to immobilization of some mineral N through manure decomposition processes (Nyamangara et al., 2003).

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Abbreviations: AGB, aboveground biomass; AWB, aboveground weed biomass; DAP, days after planting; GDD, growing degree days; GrM, green manure; HARS, Hancock Agricultural Research Station; HI, harvest index; IE, interactive effect; INT, intense weed management; MOD, moderate weed management; NM, no manure; NOP, National Organic Program; NUE, nitrogen use efficiency; PAN, plant available nitrogen; PPM, pelletized poultry manure; SPAL, University of Wisconsin Soil and Plant Analysis Laboratory; WISP, Wisconsin irrigation scheduling program.

Feather meal is a poultry processing byproduct comprised of rendered feathers treated with heat and pressure to break strong disulfide bonds that stabilize keratin-N (Hadas and Kautsky, 1994). Feather meal has a relatively high N content (11–14% N) compared to other organic fertility amendments and is commonly available in a stable crumbled or powdered form with minimal odor. Feather meal is a good option for in-season split-application because it decomposes quickly (C/N ratio = 3.5), allowing for rapid N mineralization within the first week (30–50%) with a slower release lasting 8 wk or more (Hadas and Kautsky, 1994; Hartz and Johnstone, 2006).

Spring-seeded cover crops can take up nutrients that may be subject to spring leaching (Berry et al., 2002; Watson et al., 2002). Leguminous cover crops can provide organic N rapidly when incorporated as green manure, with 50% of total N released within 4 wk of incorporation and nearly all N released by 10 wk (Olesen et al., 2009; Sparkes et al., 2006; Stute and Posner, 1995). The potential for short-season leguminous cover crops as green manure has been demonstrated; cowpea (*Vinga unguiculata* L.) incorporated just 4 wk after planting had an effective rate of 30 kg N ha^{-1} in mint (*Mentha arvensis* L.) production on a sandy loam in India (Singh et al., 2010). In another study, winter pea grown for 6 wk accumulated almost 200 kg N ha^{-1}, producing a high yielding corn crop unresponsive to mineral N fertilizer application (Karpenstein-Machan and Stuelpnagel, 2000). Research has demonstrated the potential for green manure to supply sufficient N for sweet corn, producing yields comparable to those of conventional methods (Griffin et al., 2000; Cline and Silvernail, 2002). Further, varieties of pea (field pea, cowpea, Australian pea, and winter pea) have increased yields of various crops, reduced rate of fertilizer application, or both (Haynes et al., 1993; Burket et al., 1997; Karpenstein-Machan and Stuelpnagel, 2000). However, further evaluation of green manure use is necessary due to challenges with asynchronous N-availability and leaching, and wide variation in C/N ratio (Cline and Silvernail, 2002; Burket et al., 1997; Ranells and Wagger, 1996; Teasdale et al., 2008; Cassman et al., 2002). Short-term benefits of green manure use on sandy soil must alone justify usage because rapid decomposition of organic material on coarse soil limits potential for long-term benefits such as increased soil organic matter (Olesen et al., 2009; Cherr et al., 2006b).

Weeds can compete with crops by utilizing soil water and plant available nitrogen (PAN), thus competing with crops for these resources (Lindquist et al, 2010). Weeds are effectively managed with herbicides in conventional systems, but must be managed with preventative approaches in organic systems, such as cover cropping and rotation, as well as intensive in-season manual techniques (Smith et al., 2010; Watson et al., 2002; Sparkes et al., 2006). Shallow cultivation effectively manages weeds before corn emergence with minimal damage to the crop and soil structure (Colquhoun et al., 1999; Johnson et al., 2010). Hand weeding can also effectively control weeds, though only practical on a small scale (Johnson et al., 2010; Abouziena et al., 2007; Gomiero et al., 2011).

Improved understanding of N availability from organic amendments used on coarse soil is needed by growers interested in accessing the U.S. organic market. As of 2011, there were almost 13,000 organic farms covering more than 2 million U.S. hectares (USDA ERS, 2013a). Wisconsin has the second most certified organic farms of all U.S. states, making organic industry growth on the whole important for local economies (USDA ERS, 2013b). Wisconsin is also the second highest state in processing vegetable production and the third highest state in processing sweet corn production (USDA NASS, 2013). There is an opportunity to expand production of organically grown sweet corn in Wisconsin given improvements in organic N management.

The goal of this study was to evaluate organic N management practices on an irrigated loamy sand soil characteristic of processing vegetable production in Wisconsin. The main objectives were to determine the effects of early season manure applications, weed management intensity, feather meal application rate, and their interactions on yield, soil N concentrations, and weed populations. An additional objective, added after the 2012 growing season, was to evaluate the effect of irrigation on yield response to organic fertility sources.

MATERIALS AND METHODS

Experimental Site, Experimental Design, and Cultural Practices

A 2-yr field experiment was conducted during the 2011 and 2012 growing seasons at the University of Wisconsin Hancock Agricultural Research Station (HARS; 44°8′23″ N, 89°31′23″ W, 328 m asl) on overhead irrigated Sparta loamy sand soil (sandy, mixed, mesic Entic Hapludoll). The experimental design was a randomized complete block strip-split plot arrangement with two whole-plot factors, replicated four times. The first whole plot factor was manure system, including spring-seeded field pea as green manure (GrM), pelletized poultry manure (PPM), and no manure (NM). The second whole plot factor was weed management intensity, including moderate (MOD), in which weeds were allowed to persist, and intense (INT), in which weeds were well controlled. The split-plot factor was feather meal N rate. Replicated blocks were separated by 9.1-m alleys, with 1.5 m spacing between manure system treatments within each replicate. Individual plots measured 6.1 by 4.6 m (six rows) in 2011 or 3.0 m (four rows) in 2012.

Potato (*Solanum tuberosum* L.) followed by fall-seeded winter rye (*Secale cereale* L.; variety not stated, from a local farm source) cover crop preceded each sweet corn growing season. Winter rye seed was spread and incorporated with a soil finishing tool in October and killed in early April of each year by moldboard plow. The 2009 fall soil test for the 2011 field indicated 6.2 pH, 1.0% organic matter, 108 mg P_2O_5 kg^{-1}, and 110 mg K_2O kg^{-1}. The 2010 fall soil test for the 2012 field indicated 6.6 pH, 1.0% organic matter, 85 mg P_2O_5 kg^{-1}, and 55 mg K_2O kg^{-1}. Potassium chloride (manufactured by Mosaic, procured from Crop Production Services, Plainfield, WI) was broadcast applied just before soil finishing at rates based on field soil test results (112 kg K_2O ha^{-1} applied in 2011 and 168 kg K_2O ha^{-1} in 2012).

To establish the GrM system, certified organic field pea (variety 4010 from Welter Seed & Honey Co., Onslow, IA) was drill-seeded following soil finishing on 15 Apr. 2011 and 10 Apr. 2012 at a target rate of 300,000 seeds ha^{-1} with resulting densities of 258,600 plants ha^{-1} in 2011 and 212,100 plants ha^{-1} in 2012. Approximately 7 wk after planting (3 June 2011 and 29 May 2012), field pea aboveground biomass (AGB) was incorporated by moldboard plow to a depth of 20 cm. On this same day in each study year, USDA National Organic Program (NOP)-compliant

PPM (labeled as "Composted Poultry Manure"; $N–P_2O_5–K_2O$: 4–5–3, from Cashton Farm Supply, Ltd., Cashton, WI) was broadcast applied to PPM plots by hand at a rate of 75 and 90 kg N ha^{-1} in 2011 and 2012, respectively, and incorporated by moldboard plow. No manure system plots were also subjected to moldboard plowing. For clarification, the PPM is not a composted product, but rather heated and pelletized. Analysis by the UW-Madison Soil and Plant Analysis Laboratory (SPAL) determined actual nutrient content. In 2011, $N–P_2O_5–K_2O$ was 5–4–3 and in 2012 $N–P_2O_5–K_2O$ was 6–5–2. Irrigation was managed by HARS at standard rates for field corn using the Wisconsin Irrigation Scheduling Program (WISP), which incorporates crop growth stage/canopy, weather, and evapotranspiration models to estimate crop water need, and determines deep drainage based on soil water holding capacity (Curwin and Massie, 1994; University of Wisconsin, 2014). Irrigation water was applied based on needs of the adjacent fields on the same overhead irrigation line, which were planted to field corn about 6 wk before sweet corn. When the application rates were back calculated for the sweet corn crop, it was found that applied irrigation rates were sometimes excessive, particularly during the 2012 growing season.

Untreated sweet corn seed (Hybrid yellow, variety DMC 21-84, Del Monte, Idaho Falls, ID) was planted at the optimum rate of 59,300 plants ha^{-1} at 0.76 m row spacing (Thomison and Jordan, 1995) following soil finishing on 17 June 2011 and 13 June 2012. Two weeks elapsed between manure incorporation and sweet corn planting to avoid predation by seedcorn maggots (*Delia platura*; Gaskell and Smith, 2007; Hammond and Cooper, 1993). Starter fertilizer was applied at planting in the form of USDA NOP-compliant composted poultry manure crumbles ($N–P_2O_5–K_2O$: 5–3–2, from Midwestern Bio Ag, Blue Mounds, WI) at a rate providing 22 kg N ha^{-1}, 13 kg P_2O_5 ha^{-1}, and 9 kg K_2O ha^{-1}, applied in a band 7 cm below and 5 cm laterally from the seed. In 2012, plots were thinned by hand after corn emergence due to overplanting. The sweet corn hybrid was chosen as a popular variety in the region, and was not certified organic seed.

In both MOD and INT weed management treatments, plots were cultivated once with a rotary hoe within 7 d of corn planting (22 June 2011, 19 June 2012). Additionally, the INT treatment plots were weeded with hand-held hoe three times before canopy closure (15, 22, and 29 July 2011; 11, 18, and 25 July 2012).

USDA NOP-compliant crumbled feather meal (advertised $N–P_2O_5–K_2O$: 11–0–0, Renaissance All Natural Fertilizer distributed by PJC Ecological Land Care, Rowley, MA) was broadcast applied by hand in two equal split side dress applications at approximately the V4 and V8 growth stages which occurred on 7 and 25 July 2011 and 3 and 18 July 2012. Feather meal was applied based on advertised N concentration of feather meal at target rates of 112, 168, and 224 kg N ha^{-1} (112N, 168N, 224N), with the addition of a 280 kg N ha^{-1} (280N) treatment in 2012. The high N rate in 2012 was added because 2011 yields did not plateau, indicating potential to maximize yields with increased N rate. The feather meal was analyzed each year by SPAL to determine actual nutrient content. In 2011, $N–P_2O_5–K_2O$ was 12–1–0 and in 2012, $N–P_2O_5–K_2O$ was 14–1–0, resulting in actual application rates of 122, 183, and 245 kg N ha^{-1} in 2011 and 148, 222, 296, and 369 kg N ha^{-1} in 2012. Six control plots representing each manure system and weed management combination were included in each replicate with no N applied as feather meal (0N).

Sample Collection and Analysis

Mean monthly air temperature (mean of all daily maximum and minimum temperatures) and total monthly precipitation are presented as deviations from the 30-yr normal (1980 through 2010) as reported for HARS by NOAA (Table 1). Growing degree days (GDD) were calculated using the modified method with a lower threshold of 10°C and upper threshold of 30°C (Russelle et al., 1984). Field pea AGB was sampled and stems were enumerated and measured for length from four random 0.19 m^2 sampling areas within in each GrM strip just before incorporation. Aboveground weed biomass (AWB) was quantified at first sign of senescence (26 and 29 Aug. 2011, 15 and 16 Aug. 2012) by enumeration, identification, and collection of all weeds in six 0.58 m^2 sampling areas per split plot. Field pea and weed biomass samples were dried at 60°C for a minimum of 1 wk, mechanically ground to pass through a 0.5-mm sieve, and analyzed for total N content by flash combustion with a Flash EA 1112 CHN Automatic Elemental Analyzer

Table 1. Mean monthly air temperature (mean of all daily maximum and minimum temperatures) and total monthly precipitation presented as deviations from 30-yr normals for Hancock, WI (1980 through 2010) as reported by NOAA.

	Mean air temperature			Total precipitation		
		Deviation from normal			Deviation from normal	
Month	30-yr normal	2011	2012	30-yr normal	2011	2012
	°C			cm		
Jan.	–9	–2	4	2.5	–1.0	–0.9
Feb.	–7	0	5	2.5	0.1	–1.8
Mar.	0	–3	9	4.4	1.3	2.8
Apr.	8	–3	0	8.0	4.2	0.5
May	14	–1	3	9.5	–1.1	5.9
June	19	–1	1	11.5	–2.2	–6.8
July	21	3	4	11.2	–3.5	–9.7
Aug.	20	1	1	10.6	–4.5	–3.1
Sept.	16	–1	0	8.6	7.4	–5.9
Oct.	9	2	–1	6.3	–1.4	7.8
Nov.	1	3	1	5.4	0.2	–1.8
Dec.	–7	4	3	2.7	0.2	2.1

(Thermo Finnigan, Milan, Italy). Field pea and weed biomass are reported on a dry matter basis. Sweet corn was harvested at approximately 1550 GDD (13 and 14 Sept. 2011) and 1600 GDD (4 and 5 Sept. 2012). All fully-developed ears from the two centermost plot rows were hand-harvested for yield determination. Fresh market yield is number of ears ha^{-1} and processing yield is unhusked fresh ear weight ha^{-1}. At the time of harvest, six stalks with ears per plot were collected, unhusked ears were removed and each portion (ears and stalks) was weighed separately and retained. Soil samples were collected from each plot post-harvest in 2011 and 2012 (16 September and 5 September, respectively) and additionally from INT weed management plots at 0N, 168N, and 280N at emergence [9 d after planting (DAP)], V4 (20 DAP), V8 (35 DAP), and tassel (49 DAP) in 2012 (22 June, 3 July, 18 July, 1 August, respectively). Each sample was a composite of four cores (1.8 cm diam.) collected to a depth of 30 cm. Soil NO_3 was measured following extraction with 2 M KCl using the Vanadium reduction of NO_3 method as described in Doane and Horwáth (2003). Soil NH_4 was determined using the Berthelot reaction (Rhine et al., 1998) for soil collected during the 2012 growing season. Total PAN was determined by summing NO_3 and NH_4. Nitrate contributed by irrigation was estimated using HARS irrigation volume reporting and a concentration of 18 mg L^{-1} groundwater NO_3–N as measured by Bundy and Andraski (2005) and supported by measurements made at HARS in 2010 ranging from 11 to 28 mg L^{-1} (Bero et al., 2014).

Harvest index (HI) is a ratio of the dry unhusked ear weight to stalk weight (Abedon and Tracy, 1998). Interactive effect (IE) is the yield change attributed to combined fertilizer use as compared to the yield achieved by each fertilizer source alone. The IE of each combined manure and feather meal application on sweet corn processing yield was calculated using a modification of the method of Vanlauwe et al. (2001):

$$IE = Y_{Manure + FM} - Y_{0N} - (Y_{FM} - Y_{0N}) - (Y_{Manure + 0N} - Y_{0N})$$

where $Y_{Manure + FM}$ is the yield of a combined manure and feather meal treatment; Y_{0N} is the yield with no manure or feather meal; Y_{FM} is the yield of the feather meal treatment without manure; and $Y_{Manure + 0N}$ is the yield of the manure treatment without feather meal. A 90% confidence interval was calculated for each manure system–N rate treatment combination to determine if IE was different than zero. A positive IE suggests an added benefit to the combined use of fertility sources, whereas a negative IE indicates that the yield benefit did not exceed the sum of the benefits achieved by each fertility source alone. Confidence intervals that span zero indicate an additive effect of combined fertility treatments, with no additional benefit.

Statistical Analysis

Sweet corn processing yield, fresh market yield, HI, AWB, weed population density, soil NO_3, soil NH_4, and total PAN data were subjected to an ANOVA based on experimental design using the MIXED model procedure for SAS (version 9.2, SAS Institute, 2002). Manure system, weed management, feather meal-N rate, and interactions between these treatment factors were treated as fixed effects. Block and its interaction with the whole-plot factors (manure system and weed management treatments) were treated as random effects. Treatment means were estimated using the method of residual maximum likelihood (REML, Searle et al., 2009) and statistical significance was determined at $\alpha \leq 0.10$. Mean separations were determined using the probability of differences ($P < 0.10$) of least squared means (PDIFF option in LSMEANS statement). When two-way and three-way factor interaction was significant, estimate statements were used to directly compare treatment factors within levels of another treatment factor. Study years were analyzed separately due to vast seasonal differences. Yield data from 0N (control) plots were used for IE calculations and analyzed separately for comparisons of manure system and weed management effects without feather meal application.

Mean AWB and weed population density in MOD and INT were analyzed to verify significant differences in weed growth, and thus efficacy of the weed management. Full statistical analysis was then conducted on AWB and weed population density as described above for MOD weed treatment only.

Data from 2012 in-season soil sampling were analyzed by sampling date. The NO_3, NH_4, and total PAN at emergence and V4 targeted effects of early season manure treatments. Soil sampling at V8, tassel, and post-harvest illustrate potential effects on NO_3, NH_4, and total PAN of both manure system and feather meal-N application. Post-harvest NO_3 data were analyzed across all study treatments in 2011 and 2012.

RESULTS

Weather

Monthly air temperature means in 2011 were equal to or below normal through June, whereas monthly means in 2012 were equal to or above normal through August, with March averaging 9°C above normal (Table 1). Monthly precipitation totals were below normal over the 2011 growing season by about 12 to 42% with the exception of April (Table 1). In 2012, May was exceptionally rainy, followed below normal rainfall through September with only 13.7 cm of precipitation in June, July, and August combined, whereas normal precipitation rates exceed 10.0 cm for each of these months. July 2012 had only 1.5 cm precipitation (compared to 11.2 cm normal). Total water (precipitation plus irrigation) during the sweet corn growing season was 52.0 cm in 2011 and 59.5 cm in 2012 (Fig. 1). Irrigation contributed 78% of total water in 2012 as compared to 47% in 2011, resulting in an estimated contribution of 85 kg NO_3–N ha^{-1} from irrigation water in 2012, compared to 45 kg NO_3–N ha^{-1} in 2011 (Fig. 1).

Green Manure Growth

In 2011, field pea produced 723 kg ha^{-1} of AGB with an N content of 33 kg ha^{-1} and in 2012, field pea produced 1815 kg ha^{-1} of AGB with an N content of 91 kg N ha^{-1}. The average height of field pea was 26 cm in 2011 and 20 cm in 2012. The two- to threefold increase in pea biomass and N uptake in 2012 compared to 2011 may be attributed to the 65% increase in total water application to field pea in 2012, with an estimated 18 kg NO_3–N ha^{-1} applied to field pea via irrigation in 2012 compared to a negligible amount in 2011 (Fig. 1). The C/N ratio of field pea AGB was 9.5 and 8.6 in 2011 and 2012, respectively.

Weed Growth

In 2011, weed density averaged 115,000 weeds ha^{-1} in MOD with aboveground weed biomass of 178 kg ha^{-1}, and N content of AWB averaging 5 kg AWB-N ha^{-1}. Within the MOD

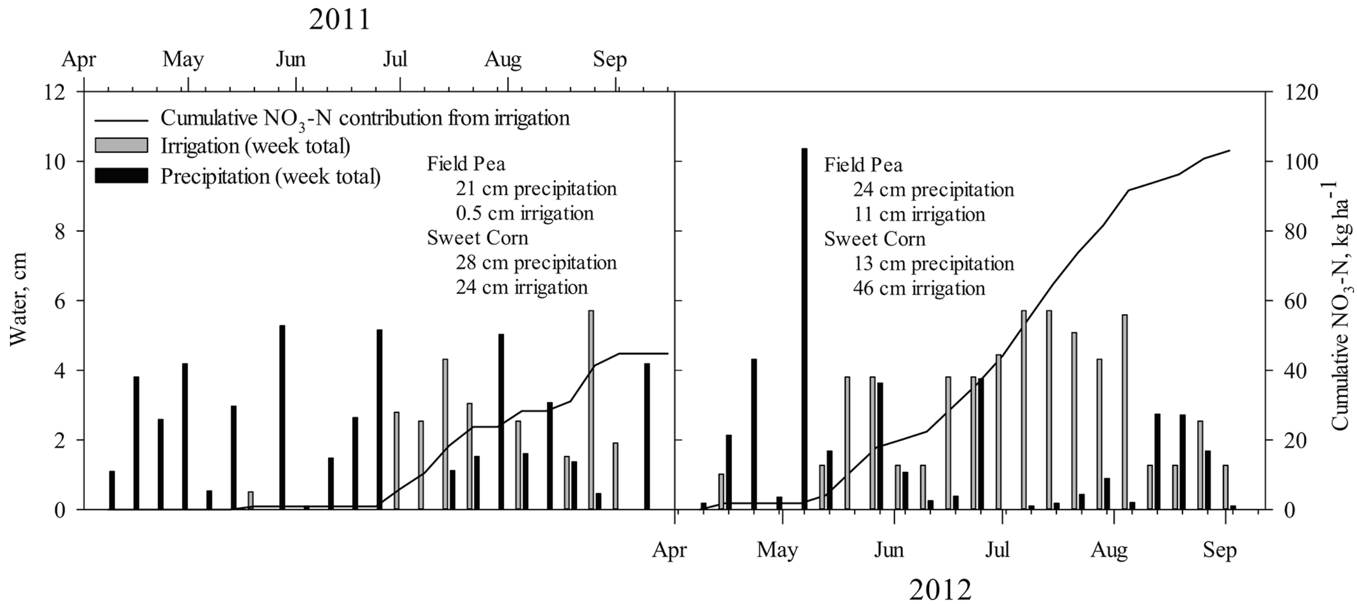

Fig. 1. Weekly accumulated precipitation and irrigation for field pea (15 Apr.–3 June 2011, 10 Apr.–29 May 2012) and sweet corn (17 June–14 Sept. 2011, 13 June–5 Sept. 2012) growth seasons with estimated cumulative NO_3–N contribution from irrigation (derived using 18 mg L^{-1} NO_3–N concentration in ground water [Bundy and Andraski, 2005]).

treatment, there was no significant effect of manure system, N rate, or their interaction on either weed density or AWB in 2011 (Table 2). In 2012, weed density averaged 297,000 weeds ha^{-1} in MOD, with 925 kg AWB ha^{-1}, and 31 kg AWB-N ha^{-1}. There was a significant effect of manure system and its interaction with N rate on MOD AWB in 2012, but no significant treatment effects on weed population density. The GrM-MOD produced 1138 kg AWB ha^{-1}, a 52% increase over PPM-MOD (750 kg AWB ha^{-1}); AWB produced in both PPM and GrM systems was statistically similar to that of NM (Table 2). Within manure systems, mean AWB at 168N was highest in the NM system, but lowest in the GrM system despite AWB in GrM being generally higher than that of NM or PPM at all other N rates. The INT weed treatment suppressed 88 and 94% of AWB compared to MOD in 2011 and 2012, respectively, with negligible N accumulation in AWB of INT plots in either study year. Weed population density was suppressed 41 and 61% in INT compared to MOD in 2011 and 2012, respectively.

Common purslane (*Portulaca oleracea* L.) and catchweed bedstraw (*Galium aparine* L.) comprised more than 50% of weeds in sweet corn plots in both study years, with percentage of purslane increasing under INT weed management. Other common weed species found in both years include fall panicum (*Panicum dichotomiflorum* L.), common lambsquarters (*Chenopodium album* L.), large crabgrass (*Digitaria sanguinalis* L.), and hairy nightshade (*Solanum sarrachoides* L.). These species are representative of weed populations found in agricultural soils throughout south-central Wisconsin (Williams et al., 2008).

Yield, Harvest Index, and Interactive Effect

In 2011, there were main effects of manure system and N rate on processing yield, with no effect of weed management or treatment factor interaction (Table 3). Processing yield of neither PPM nor GrM was different from that of NM, but 17.2 Mg ha^{-1} yield in PPM was significantly higher than 15.5 Mg ha^{-1} yield in GrM. There was a significant increase in processing yield of about 14% associated with increase in N rate from 112N to 168N, and again from 168N to 224N with mean processing yield of 18.6 Mg ha^{-1} at 224N.

Analysis of fresh market yield in 2011 showed an effect of manure system × weed management × N rate interaction, manure system × weed management interaction and main effects of manure system and N rate (Table 3, Fig. 2). The interaction effects are nuanced and differences typically occur in just one treatment combination. For example, fresh market yields for

Table 2. Average aboveground weed biomass (AWB) and population density within moderate weed management (MOD) treatment with ANOVA results as affected by manure system and feather meal-N rate. Within each column for significant treatment factors, means followed by the same letter are not significantly different (α = 0.1).

	2011		2012	
Treatment	AWB	Population	AWB	Population
	kg ha^{-1}	1000 ha^{-1}	kg ha^{-1}	1000 ha^{-1}
Manure system†				
NM	148.9	119	888.0ab	247
PPM	149.8	105	749.8b	300
GrM	234.3	122	1138.4a	343
N rate ‡, kg ha^{-1}				
112	187.6	122	762.0	287
168	203.9	122	1035.6	298
224	141.5	100	895.2	287
280	–	–	1008.8	315
		P value		
Source of variation				
Manure system (S)	0.112	0.746	0.072	0.182
N rate (N)	0.366	0.584	0.473	0.856
S × N	0.103	0.124	0.067	0.224

† NM = no manure, PPM = pelletized poultry manure, GrM = green manure (spring-seeded field pea).

‡ N applied as feather meal, split-applied at approximately the V4 and V8 growth stages.

Table 3. Average sweet corn processing yield, fresh market yield, and harvest index (HI) with ANOVA results as affected by manure system, weed treatment, and feather meal-N rate. Within each column for significant treatment factors, means followed by the same letter are not significantly different ($\alpha = 0.1$).

Treatment	2011 Processing yield	2011 Fresh market yield	2011 HI†	2012 Processing yield	2012 Fresh market yield	2012 HI†
	Mg ha^{-1}	1000 ears ha^{-1}		Mg ha^{-1}	1000 ears ha^{-1}	
Manure system‡						
NM	16.5ab	46.4a	0.42a	21.2	58.2	0.75b
PPM	17.2a	45.8a	0.42a	22.5	60.1	0.80b
GrM	15.5b	42.5b	0.36b	22.9	61.4	0.91a
Weed management§						
MOD	16.0	42.9	0.37b	21.7	58.6b	0.87
INT	16.8	46.9	0.42a	22.7	61.1a	0.77
N rate¶, kg ha^{-1}						
112	14.3c	41.0c	0.37b	21.5	57.5b	0.86a
168	16.3b	45.2b	0.39b	22.1	59.9ab	0.82ab
224	18.6a	48.6a	0.43a	22.9	61.5a	0.85a
280	–	–	–	22.4	60.6a	0.76b
Source of variation			*P* value			
Manure system (S)	0.071	0.067	0.035	0.135	0.248	0.018
Weed (W)	0.347	0.175	0.083	0.113	0.032	0.105
S × W	0.118	0.028	0.330	0.105	0.080	0.843
N rate (N)	<0.001	<0.001	0.023	0.102	0.098	0.041
S × N	0.806	0.426	0.348	0.957	0.968	0.037
W × N	0.300	0.340	0.593	0.338	0.075	0.721
S × W × N	0.651	0.054	0.048	0.034	0.213	0.839

† HI = harvest index; ratio of oven dry unhusked ear to stalk weight.
‡ NM = no manure, PPM = pelletized poultry manure, GrM = green manure (spring-seeded field pea).
§ MOD = moderate weed management, INT = intense weed management.
¶ N applied as feather meal, split-applied at approximately the V4 and V8 growth stages.

INT treatment combinations are statistically similar with the exception of increased yield in NM-INT-168N and GrM-INT-224N (Fig. 2). Fresh market yields at MOD in NM and PPM increased at 224N compared to lower N rates; however, there were no yield differences in GrM-MOD across N rates, with significantly lower yield at GrM-MOD-224N compared to NM and PPM at 224N (Fig. 2). Whole plot treatment effects on fresh market yields corroborated trends in processing yields. The GrM system resulted in significantly lower mean fresh market yields than the NM and PPM systems and there was an 8 to 10% increase in yield associated with each increase in N rate with 224N averaging 48,600 ears ha^{-1} (Table 3).

In 2012, processing yield was 21.5 Mg ha^{-1} at 112N, with modest yield increases of up to 6.5% at higher N rates (not significant). There was a significant three-way interaction effect of manure system × weed management × N rate on processing

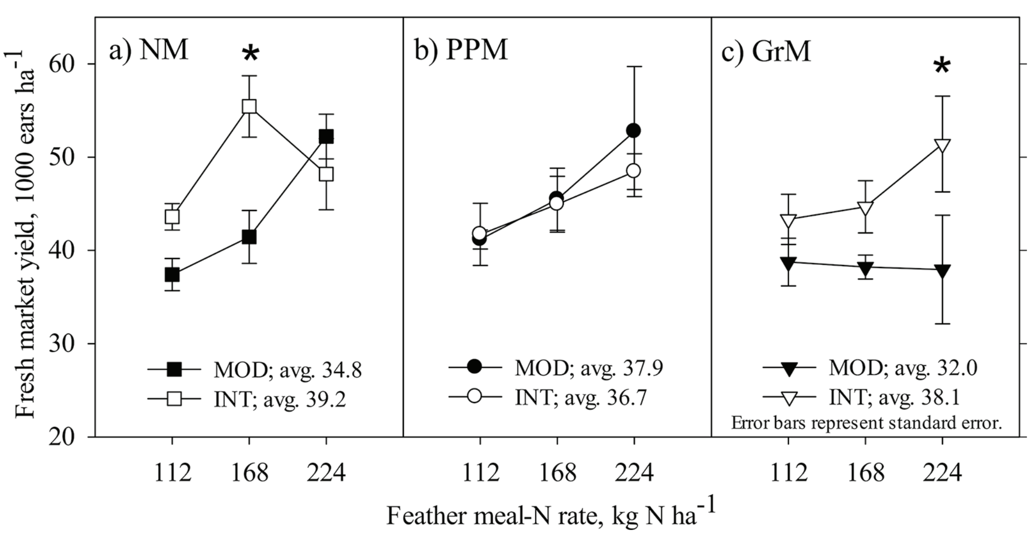

Fig. 2. Sweet corn fresh market yield in 2011 by manure system, weed management, and feather meal-N rate, reported in 1000 ears ha^{-1} with manure system × weed management means. (a) NM = no manure; (b) PPM = pelletized poultry manure; (c) GrM = green manure (spring-seeded field pea); MOD = moderate weed management; INT = intense weed management; * Significant difference ($\alpha = 0.1$).

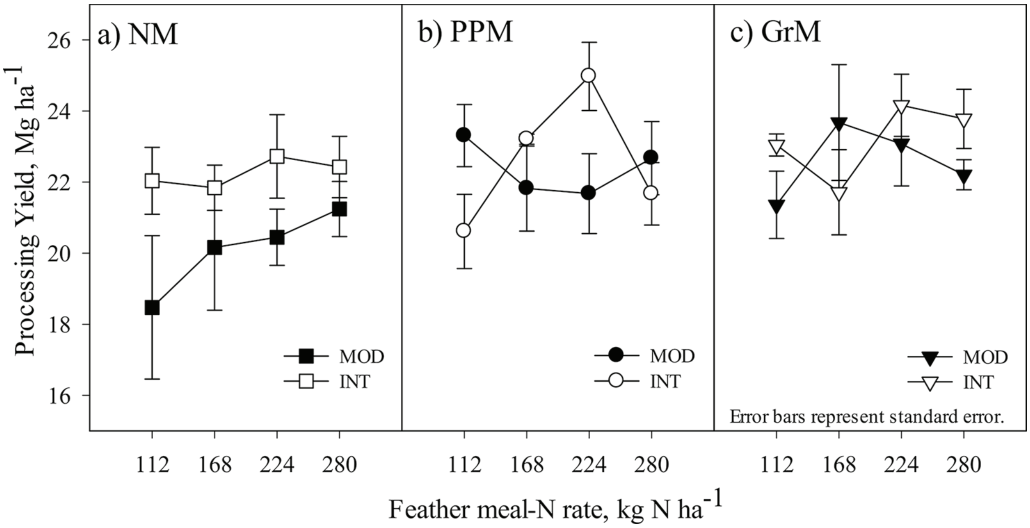

Fig. 3. Sweet corn processing yield in 2012 by manure system, weed management, and feather meal-N rate. (a) NM = no manure; (b) PPM = pelletized poultry manure; (c) GrM = green manure (spring-seeded field pea); MOD = moderate weed management; INT = intense weed management.

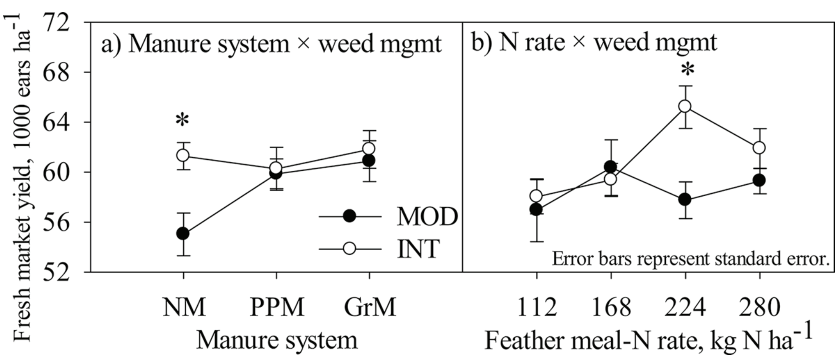

Fig. 4. Sweet corn fresh market yield in 2012 by (a) manure system × weed management interaction and (b) feather meal-N rate × weed management interaction. (a) NM = no manure; (b) PPM = pelletized poultry manure; (c) GrM = green manure (spring-seeded field pea); MOD = moderate weed management; INT = intense weed management; * Significant difference (α = 0.1).

yield, but no main treatment effects or other interaction effects (Table 3). The three-way interaction lacks clear trends in response to treatment factor combinations (Fig. 3).

Fresh market yield in 2012 demonstrated manure system × weed management interaction and weed management × N rate interaction effects (Table 3, Fig. 4). In 2012, fresh market yield in each manure system and weed management combination, when averaged across N rates, was statistically similar except NM-MOD, which had lower yield compared to NM-INT (Fig. 4a). The weed management × N rate interaction effect showed fresh market yield to be statistically similar across MOD treatments and greater at 224N compared to 112N and 168N in INT weed management with yield at INT-224N also significantly greater than MOD-224N (Fig. 4b). There was also a main treatment effect of N rate on fresh market yield in 2012 (Table 3); 224N and 280N significantly increased fresh market yield by 7 and 5%, respectively, compared to 112N.

Mean yield at 0N was 2.9 Mg ha^{-1} and 11,200 ears ha^{-1} in 2011; and 13.7 Mg ha^{-1} and 45,400 ears ha^{-1} in 2012. There was a significant effect of manure system on fresh market yield at 0N in 2011 (Table 4) as the PPM and GrM systems yielded 12,000 and 13,100 ears ha^{-1}, respectively, both significantly higher than that of NM (8600 ears ha^{-1}). This effect was not significant in processing yield (P = 0.158). There were no treatment effects of manure system or weed management on processing or fresh market yields at 0N in 2012.

Table 4. Yield for 0N control with ANOVA results by manure system and weed management treatments. Within each column for significant treatment factors, means followed by the same letter are not significantly different (α = 0.1).

Treatment	2011		2012	
	Processing yield	Fresh market yield	Processing yield	Fresh market yield
	Mg ha^{-1}	1000 ears ha^{-1}	Mg ha^{-1}	1000 ears ha^{-1}
Manure system†				
NM	2.3	8.6b	13.4	44.1
PPM	3.2	12.0a	13.2	43.3
GrM	3.2	13.1a	14.5	48.7
Weed management‡				
MOD	2.7	11.0	12.9	42.3
INT	3.1	11.5	14.5	48.5
		<u>P value</u>		
Source of variation				
Manure system (S)	0.158	0.083	0.664	0.343
Weed (W)	0.610	0.836	0.175	0.128
S × W	0.968	0.834	0.990	0.626

† NM = no manure, PPM = pelletized poultry manure, GrM = green manure (spring-seeded field pea).

‡ MOD = moderate weed management, INT = intense weed management.

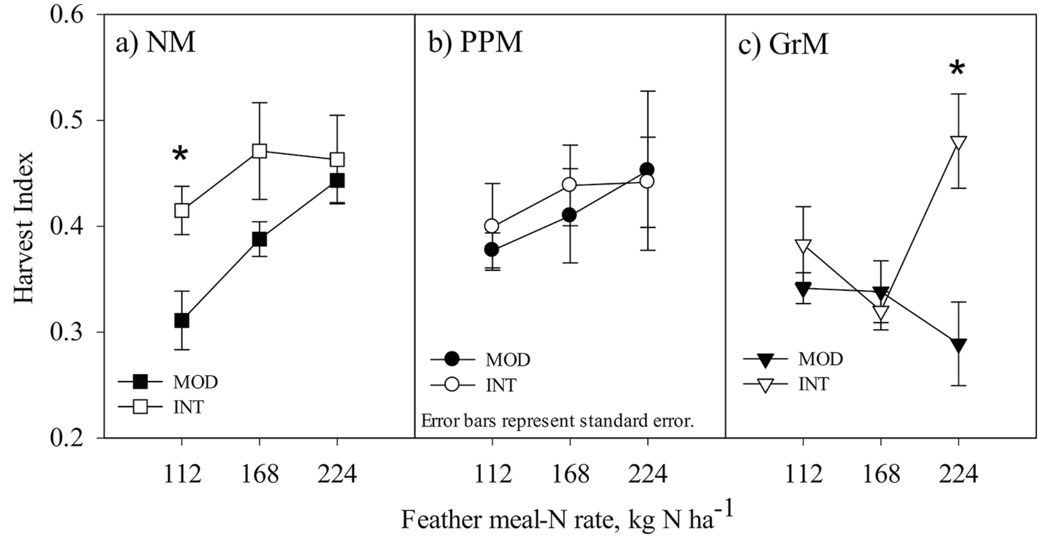

Fig. 5. Harvest index in sweet corn in 2011, reported by manure system, weed management, and feather meal N rate. (a) NM = no manure; (b) PPM = pelletized poultry manure; (c) GrM = green manure (spring-seeded field pea); MOD = moderate weed management; INT = intense weed management; * Significant difference (α = 0.1).

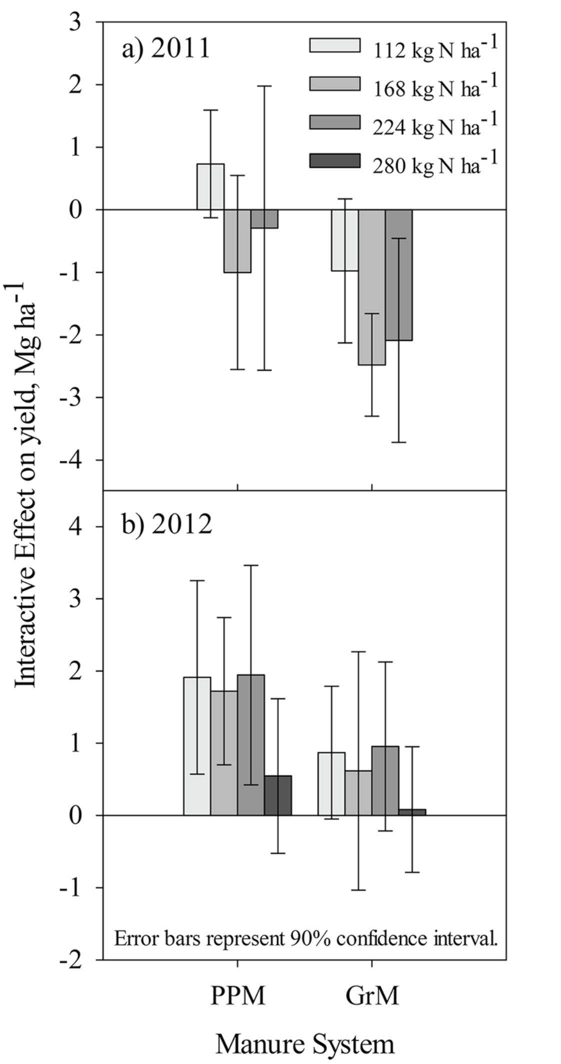

Fig. 6. Interactive effect of organic manures and feather meal on mean sweet corn processing yield in (a) 2011 and (b) 2012 by feather meal-N rate and manure system. PPM = pelletized poultry manure; GrM = green manure (spring-seeded field pea).

There was a significant effect of manure system × weed treatment × N rate interaction and significant main effects of manure system, weed management, and N rate (Table 3) on HI in 2011. Harvest index increased in NM-INT relative to NM-MOD at 112N and increased in GrM-INT relative to MOD at 224N (Fig. 5). The significant main effect of manure system on HI demonstrated significant increases in both NM and PPM (0.42 HI in both) over that of GrM (0.36). Mean HI for INT was 0.42, significantly higher than that of MOD (0.37). Harvest index at 224N was 0.43, and was significantly greater than HI at 112N and 168N (0.37 and 0.39, respectively).

In 2012, there was a significant effect of manure system × N rate interaction and main effects of manure system and N rate on HI (Table 3). The manure system × N rate interaction demonstrated HI in GrM exceeding that of NM at 112N, 224N, and 280N, and that of PPM at 112N and 280N. The HI in PPM also exceeded HI in NM at 224N. Interestingly, these trends dissipated and HI values were similar across manure systems at 168N. Opposite the trend from 2011, the GrM system had significantly higher HI (0.91) compared to NM and PPM (0.75 and 0.80, respectively). Harvest index was significantly lower at 280N compared to 224N and 112N.

In 2011, the interactive effect for combined use of GrM and feather meal at 168N and 224N was negative (Fig. 6a). The 90% confidence interval spanned zero for other manure-feather meal combinations. In 2012, the interactive effect for combined use of PPM and feather meal at 112N, 168N, and 224N demonstrated an increase in processing yield of 1.9, 1.7, and 2.0 Mg ha^{-1}, respectively (Fig. 6b), indicating that yield effects with combined use of these amendments exceeded the individual benefit of either PPM or feather meal alone. There was no interactive effect in PPM-280N or GrM at any N rate in 2012.

Plant Available Nitrogen

In 2012, there were no significant differences in the soil NO_3, soil NH_4, or total PAN concentrations of soil samples collected from the different manure system treatments on 22 June (sweet corn emergence) with mean concentration of 7.8 mg kg^{-1} total

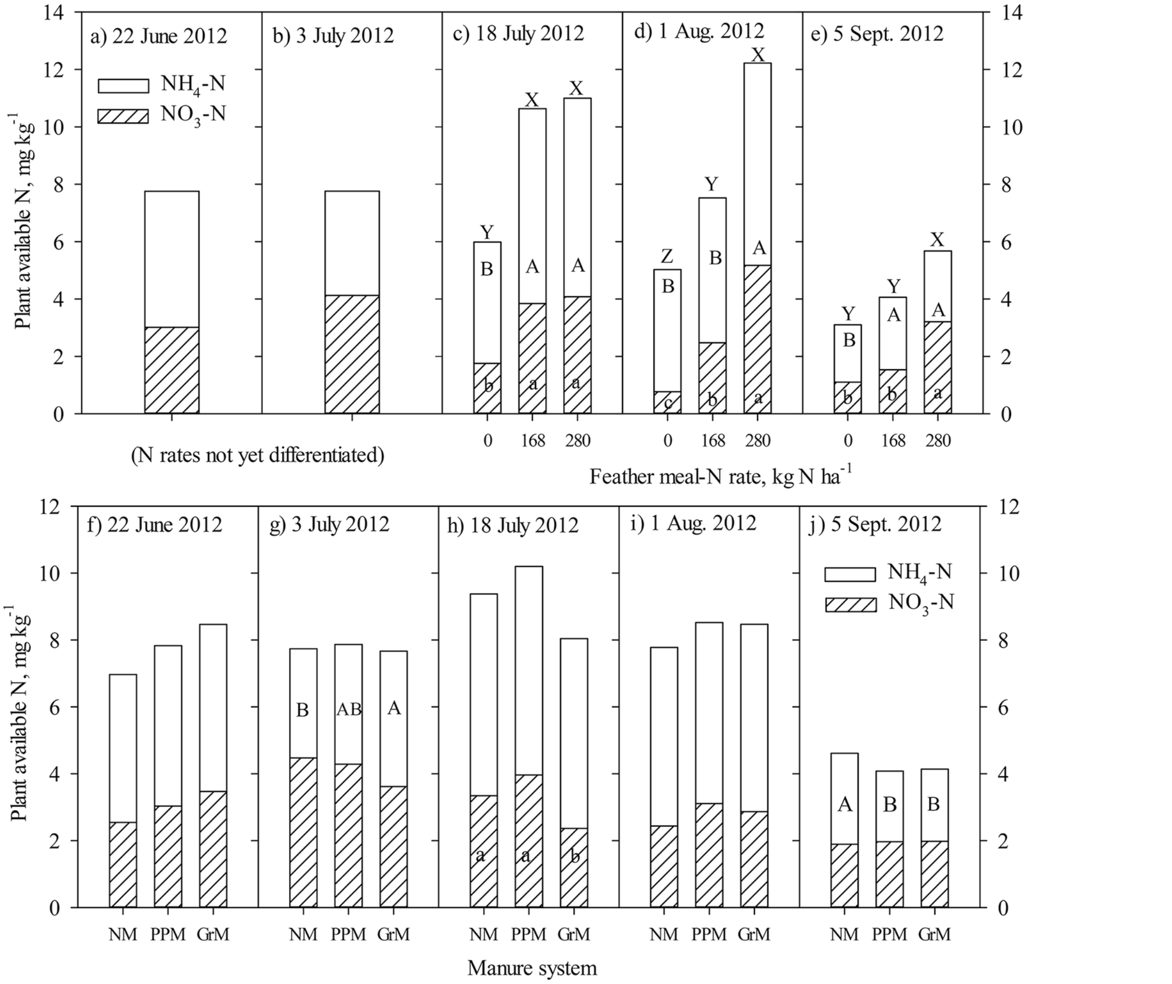

Fig. 7. Plant available soil N concentration (0–30 cm) for sweet corn by (a, b, c, d, e) feather meal-N rate and (f, g, h, i, j) manure system. Feather meal was applied on 3 July 2012 and 18 July 2012 directly following soil sampling (half rate of feather meal-N applied per treatment). NM = no manure; PPM = pelletized poultry manure; GrM = green manure (spring-seeded field pea). Plant available N concentrations within the same date are significantly different if denoted by different letters.

PAN across treatments. On 3 July (V4; 20 DAP), there was a significant effect of manure system on NH_4, with mean NH_4 in the GrM system greater than that of NM (4.1 and 3.3 mg NH_4–N kg^{-1}, respectively; Fig. 7g). On 18 July (V8; 35 DAP), mean NO_3 showed a significant effect of manure system with mean NO_3 values in NM and PPM both greater than NO_3 in GrM, though similar to each other (3.4, 4.0, 2.4 mg NO_3–N kg^{-1}, respectively; Fig. 7h). On this date, there was also a significant effect of N rate on NO_3, NH_4, and total PAN in which values at 168N and 280N were all significantly greater than those of 0N (Fig. 7c). On 1 August (tassel; 49 DAP), NO_3 and total PAN concentrations at each N rate were significantly different from each other, with greatest NO_3 and total PAN at 280N, and lowest values at 0N. Additionally, NH_4 at 280N was significantly greater than that of 0N or 168N. On 5 September (harvest; 84 DAP), NO_3, NH_4, and total PAN in both 168N and 280N had decreased relative to respective values at tassel, but NO_3 and total PAN values at 280N were still significantly greater than respective values at 0N or 168N, and NH_4 at 168N and 280N was greater than that of 0N (Fig. 8A). There was also a significant increase in NH_4 in NM compared to PPM and GrM at harvest. Analysis of NO_3 in all treatments at harvest showed NO_3 at 224N was greater than NO_3 at 112N, NO_3 at 224N and 168N was greater than NO_3 at 0N, and NO_3 at 112N and 0N were similar. There was also a significant effect of weed management at harvest by which NO_3 at INT (1.8 mg kg^{-1}) was greater than NO_3 at MOD (1.4 mg kg^{-1}). There were no treatment effects on NO_3 at harvest in 2011, with an average NO_3 concentration of 0.8 mg kg^{-1} across all treatments.

DISCUSSION

Manure Nitrogen Credits

Nitrogen credits for early season manure inputs on loamy sand soil were not determined in this study due to yield differences between the two study years, and treatment factor interaction. However, indications of potential benefits of early season manure include increased fresh market yield at 0N with PPM and GrM relative to NM in 2011, and a positive IE attributed to combined use of PPM and feather meal at some N rates in 2012. It is likely that manure-N availability and crop need were asynchronous, a phenomenon attributed to rapid N mineralization on sandy soil and subsequent leaching of N beyond the crop root zone. In this study, early-season N loss was likely exacerbated by the 14 d gap between manure incorporation and sweet corn planting, intended to mitigate risk of seed and seedling predation by seedcorn maggots (Gaskell and Smith, 2007; Hammond and Cooper, 1993). Our results corroborate those of Johnson et al. (2012) who found pea biomass and poultry manure to decompose very quickly in an incubation study using this soil, and posited that corn would not utilize these organic

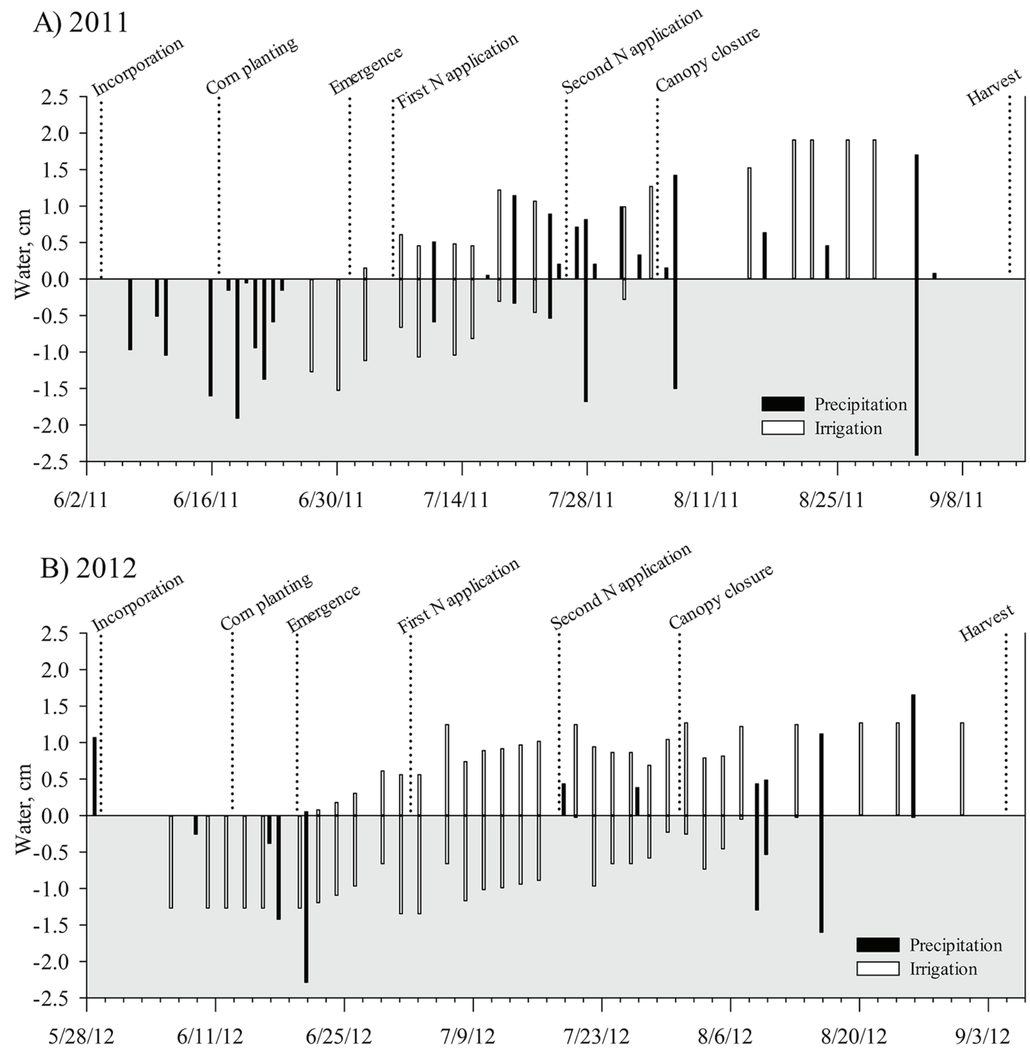

Fig. 8. Precipitation and irrigation events in sweet corn in (A) 2011 and (B) 2012. Each bar represents a single water event, with bars extending north of zero on the y axis representing water utilized by the crop, and bars extending south of zero representing water in excess of field capacity (15%) and thus likely contributing to deep drainage. The utilized vs. excess estimates were calculated using the Wisconsin Irrigation System Program (WISP) tool. As the crop matures, increased water utilization is apparent, as the bars are increasingly positive.

sources of N well due to the lapse between incorporation and crop-N uptake. In this study, in-season measurement of soil NO_3 and NH_4 in 2012 demonstrated no significant increases attributable to PPM or GrM at the time of crop emergence, with a significant but slight increase in NH_4 concentration in GrM relative to NM at V4. One factor that may diminish potential N credits from pre-plant manure applications is early season precipitation and irrigation. Deep drainage estimates indicate that irrigation was applied in excess of the sweet corn crop need by 8.5 and 20.7 cm in 2011 and 2012, respectively, particularly early in 2012 with 7.6 cm excess irrigation between the time of manure incorporation and sweet corn emergence and an additional 6.6 cm before V4 (Fig. 8). The seemingly excessive use of irrigation early in the 2012 season is because adjacent fields on the same overhead irrigation line were planted to field corn about 6 wk before sweet corn and thus had greater water needs per WISP estimates of evapotranspiration. Early season deep drainage estimates in 2011 were attributed to precipitation, and totaled 9.3 cm from manure incorporation to sweet corn emergence. Water utilization increases as the crop grows, as visualized in Fig. 8 with the bars representing total water supplied as irrigation and precipitation events shifting from negative (contributing to deep drainage) to positive (utilized by crop) over the cropping season. Cherr et al. (2006a) indicate that finer textured soils will retain N when there is a lag between cover crop termination and peak N uptake, though green manure N credits are elusive on coarse soil (Cherr et al., 2007).

Our yield results for 0N treatments support our irrigation effect theory as the PPM and GrM treatments increased fresh market yield at 0N in 2011 (although not significant for processing yield), with no significant yield difference in 2012 under increased irrigation and temperature. This indicates that N from the GrM and PPM treatments likely underwent rapid mineralization and leached beyond the shallow seedling root zone on the loamy sand soil, as confirmed in other studies that measured content of leachate from manured sandy soils (Olesen et al., 2009; Berntsen et al., 2006; Endelman et al., 1974). Interestingly, the 2011 yield increase with manure is apparent only at 0N, and with combined use of GrM and feather meal at 168N and 224N we saw a negative interactive effect (Fig. 6a) and a drop in HI (Fig. 5c). A composted poultry manure product may be more effective on loamy sand because the composting process reduces rapid mineralization of N at application, and results in higher and more consistent soil PAN concentration over the growing season (Preusch et al., 2002; Wild et al., 2011; Tyson and Cabrera, 1993).

Annual Variation

The difference between yield response trends noted in the two study years hinders assessment of optimum feather meal application rate. Sweet corn processing yield in both study years was comparable to that of studies receiving mineral fertilizer at the same location (Bundy and Andraski, 2005; Johnson et al., 2012) and at other locations (Williams, 2008; Heckman, 2007), but yield did not plateau over N rates in 2011, and the relevance of the yield plateau in 2012 is dubious due to inflated yield at 0N. Though counter-intuitive, the drought conditions indirectly improved yields in 2012 due to increased NO_3 application through irrigation, as shown by four-to-fivefold increase in yields at 0N in 2012 compared to 2011. The sweet corn crop received an estimated 85 kg N ha^{-1} via irrigation water in 2012, as compared to 45 kg N ha^{-1} in 2011, and also received more total water over the 2012 growing season (Fig. 1). The 2012 crop received irrigation almost every other day, whereas the 2011 crop received sporadic irrigation at a lower rate per event (Fig. 8). Shapiro (1999) found that the equivalent of 120 kg N ha^{-1} applied to a corn crop in loamy sand soil via high NO_3 irrigation water produced similar yields as mineral applications exceeding 300 kg N ha^{-1}. Though the increased irrigation likely flushed out the potential benefit of the early season manure treatments, it seems that there was an unintended advantage across all treatments.

The preceding winter rye cover crop also may have contributed to higher yields in 2012 relative to 2011. Volunteer winter rye in 2012 had 26 kg N ha^{-1} in the AGB sampled from non-GrM plots (which were not yet differentiated into PPM and NM treatments), and 17 kg N ha^{-1} in GrM plots (data not shown). Bundy and Andraski (2005) found sweet corn yield to increase following a winter rye cover crop at this location as compared to no cover crop, and Olesen et al. (2007) attributed a significant yield response and increased efficiency to winter rye, with the largest effect on sandy soil.

Weed Pressure

Despite effective suppression of weeds in INT treatments, there were no clear yield trends associated with weed management in either study year. Colquhoun et al. (1999) also found intensity of weed management to have an unclear effect on yield. Abundance of weeds alone does not constitute weed pressure or competition due to variation in interspecific plant relationships and utilization of non-overlapping or non-limiting resource pools (Smith et al., 2010; Lindquist et al., 2010). Organic systems with diverse nutrient sources and resource pools can be resistant to yield losses associated with abundant weed populations (Smith et al., 2010; Ryan et al., 2009). Repeated tillage before mid-June sweet corn planting dates in this study likely contributed to a stale seedbed effect across both weed treatments, obviating the benefit of in-season weed management because many weeds were eliminated before crop planting (Johnson et al., 2010).

CONCLUSIONS

This research highlights challenges of organic N management on loamy sand soil. Sweet corn yields of 18.6 and 22.9 Mg ha^{-1} in 2011 and 2012, respectively, are partially attributed to feather meal application, indicating potential for in-season organic N options. Weed management may have contributed to increased yield and HI in some treatment combinations through treatment factor interaction, with results indicating that early season tillage may have provided sufficient weed control. However, with complex factors affecting the performance of organic inputs, the pre-plant manure applications (GrM and PPM) were not well-utilized sources of N for sweet corn in this setting. Both study years may have been marked by early season leaching losses, as exacerbated by the delay between manure incorporation and sweet corn planting, and early season precipitation and irrigation. Use of early season incorporated manure in this system may require development of an organic-compliant seed treatment for seedcorn maggot or a resistant cultivar, thus obviating need to delay planting.

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