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Soil Nitrogen and Forage Yields of Corn Grown with Clover or Grass Companion Crops and Manure

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ABSTRACT

Few studies have compared the agronomic performance of cover crop and living mulch systems for no-till silage corn (*Zea mays* L.). In a 4-yr Wisconsin study, we evaluated soil N levels and forage yields from manured rotations of corn grown with kura clover (*Trifolium ambiguum* M. Bieb.) living mulch or interseeded red clover (*T. pratense* L.) followed by a year of clover production and from manured continuous corn grown with interseeded Italian ryegrass (*Lolium multiflorum* Lam.), fall-seeded winter rye (*Secale cereale* L.), or no companion. Companion crops influenced spring and fall nitrate concentrations near the soil surface but had little effect on total residual fall nitrate to a 1.2-m depth. Residual nitrate was not related to N balance (inputs minus outputs), but excessive N inputs into corn–clover systems accumulated as organic soil N. Averaged across both phases of the rotation, corn–clover systems provided 0 to 23% less dry matter yield, but 26 to 60% more crude protein yield than continuous corn systems, with corn–red clover often producing the highest silage corn and clover yields. Kura clover provided superior ground cover and nitrate uptake, but it often excessively competed with corn and had low forage yields. Applying fall manure to ryegrass and spring manure to rye maximized silage yields of continuous corn, but manure application time had no other effect on forage yields or on soil N. Overall, no system excelled in all characteristics, thus selection of companion crop and manure management systems for silage corn will depend on feed production and environmental goals.

Corn silage is commonly fed to dairy cattle (*Bos taurus*) and other types of ruminant livestock, but its production can leave cropland vulnerable to nitrate leaching and runoff of nutrients and sediment. As result, a wide variety of cover crops or living mulches (collectively referred to here as “companion crops”) have been developed and promoted to mitigate the adverse environmental impacts of corn production and to improve crop yields, nutrient cycling, and soil quality (Hartwig and Ammon, 2002; Miguez and Bollero, 2005; Fageria et al., 2005; Cherr et al., 2006). A few of the more promising companion crops for corn in the colder continental regions of North America include winter rye, Italian ryegrass, red clover, and kura clover.

Winter rye is commonly seeded in the fall after corn harvest. Although it often provides little ground cover in the fall and winter, fall-seeded rye grows vigorously during the spring to protect soil and remove residual soil nitrate (Clark, 2007). Rye can be grazed or harvested for forage before a late planting of corn, but earlier spring termination is often used because rye can deplete soil moisture, immobilize N, and depress corn yields (Ewing et al., 1991; Crandall et al., 2005; Duiker and Curran, 2005).

Italian ryegrass and red clover are often interseeded about 4 to 6 wk after corn planting to permit establishment without excessive competition with corn (Scott et al., 1987; Abdin et al., 1997; Clark, 2007; Baributsa et al., 2008). In the fall, interseeded ryegrass usually provides greater ground cover and soil nitrate scavenging than fall-seeded rye and it can be grazed or harvested for forage. Ryegrass often winterkills to provide short-lived mulch for spring-seeded crops such as corn and it tends to have a neutral effect on corn yields unless its growth and uptake of soil nitrate are too vigorous (Kramberger et al., 2009). By contrast, interseeded red clover normally overwinters to provide moderate ground cover and uptake of soil nitrate during both the fall and spring. Red clover cover crops supply N to succeeding crops and they can enhance corn yields (Vyn et al., 1999). A seemingly overlooked option would be to keep interseeded red clover in production for at least 1 yr following corn to provide high quality forage and to boost subsequent corn yields through greater N and non-N rotational effects (Bruulsema and Christie, 1987; Fox and Piekielek, 1988).

In addition to short-lived cover crops, perennial forages such as kura clover may serve as dual purpose crops when grown in alternate years as forage crops and as living mulches for corn (Zemenchik et al., 2000). Corn grown in herbicide-suppressed kura clover can produce yields comparable to corn grown after

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Abbreviations: CPY, crude protein yield; DMY, dry matter yield; PSNT, pre-sidedress soil nitrate test.

killed kura clover, but excessive competition by the living mulch can depress corn yields (Zemenchik et al., 2000; Affeldt et al., 2004; Ochsner et al., 2010; Sawyer et al., 2010). Following corn production, kura clover living mulch can recover to full forage production by midsummer of the following year (Zemenchik et al., 2000; Affeldt et al., 2004). The performance of the kura–corn system has not, however, been directly compared to other companion crop systems for corn.

Although the aforementioned corn-companion crop systems are often recommended to producers, few if any studies have directly compared their agronomic and environmental performance across several cropping seasons. Therefore, we conducted a 4-yr study in Wisconsin to compare 2-yr rotations of corn grown with kura clover living mulch or interseeded red clover followed by a year of clover production to continuous corn grown with interseeded ryegrass, fall-seeded rye, or no companion. Because forages are usually heavy manured on farms, we also assessed the effects of fall vs. spring manure applications on the performance of these corn-companion crop systems. Previous papers published from this study reported the off-season herbage production and N uptake of companion crops fertilized with manure and their effects on spring runoff and soil quality (Jokela et al., 2009; Grabber and Jokela, 2013). The current and final paper examines the soil N levels and forage yields of these manured corn-companion crop systems in relation to continuous corn fertilized solely with inorganic N.

MATERIALS AND METHODS

Crop Management

The study was conducted near Prairie du Sac, WI (43°20′ N, 89°43′ W), on a Bertrand silt loam soil (fine-silty, mixed, superactive, mesic Typic Hapludalfs). Before the study, the site was regularly manured and managed under a corn based no-till crop rotation for at least 15 yr. At the start of the trial, the soil to a 15-cm depth had a pH of 6.7 in water, an organic matter content of 37 g kg^{-1} by combustion, excessive levels of available P (36 mg kg^{-1}) and high levels of exchangeable K (155 mg kg^{-1}) by Bray P1, and adequate levels of S and B (Peters, 2007). As reported previously (Grabber and Jokela, 2013), precipitation and temperatures during crop growth differed considerably across the 4 yr of the study. Cumulative precipitation during the May through September growing season totaled 423 mm in 2003, 642 mm in 2004, 369 mm in 2005, and 612 mm in 2006 compared to a 30-yr average of 465 mm. Air temperature from May through September averaged 19.0°C in 2003, 17.5°C in 2004, 19.3°C in 2005, and 17.9°C in 2006 compared to a 30-yr average of 18.7°C.

Factorial combinations of two manure treatments and five corn-companion crop systems were assigned to 6 by 12 m plots arranged in a randomized complete block design with four replications. After initiating cropping sequences in 2001 and 2002, the main study was conducted from 2003 to 2006 with both phases of the 2-yr corn–clover rotations present every year (Grabber and Jokela, 2013). Starting in the fall of 2002, continuous corn and both phases of the corn–clover rotations received surface-banded liquid dairy manure applied near 14 November or 9 April at a rate of 112,000 L ha^{-1}(Grabber and Jokela, 2013). Due to excessive soil test P, manure was applied to match the yearly uptake of P by crops rather than their N fertilizer requirements. Based on standard analyses (Peters, 2003), the manure had a solids content of 38 (SD 16.9) g kg^{-1} and provided an average of 263 (SD 19.5) kg ha^{-1} of total N, 150 (SD 11.6) kg ha^{-1} of ammonium N, 36 (SD 6.3) kg ha^{-1} of P, 185 (SD 30.4) kg ha^{-1} of K and 16 (SD 3.8) kg ha^{-1} of S at each application. Manure N credits for corn were set at 30, 10, and 5% of total N applied in the first, second, and third years, respectively, after spreading (Laboski et al., 2012). Owing to yearly variations in manure composition, manure N credits contributed 95 to 140 kg ha^{-1} of the 180 kg ha^{-1} of available N recommended for corn at our site (Laboski et al., 2012). The balance of N for continuous corn was provided by 40 to 85 kg ha^{-1} of N as NH_4NO_3 broadcast at planting. Legume credits for first year corn were set at 135 kg N ha^{-1} for fall-terminated red clover (Laboski et al., 2012). Kura clover living mulch was also assumed to provide 135 kg N ha^{-1} of N for corn, but N credits have not been clearly defined from previous studies (Zemenchik et al., 2000; Affeldt et al., 2004; Sawyer et al., 2010)(R.J. Berkevich. 2008. Kura clover used as a living mulch in a mixed cropping system. M.S. thesis. Univ. of Wisconsin, Madison). Thus combined legume and manure N credits for first year corn in rotation ranged from 230 to 275 kg ha^{-1}. To help us assess the effects of these differing N inputs on response variables, the study included additional non-manured continuous corn plots grown without companion crops that were fertilized solely with 0, 85, 170, and 255 kg ha^{-1} of N as NH_4NO_3 broadcast at planting; the two highest rates were selected to closely correspond to estimated N inputs for manured continuous corn and manured corn grown in rotation with clovers.

Throughout the trial, a glyphosate-resistant hybrid corn (Croplan Genetics 364RR LR-B1, 95 d) was no-till planted near 9 May at an average population of 82,200 seeds ha^{-1} in eight rows per plot spaced 76 cm apart. Corn was planted with a John Deere 1750 Maxemerge Plus (John Deere, Moline, IL) equipped with fluted coulters, toothed row cleaners, and double-disc openers. Within-row granular tefluthrin [(1*S*,3*S*)-*rel*-2,3,5,6-tetrafluoro-4-methylbenzyl 3-((*Z*)-2-chloro-3,3,3-trifluoroprop-1-en-1-yl)-2,2-dimethylcyclopropanecarboxylate] insecticide (0.16 kg a.i. ha^{-1}) and side-banded starter fertilizer (6, 7, and 39 kg ha^{-1} of N, P, and K, respectively) were applied at planting. Starter, manure, and soil reserves provided ample P and K for crop production in corn-companion crop treatments, but 65 kg ha^{-1} of K as KCl was broadcast in October 2004 and May 2006 to maintain recommended soil test levels in non-manured continuous corn treatments fertilized with inorganic N.

Following an application of 1.26 kg a.e. ha^{-1} of glyphosate [N-(phosophonomethyl)glycine], clovers were first established in 2001 by no-till drilling kura clover (Endura) at 14.6 kg ha^{-1} and red clover (Cinnamon) at 9 kg ha^{-1} on 30 April and 8 August, respectively. During establishment, kura clover was sprayed with 0.32 kg a.i. ha^{-1} of sethoxydim (2-[1-(ethoxyimino)butyl]-5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one) on 1 June 2001 and with 1.68 kg a.e. ha^{-1} of 2,4-DB (4-(2,4-dichlorophenoxy)butyric acid) on 28 June 2001 for weed control, and harvested once on 31 Aug. 2001. In 2002, clovers were harvested on 21 June and 5 August.

During corn production, established kura clover stands and weeds were suppressed with 1.0 kg a.e. ha^{-1} of glyphosate plus 0.14 kg a.e. ha^{-1} of dicamba (3,6-dichloro-2-methoxybenzoic acid) sprayed near 29 April and with 1.0 kg a.e. ha^{-1} of glyphosate sprayed near 6 June. Kura clover growing within each corn row was killed by a band application of 0.21 kg a.e. ha^{-1} of clopyralid

(3,6-dichloro-2-pyridinecarboxylic acid) applied near 12 May. Weeds in all other corn plots were sprayed with 2.0 kg a.e. ha^{-1} of glyphosate near 29 April, followed by 1.12 kg a.e. ha^{-1} 2,4-D (2,4-dichlorophenoxyacetic acid) near 12 May, and 1.0 kg a.e. ha^{-1} of glyphosate near 6 June. Due to a severe infestation of annual grasses, 1.5 kg a.e. ha^{-1} of glyphosate was also applied on 28 June 2005 to the rye and no-companion continuous corn treatments.

Starting in 2002, inter-row areas between corn were interseeded near 11 June with four rows of red clover (Marathon or C328) at 13.4 kg ha^{-1} or tetraploid Italian ryegrass (Aurelia or Monarque) at 33.6 kg ha^{-1} using a no-till drill (TYE Pasture Pleaser, AGCO, Duluth, GA) equipped with ripple coulters and double-disc openers. The drill was also used to seed rye (Homil 21 or variety not specified) at 112 kg ha^{-1} near 20 September in 2002, 2003, and 2005 and on 5 October in 2004. Interseeding produced acceptable stands of red clover (>85 plants m^{-2}) for forage production in 2003 and 2005. In 2004 and 2006, red clover was reseeded near 15 April because interseedings made the previous year failed during dry August conditions. During establishment, spring reseeded red clover was sprayed with 1.12 kg a.e. ha^{-1} of 2,4-DB near 8 May and with 0.32 kg a.i. ha^{-1} of sethoxydim near 19 May. During forage production, red and kura clovers were sprayed with 0.32 kg a.i. ha^{-1} of sethoxydim about 10 d following the first harvest in 2006 to suppress annual grasses. Lambda-cyhalothrin (3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethyl-cyano(3-phenoxyphenyl)methyl cyclopropanecarboxylate) at 0.03 kg a.i. ha^{-1} was sprayed yearly as needed to control leafhoppers (*Empoasca fabae*) on clovers. Following forage production, red clover was killed with 4.2 kg a.e. ha^{-1} of glyphosate applied near 18 October in preparation for corn planting the following spring.

Soil Sampling and Forage Harvest from 2003 to 2006

Near 16 June, three within-row and three between-row cores were taken yearly from each corn plot to a depth of 30 cm using a 2.5-cm diam. hand probe and combined for a pre-sidedress soil nitrate test (PSNT). Around 30 October, two within-row and two between-row cores per plot were taken each year with a 4-cm diam. tractor-mounted hydraulic probe (Giddings Machine Co., Ft. Collins, CO) to a depth of 120 cm. Soil cores were divided into 0 to 30, 30 to 60, and 60 to 120 cm increments, composited by depth, and subsampled for analysis. After drying at 35°C in forced-air ovens, 1.5 g soil samples passed through a 2-mm screen were extracted for 15 min with 15 mL of 2 M KCl and filtrates were analyzed for nitrate N by flow injection analysis (QuickChem Method 12-107-04-1-B; Lachat Instruments, Loveland, CO). Total N was determined by dry combustion (Elementar VarioMax CN analyzer, Elementar Americas, Inc., Mt. Laurel, NJ). Soil bulk densities at each depth increment, determined by drying cores at 105°C, were used to calculate kg ha^{-1} of residual fall nitrate N and total N in the soil profile.

Whole corn plants from four 6-m rows per plot were harvested 15 cm above the soil surface and weighed with a plot harvester (Hege 212, Wintersteiger Inc, Salt Lake City, UT) equipped with a row-independent corn chopper (Kemper, Stadtlohn, Germany). Corn was harvested around 10 September in 2003, 2005, and 2006 at an average moisture content of 560 g kg^{-1}. Equipment failure in 2004 delayed corn harvested until 28 September at an average moisture content of 460 g kg^{-1}. During forage production, a 1.5 by 6-m strip through the middle of kura clover and red clover plots were harvested 5 cm above the soil surface and weighed using a Hege 212 plot harvester equipped with a double-sickle cutter bar around 13 June, 26 July, and 7 September. Red clover reseeded in April of 2004 and 2006 was harvested twice for yield around 10 July, and 7 September. Subsamples of corn and clover forage were taken at harvest and dried at 55°C in forced-air ovens to determine moisture content. Dried plant samples were ground to pass through a 1-mm screen with a Wiley mill (Arthor H. Thomas Co., Philadelphia, PA) and analyzed for total N by dry combustion (FP2000 analyzer, LECO Corporation, St Joseph, MI) or by a micro-Kjeldahl technique (QuikChem Method 13-107-06-2-D; Lachat Instruments, Loveland, CO). Crude protein was calculated as 6.25 × total N.

Nitrogen balance was calculated from measured inputs of N from fertilizer and manure plus estimates of biological fixation minus crop N removal at harvest. We assumed that biologically fixed N represented 80% of total legume plant N (minus adjustments for available manure and fertilizer N) and that aboveground measured plant N accounted for two-thirds of total plant N (Meisinger and Randall, 1991; Michael Russelle, personal communication, 2013).

Statistical Analyses

We subjected soil N and crop yield data from 2003 to 2006 to a mixed model analysis in a factorial design by running PROC MIXED (SAS, 2003). Data were initially analyzed by year and then repeated measures analyses with first-order autoregressive variance structures were run across years (Yandell, 1997). Cropping system, manure application time, soil depth, and rotation cycle were considered fixed effects and blocks or blocks within years and years were considered random effects. In analyses run across years, rotation cycle was used to assess shifts in soil nitrate and crop yield over time. Each rotation cycle lasted 2 yr (cycle 1, years 2003 and 2004; cycle 2, years 2005 and 2006), which corresponded to the minimum length of time needed for all cropping systems to complete a rotation sequence and return to the same plot of land. In most cases, manure application time had nonsignificant ($P > 0.05$) effects on response variables. Therefore, data from corn-companion crop systems were usually pooled across fall vs. spring manure treatments for statistical analyses that included non-manured continuous corn treatments fertilized with inorganic N. If F tests were significant ($P \leq 0.05$), then least square means of fixed effects were compared at $P = 0.05$ using a t tests performed by a SAS pdmix800 macro (Saxton, 1998). Unless noted otherwise, treatment differences described in the text were significant at $P = 0.05$.

RESULTS

Pre-sidedress Soil Nitrate Test and Residual Fall Nitrate in the Soil Profile

Cropping system significantly affected PSNT estimates of available N in mid-June and residual fall nitrate levels in late October in soil sampled to a depth of 30 cm (Table 1). Rotation cycle and the timing of manure application had no effect on PSNT or residual fall nitrate concentrations. Among manured treatments, PSNT concentrations were greatest for continuous corn grown with interseeded ryegrass, fall seeded rye, or no companion and lowest for corn grown in rotation with kura clover living mulch. During the first year of each rotation cycle (2003 and 2005) all manured treatments equaled or exceeded the PSNT threshold of 21 mg kg^{-1}, a level above which no additional N is recommended in Wisconsin (Laboski et al., 2012). By contrast, these treatments had PSNT concentrations below 17 mg kg^{-1} during the second year of each rotation cycle (2004 and 2006, Fig. 1). Non-manured continuous corn grown solely with inorganic N followed a similar yearly pattern in PSNT concentrations, with the 85 kg ha^{-1} N application tracking most closely with the manured treatments (data not shown). By the late October sampling, residual fall nitrate concentrations in the top 30 cm of soil had declined, but among the manured treatments concentrations were now highest for corn grown with kura clover living mulch (Table 1). Manured corn grown with interseeded ryegrass and manured clovers in forage production had the lowest residual fall nitrate concentrations that were comparable to non-manured continuous corn fertilized with 0 or 85 kg ha^{-1} of inorganic N.

The distribution and total quantity of residual fall nitrate in soil to a depth of 120 cm differed considerably between cropping systems (Table 2). Differences were most pronounced in the top 30 cm of soil, which contributed to a significant cropping system × soil depth interaction. Among manured treatments, corn grown with kura clover living mulch or interseeded red clover had the highest quantities of total residual fall nitrate to a depth of 120 cm, which were comparable to continuous corn fertilized solely with 170 kg ha^{-1} of inorganic N. By contrast, manured clovers in forage production had the lowest quantities of total residual fall nitrate. When successfully established the previous year by interseeding, red clover in forage production during 2003 and 2005 had total residual fall nitrate levels that equaled kura clover, averaging 11.6 kg N ha^{-1} (Fig. 2). When interseedings failed, however, spring-reseeded red clover in forage production during 2004 and 2006 had total residual fall nitrate that was twofold higher than kura clover (37.4 vs. 18.0 kg N ha^{-1}). Manured continuous corn treatments had intermediate amounts of total residual fall nitrate (Table 2). When averaged across both phases of the crop rotation, the total quantity of residual fall nitrate for the manured corn–kura clover system (31.9 kg ha^{-1}) and the corn–red clover system (38.7 kg ha^{-1}) were within the range observed for manured continuous corn systems (30.0–41.2 kg ha^{-1}).

Total residual fall nitrate was related to N balance (fertilizer N inputs minus crop N removal) in non-manured continuous corn fertilized with inorganic N (Fig. 3). Total residual fall nitrate was not, however, related to N balance in corn-companion crop systems amended with manure (data not shown). The manured treatments, however, accumulated differing amounts of total soil N by the second rotation cycle and there was a cropping system × soil depth interaction ($P < 0.09$). Total N for manured corn-clover rotations averaged 7377 kg ha^{-1} compared to 6713 kg ha^{-1} for continuous corn treatments in the top 30 cm of soil (Fig. 4). Total soil N averaged 2200 kg ha^{-1} at the 30- to 60-cm depth and 1460 kg ha^{-1} at the 60- to 120-cm depths with no differences between cropping systems (data not shown).

Table 1. Pre-sidedress soil nitrate test (PSNT) and residual fall nitrate concentrations in soil sampled to a depth of 30 cm as influenced by cropping system. Data are averaged across rotation cycles and manure application times.

Cropping system	PSNT	Residual nitrate
	—— NO_3–N mg kg^{-1} ——	
Manured annually		
Corn–Kura clover rotation		
Kura clover phase	–	1.36f
Corn/kura clover living mulch phase†	16.0e‡	8.14b
Corn–Red clover rotation		
Red clover phase	–	2.17f
Corn/interseeded red clover phase†	22.2d	6.57bc
Continuous corn/interseeded ryegrass§	27.5c	2.77f
Continuous corn/fall-seeded rye§	24.9cd	5.68cd
Continuous corn/no companion§	26.7c	4.67de
No manure		
Continuous corn/no companion¶		
0 kg ha^{-1} N yr^{-1}	7.5f	1.80f
85 kg ha^{-1} N yr^{-1}	26.5c	2.89ef
170 kg ha^{-1} N yr^{-1}	41.1b	5.68cd
255 kg ha^{-1} N yr^{-1}	59.2a	15.74a

† Manure and legume credits provided about 250 kg ha^{-1} yr^{-1} of N for corn.

‡ In each column, least square means followed by the same letter are not statistically different at $P = 0.05$.

§ Manure credits and inorganic fertilizer provided about 180 kg ha^{-1} yr^{-1} of N for corn.

¶ Nitrogen amendments only from inorganic fertilizer.

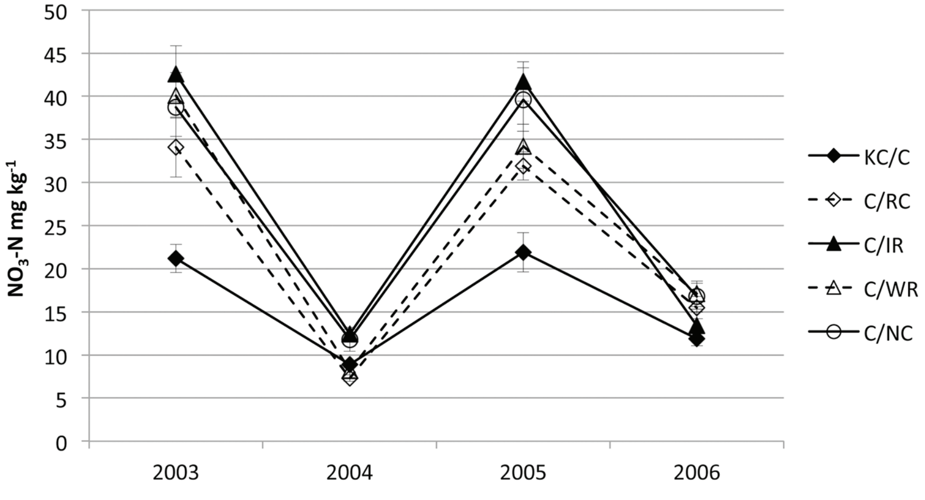

Fig. 1. Annual presidedress soil nitrate test concentrations for rotational corn grown with kura clover living mulch (KC/C) or interseeded red clover (C/RC) and for continuous corn grown with interseeded Italian ryegrass (C/IR), fall-seeded winter rye (C/WR), or no companion (C/NC). Data are averaged across manure application times and bars indicate SE.

Table 2. Distribution and total quantity of residual fall nitrate in soil sampled to a 120 cm depth as influenced by cropping system. Data are averaged across rotation cycles and manure application times.

Cropping system	Distribution			Total
	0–30 cm	30–60 cm	60–120 cm	0–120 cm
	NO_3–N kg ha^{-1}			
Manured annually				
Corn–Kura clover rotation				
Kura clover phase	5.4f†	2.2e	6.9ef	14.6g
Corn/kura clover living mulch phase‡	32.0b	8.2b	9.0def	49.2bc
Corn–Red clover rotation				
Red clover phase	8.7f	4.7cde	11.1cde	24.6fg
Corn/interseeded red clover phase‡	26.0bc	7.6bc	19.2b	52.8b
Continuous corn/interseeded ryegrass§	10.8f	5.0cde	14.1bcd	30.0ef
Continuous corn/fall-seeded rye§	22.4cd	7.5bc	11.2cde	41.2cde
Continuous corn/no companion§	18.8de	5.8bcd	12.3cde	36.8de
No manure				
Continuous corn/no companion¶				
0 kg ha^{-1} N yr^{-1}	7.1f	1.8e	3.7f	12.7g
85 kg ha^{-1} N yr^{-1}	11.5ef	3.0de	7.5def	22.0fg
170 kg ha^{-1} N yr^{-1}	23.0cd	7.7bc	17.5bc	48.2bcd
255 kg ha^{-1} N yr^{-1}	62.0a	33.1a	62.1a	157.3a

† In each column, least square means followed by the same letter are not statistically different at $P = 0.05$.

‡ Manure and legume credits provided about 250 kg ha^{-1} yr^{-1} of N for corn.

§ Manure credits and inorganic fertilizer provided about 180 kg ha^{-1} yr^{-1} of N for corn.

¶ Nitrogen amendments only from inorganic fertilizer.

Forage Yields

Forage dry matter yield (DMY) and crude protein yield (CPY) of manured corn-companion crop systems were influenced by a significant cropping system × rotation cycle interaction. Averaged across manure application times in the first rotation cycle, DMY and CPY of corn grown in rotation with red clover or kura clover were about 12% greater than continuous corn grown with grass companion crops while continuous corn grown without a companion crop had intermediate yields (Table 3). Yield differences were magnified in the second rotation cycle, where DMY and CPY of corn grown in rotation with red clover exceeded the rotation with kura clover by about 18%, and all continuous corn treatments by about of 35%. In the case of non-manured continuous corn, DMY and CPY in both rotation cycles peaked with 170 kg ha^{-1} of applied inorganic N. In the first rotation cycle, DMY and CPY of non-manured corn fertilized with 170 kg ha^{-1} of inorganic N equaled manured rotated corn grown with either clover and in most cases it equaled manured continuous corn grown with or without grass companion crops. In the second rotation cycle, DMY and CPY of non-manured corn fertilized with 170 kg ha^{-1} of inorganic N yielded less than manured corn grown with red clover, but equaled manured corn grown in rotation with kura clover or continuously with or without grass companion crops.

In contrast to corn, rotation cycle did not affect DMY and CPY of manured clovers during forage production. Clovers had much lower DMY than corn, with red clover averaging 10.1 Mg ha^{-1} compared to 8.5 Mg ha^{-1} for kura clover. Crude protein concentrations, however, averaged 202.0 g kg^{-1} for kura clover and 180.7 g kg^{-1} for red clover vs. an average of 67.7 g kg^{-1} for corn. As a result, CPY of clovers greatly exceeded

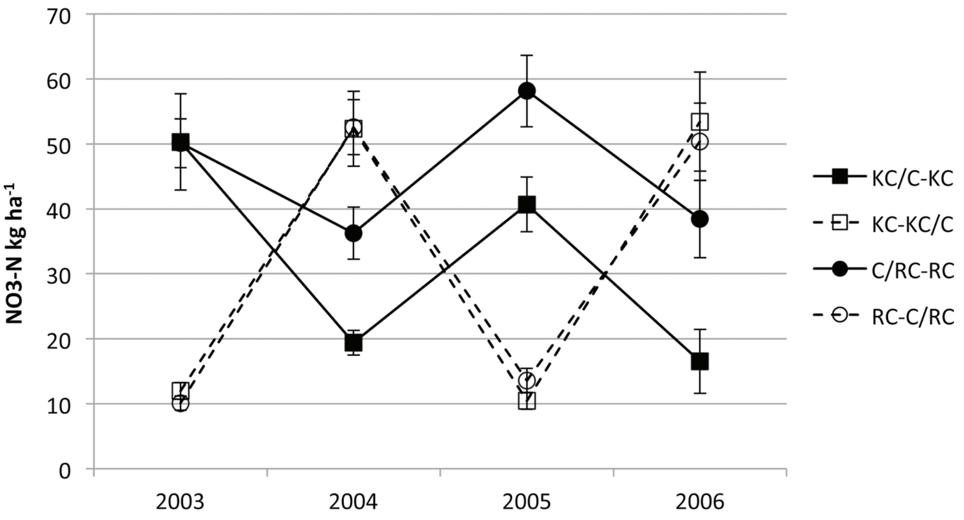

Fig. 2. Yearly quantity of total residual fall nitrate in soil sampled to a 120-cm depth for rotation sequences including alternating years of kura clover (KC) and kura clover living mulch with corn (KC/C) and alternating years of red clover (RC) and corn with interseeded red clover (C/RC). Data are averaged across manure application times and bars indicate SE.

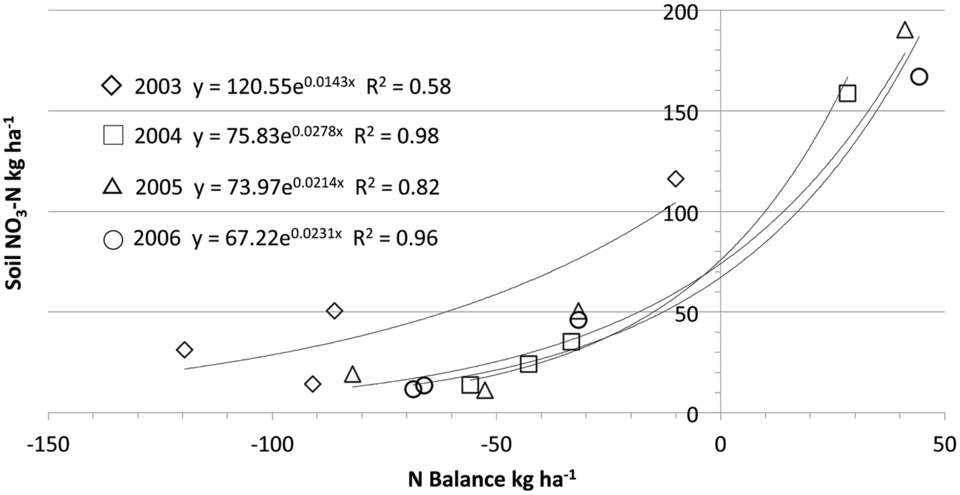

Fig. 3. Total residual fall nitrate in soil sampled to 120-cm depth for continuous corn grown with no companion crop and 0 to 255 kg N ha^{-1} from inorganic fertilizer as a function of N balance.

corn. Within each rotation cycle, yields of kura clover were relatively stable (data not shown), but yields of red clover varied considerably depending on the success of stand establishment by interseeding the previous year. When successfully established by interseeding, red clover produced average DMY of 12.1 Mg ha^{-1} and CPY of 2.2 Mg ha^{-1} during the first year of each rotation cycle. When interseedings failed, spring reseeded red clover produced lower average DMY of 8.1 Mg ha^{-1} (similar to kura clover) and CPY of 1.5 Mg ha^{-1} (lower than kura clover) during the second year of each rotation cycle.

A companion crop × manure application time interaction also influenced forage DMY and CPY of corn. Applying manure in fall rather than in spring reduced DMY and CPY of continuous corn grown with rye, but increased DMY and CPY of continuous corn grown with ryegrass (Table 4). By contrast, manure application time did not influence yields of continuous corn grown without a companion crop or yields of corn and clovers grown in rotation.

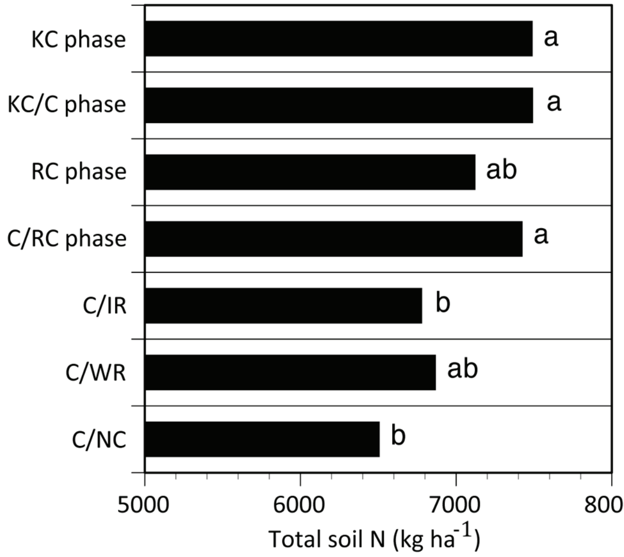

Fig. 4. Average total soil N to a depth of 30 cm in the second rotation cycle for rotation sequences including alternating years of kura clover (KC) and kura clover living mulch with corn (KC/C) and of red clover (RC) and corn with interseeded red clover (C/RC) and for continuous corn grown with Italian ryegrass (C/IR), winter rye (C/WR) or no companion (C/NC). Data are averaged across manure application times. Least square means followed by the same letter are not statistically different at $P = 0.05$.

In addition to comparing yields of individual crops, the overall feed production capacity of manured rotations in relation to manured continuous corn should be considered. When data in Table 3 are averaged across both phases of the crop rotation, the overall DMY of the corn–red clover rotation (15.4 Mg ha^{-1}) and the corn–kura clover rotation (14.3 Mg ha^{-1}) were similar, but substantially lower than continuous corn treatments (18.0–19.4 Mg ha^{-1}) in the first rotation cycle. The overall CPY of the corn–red clover rotation (1.58 Mg ha^{-1}) and the corn–kura clover rotation (1.47 Mg ha^{-1}) were also similar during the first rotation cycle, but in contrast to DMY, both rotations had greater CPY than continuous corn treatments (1.21 Mg ha^{-1}). In the second rotation cycle, overall DMY for corn–red clover rotation (14.7 Mg ha^{-1}) and continuous corn treatments (14.1 Mg ha^{-1}) were similar, but greater than the kura–corn rotation (12.3 Mg ha^{-1}). Overall CPY in the second rotation cycle was greatest for the corn–red clover rotation (1.60 Mg ha^{-1}), intermediate for the kura–corn rotation (1.48 Mg ha^{-1}) and lowest for continuous corn treatments (1.00 Mg ha^{-1}).

DISCUSSION

Pre-Sidedress Soil Nitrate Test and Residual Fall Nitrate in the Soil Profile

The PSNT of soil sampled in mid-June to a depth of 30 cm indicated all manured corn-companion crop treatments had nitrate levels that were similar to or lower than continuous corn amended solely with 85 kg ha^{-1} of inorganic N (Table 1). Corn grown in rotation with clovers, especially kura clover, had the lowest PSNT concentrations, in part because residual nitrate in the top 30 cm of soil was drawn down during forage production of clovers the previous year. Lower soil nitrate levels following clover production would be expected because legumes readily take up and use soil nitrate in preference to N fixation (Russelle and Birr, 2004). Going into corn production, spring nitrate levels with kura clover likely remained very low in the spring until stands were strongly suppressed and strip-killed at corn planting in early May. By contrast, earlier mineralization of October-terminated red clover yielded higher PSNT concentrations the following spring, suggesting this system provided

Table 3. Dry matter yields and crude protein yields of silage corn and clover as influenced by cropping system and by rotation cycle. Data are averaged across manure application times.

Cropping system	Dry matter yield		Crude protein yield	
	Cycle 1	Cycle 2	Cycle 1	Cycle 2
	Mg ha^{-1}			
Manured annually				
Corn–Kura clover rotation				
Kura clover phase	8.4g†	8.7e	1.64b	1.81a
Corn/kura clover living mulch phase‡	20.3ab	16.0b	1.31c	1.15c
Corn–Red clover rotation				
Red clover phase	9.9f	10.2d	1.78a	1.86a
Corn/interseeded red clover phase‡	20.8a	19.2a	1.35c	1.34b
Continuous corn/interseeded ryegrass§	18.0de	13.9c	1.19d	1.00cd
Continuous corn/fall-seeded rye§	18.7cd	14.2c	1.19d	0.98d
Continuous corn/no companion§	19.4bc	14.1c	1.26cd	1.01cd
No manure				
Continuous corn/no companion¶				
0 kg ha^{-1} N yr^{-1}	8.9fg	6.8f	0.46f	0.43e
85 kg ha^{-1} N yr^{-1}	17.1e	14.2c	0.99e	0.94d
170 kg ha^{-1} N yr^{-1}	19.8abc	15.5bc	1.30cd	1.11cd
255 kg ha^{-1} N yr^{-1}	18.4cde	14.5bc	1.31cd	1.09cd

† In each column, least square means followed by the same letter are not statistically different at $P = 0.05$.

‡ Manure and legume credits provided about 250 kg ha^{-1} yr^{-1} of N for corn.

§ Manure credits and inorganic fertilizer provided about 180 kg ha^{-1} yr^{-1} of N for corn.

¶ Nitrogen amendments only from inorganic fertilizer.

a better synchrony of N supply with early season N uptake by corn. By late October, however, corn grown with either kura or red clover had relatively high residual fall nitrate concentrations in the top 30 cm of soil, likely because estimated legume and manure N credits of 250 kg ha^{-1} exceeded the 180 kg ha^{-1} of N recommended for corn at the site (Laboski et al., 2012). Late season nitrate accumulation near the soil surface was also made possible by the limited uptake of N (11–32 kg ha^{-1}) by interseeded red clover and kura clover living mulch during the late summer and fall (Grabber and Jokela, 2013). While applying excess N to corn is not a recommended practice, we applied equal amounts of manure to both phases of the corn–clover rotations to balance the experimental design and to reflect typical on-farm practices for 2-yr rotations that offer limited options for manure application. Applying manure to forage legumes can be an effective strategy to reduce the risk of nitrate leaching, however, shifting more manure to the legume phase could damage stands while greater applications to the corn phase would further increase the risk of nitrate leaching (Kelling and Schmitt, 2003; Ketterings et al., 2007).

Contrary to expectations, rotated corn grown with excess legume and manure N credits of 250 kg ha^{-1} had total residual

Table 4. Dry matter yields and crude protein yields of silage corn and clover as influenced by cropping system and by fall vs. spring manure application. Data are averaged across rotation cycles.

Cropping system	Manure application	Dry matter yield	Crude protein yield
		Mg ha^{-1}	
Manured annually			
Corn–Kura clover rotation			
Kura clover phase	Fall	8.4h†	1.74a
	Spring	8.7h	1.73a
Corn/kura clover living mulch phase‡	Fall	17.7bc	1.21cd
	Spring	18.4b	1.22bc
Corn–Red clover rotation			
Red clover phase	Fall	10.1g	1.82a
	Spring	10.2g	1.83a
Corn/interseeded red clover phase‡	Fall	20.3a	1.36b
	Spring	20.0a	1.36b
Continuous corn/interseeded ryegrass§	Fall	16.8cd	1.17cd
	Spring	15.2f	1.03ef
Continuous corn/fall-seeded rye§	Fall	15.6ef	1.02f
	Spring	17.0cd	1.13cde
Continuous corn/no companion§	Fall	16.3de	1.10def
	Spring	16.9cd	1.16cd

† In each column, least square means followed by the same letter are not statistically different at $P = 0.05$.

‡ Manure and legume credits provided about 250 kg ha^{-1} yr^{-1} of N for corn.

§ Manure credits and inorganic fertilizer provided about 180 kg ha^{-1} yr^{-1} of N for corn.

fall soil nitrate levels that were similar to or only somewhat higher than manured continuous corn grown with recommended rates of N (Table 2). By contrast, continuous corn amended with 255 kg ha^{-1} of inorganic N had a threefold greater quantity of total residual fall nitrate in the soil profile (Table 2), which would undoubtedly increase the risk of nitrate leaching during and after corn production (Toth and Fox, 1998). Nitrate accumulation with excessive application of inorganic N was reflected in N balance calculations (Fig. 3), but the lack of such a relationship for manured corn grown with clovers can in part be explained by the incorporation of excess N into the organic N pool, which would be reflected in total soil N (Fig. 4). The risk of nitrate leaching in corn–clover rotations was also lessened by draw down of nitrate throughout the soil profile by clovers grown for forage after corn, but spring-seeded red clover was less effective than successfully interseeded red clover or kura clover for drawing down nitrate levels during forage production (Fig. 2). While not examined here, longer duration corn–red clover rotation sequences could more efficiently draw down fall soil nitrate levels throughout the rotation, particularly if manure applications to corn were shifted away from the first year to subsequent years where lower legume N credits would permit higher applications of manure N (Laboski et al., 2012). Lengthening the corn–kura clover rotation sequence might produce similar benefits, but consecutive years of corn could adversely affect the persistence and recovery of kura clover living mulch.

Continuous corn amended with the recommended rates of 180 kg ha^{-1} of available N from manure plus inorganic fertilizer had relatively high PSNT concentrations that were not affected by the presence or absence of rye or ryegrass companion crops (Table 1). As noted in an accompanying paper (Grabber and Jokela, 2013), rye planted in September after corn harvest had negligible fall growth, but its vigorous spring growth accumulated an average of 100 kg ha^{-1} of N by stand termination at corn planting in early May. By contrast, ryegrass interseeded into corn accumulated an average of 47 kg ha^{-1} of N before stand termination the following year at corn planting, with growth concentrated mainly during the late summer and fall (Grabber and Jokela, 2013). Thus it appears that the differing N uptake and mineralization characteristics of these grass companion crops had little effect on the availability of soil N at the onset of rapid corn growth in mid-June. Due partly to crop uptake, nitrate concentrations declined by the end of the growing season in late October, but continuous corn grown with interseeded ryegrass had 50% lower residual fall nitrate concentrations in the top 30 cm of soil than continuous corn grown with fall-seeded rye or no companion.

Although ryegrass interseeded into manured continuous corn efficiently drew down nitrate near the soil surface, its overall total residual fall nitrate levels to a depth of 120 cm were not significantly different from manured continuous corn grown with rye or no companion crop (Table 2). Among other benefits, interseeded ryegrass and fall-seeded rye are recommended for taking up excess nitrate following corn production (Clark, 2007). Our results, however, suggest these cover crops had little long-term effect on total residual fall nitrate compared to manured corn without a companion crop, perhaps because scavenged N was merely recycled.

Silage Corn and Clover Yields

When data in Table 3 are averaged across both phases of the crop rotation, the manured corn–clover production systems provided 0 to 23% less forage DMY, but 26 to 60% more forage CPY than manured continuous corn systems. Corn with interseeded red clover produced the highest and most consistent yields of silage corn, particularly during the second rotation cycle. In addition to possible N-rotation effects, superior yields of silage corn were in part due to low weed competition fostered by the crop rotation and the complete fall-killing of red clover and accompanying weeds before corn planting the following spring (Grabber and Jokela, 2013). Red clover affords little or no competition with corn if interseeded about 30 d after corn planting (Scott et al., 1987; Abdin et al., 1997; Clark, 2007; Baributsa et al., 2008), but limited seedling development before corn canopy closure contributed to frequent stand failures during dry summer conditions (Grabber and Jokela, 2013) and, as described in the results section, lower DMY and CPY of red clover following reseeding in the spring. The red clover system also provided only modest improvements in groundcover during the off-season period and reductions in soil and nutrient runoff compared to continuous corn grown without a companion crop (Grabber and Jokela, 2013). Finally, interseeding red clover with a no-till drill was difficult, requiring great care to avoid damaging corn plants. Many of these difficulties could be overcome shifting red clover stand termination to the spring and by earlier interseeding to permit greater red clover seedling development before corn canopy closure, but other studies suggest these management practices would likely reduce corn yields (Barnett, 1990; Smith et al., 1992; De Haan et al., 1997). If developed, improved techniques for establishing interseeded red clover would not only improve its value as a cover crop, but also boost DMY of short duration corn–red clover rotations to levels comparable to that of continuous corn, yet with substantially greater CPY and lower N fertilizer inputs.

Strongly suppressed and strip-killed kura clover living mulch produced corn yields that were equal to corn grown with red clover during the first rotation cycle, but intermediate between corn grown with red clover and continuous corn grown with or without grass companion crops during the second rotation cycle (Table 3). Previous shorter-term studies suggest kura clover living mulch can have positive, neutral, or negative effects on corn yields (Zemenchik et al., 2000; Affeldt et al., 2004; Sawyer et al., 2010). Of the companion crop systems we examined, kura clover came the closest to providing reliable year-round groundcover, but it produced arguably excessive growth in the spring before corn planting and marginal regrowth following corn that permitted substantial ingress of weeds (Grabber and Jokela, 2013). At times the vigorous spring growth of kura clover and weeds may excessively compete for soil moisture and soil nitrate, and this may account for disappointing yields of corn observed in the second rotation cycle and in some other studies (Ochsner et al., 2010; Sawyer et al., 2010). Throughout our study, yields of manured corn grown with kura clover equaled continuous corn fertilized solely with 170 kg ha^{-1} of inorganic N, suggesting that this system conferred no rotational benefits to corn. While more consistent, the yield potential of kura clover was much lower than red clover (Table 3) and this in part was related to its slow recovery following corn production (Zemenchik et al., 2000). Seeding a winter cereal into kura clover after silage corn harvest could improve forage yields and limit weed ingress the following spring, but previous work (Contreras-Govea and Albrecht, 2005) suggests clover recovery would further be delayed without boosting total season yields. Growing rapidly spreading and more vigorous kura clover germplasm (Riday and Albrecht, 2010) might improve forage production, but greater competitiveness of kura clover could adversely affect corn yields.

In contrast to other companion crop systems, DMY and CPY of continuous corn grown with annual grasses were sensitive to the timing of manure application (Table 4). During both rotation cycles, applying manure in the fall maximized yields of corn grown with ryegrass while spring manure applications maximized yields of corn grown with rye. With optimally timed manure applications, yields of continuous corn grown with ryegrass or rye equaled continuous corn grown without a companion crop, but ill-timed manure applications on these grass companion crops depressed corn yields by 7%. If growth is excessive, rye or ryegrass can compete too vigorously with corn for moisture, N, or other nutrients (Ewing et al., 1991; Crandall et al., 2005; Kramberger et al., 2009), but in our study the effects of manure on corn yields were poorly associated with biomass DMY or N accumulation in rye or ryegrass (Grabber and Jokela, 2013). A meta-analysis by Miguez and Bollero (2005), indicated that annual grass cover crops typically have neutral to negative effects on continuous corn yields, but our study may be the first to document the differential response of fall vs. spring manure applications on corn grown with rye or ryegrass. The cause of this differing yield response in corn is not known and merits further investigation. In the absence of companion crops, fall vs. spring manure applications appear to have mixed effects on yields of monoculture corn grown in colder continental regions (Culley et al., 1981; Randall et al., 1999; van Es et al., 2006). Manure applications usually have little effect on the yields of perennial forage legumes or first year corn following legumes in a rotation (Daliparthy et al., 1994; Lory et al., 1995). While these grass companion crops had neutral to slightly negative effects on silage corn yields, an associated study (Grabber and Jokela, 2013) indicated the vigorous spring growth of fall-seeded rye made it the most effective companion crop examined for limiting spring runoff following corn production and fall manuring, but greater fall growth by interseeded ryegrass might make it a better choice to reduce runoff throughout the off season period. Recently applied manure, however, overrode the beneficial effects of grass companion crops on spring runoff and substantially increased loading of reactive P.

Yields of manured continuous corn grown with or without grass companion crops declined from the first to the second rotation cycle (Table 4) and this was due in part to increasing weed pressure (Grabber and Jokela, 2013). Although cover crops like winter rye and interseeded ryegrass are viewed as an effective means of suppressing weed growth in crops (Clark, 2007), their use can limit weed control options for corn (Tharp and Kells, 2000). To minimize experimental confounding of weed control methods over time with companion crop treatments, we used glyphosate amended with appropriate broadleaf herbicides each year for no-till corn production and this likely contributed to increasing weed pressure as the study progressed. Rather than following a rigid regime, producers should use a more diverse array of herbicides, tillage methods, crop rotations, and companion crops to help control weeds and promote high yields of corn-based cropping systems.

Finally as noted in the results section, the PSNT suggested soil N may have been insufficient for optimal yields of manured rotated or continuous corn during the second year of each rotation cycle (2004 and 2006, Fig. 1), but this conflicted with book value recommendations (Laboski et al., 2012) which suggested all treatments had adequate or excessive available N. To avoid complicating N management, we opted to follow book values because the PSNT approach is thought to be less accurate under relatively cool early-season conditions (Andraski and Bundy, 2002; Laboski et al., 2012) such as those we encountered during the second year of each rotation cycle (Grabber and Jokela, 2013). In retrospect, manured continuous corn treatments likely suffered N deficiency during those years because corn yields averaged 1.7 to 3.2 Mg ha^{-1} less than continuous corn fertilized solely with 170 kg ha^{-1} of inorganic N or manured corn grown in rotation with clovers (data not shown). The greatest depression in corn yields occurred with interseeded ryegrass, which grew vigorously during the cooler temperatures and excessive precipitation that persisted throughout much of the 2004 and 2006 growing seasons (Grabber and Jokela, 2013). Thus additional sidedressed N on manured continuous corn amended with recommended rates of N at planting might be justified when PSNT values are low and excessive precipitation persists throughout the growing season.

CONCLUSIONS

Based on results reported here and in a previous paper (Grabber and Jokela, 2013), the corn–red clover system produced the highest and most stable yields of silage corn across rotation cycles and often the highest clover yields. Relatively low competition from red clover and weeds likely contributed to high corn yields. Unfortunately, red clover forage production was often hampered by late summer stand failures during its establishment in corn. Modest growth following corn and preceding forage production also made red clover less effective than other companion crops for limiting runoff from cropland. Under favorable growth conditions at the onset of our study, the corn–kura clover rotation produced silage corn yields similar to the corn–red clover rotation, and among the systems we examined, it came the closest to providing reliable year-round groundcover for protecting soil. As the study progressed, corn yields were reduced by excessive spring growth of kura clover living mulch, while slow regrowth of kura clover following corn limited its forage production potential and permitted substantial ingress of weeds that further limited forage yields. Excessive manure and legume N credits for corn grown with either clover resulted in only modest increases in residual fall nitrate levels in the soil profile, likely because excessive N was incorporated into the organic N pool and clover production the following year appeared to draw down nitrate throughout the soil profile levels to levels far below continuous corn. Consequently, the manured corn–clover systems may have a lower risk of nitrate leaching than continuous corn systems. Draw down of nitrate during clover production, however, contributed to low PSNT estimates of available N, particularly for corn grown with kura clover living mulch. Manured continuous corn grown with or without annual grass companion crops or grown solely with recommended rates of inorganic N produced greater overall DMY than corn–clover rotations, but CPY yields of rotations exceeded continuous corn treatments. Unlike other cropping systems we examined, yields of corn grown with annual grasses were sensitive to the timing of manure application; fall manure promoted higher yields with ryegrass while spring manure favored higher yields with rye. As with kura clover, yields of continuous corn treatments declined over rotation cycles, due in part to increasing weed pressure. Continuous corn systems had relatively high PSNT concentrations that were not affected by the presence or absence of grass companion crops. The presence or absence of grass companion crops and the form of N applied (manure plus inorganic N vs. inorganic N only) also did not appreciably influence total residual fall nitrate levels throughout the soil profile. Among the companion crops examined, surface runoff and losses of P and sediment in the spring were least with rye followed by ryegrass if manure was applied in the fall. Shifting surface-applied manure application to spring in this no-till system largely negated companion crop effects on spring runoff and substantially increased loading of dissolved reactive P.

Lastly, as reported in an associated study (Jokela et al., 2009), the use of kura clover, red clover, ryegrass, or rye as companion crops for corn improved several chemical, physical, and microbial soil properties and overall soil quality. While some specific companion crops performed better for individual soil properties, none stood out as better for the whole range of soil attributes or for overall soil quality. Taken as a whole, no companion crop or manure management system was clearly superior in all attributes related to forage production, nitrate leaching potential, runoff, and soil quality. Thus the most appropriate choice of companion crops and manure management for no-till silage corn will depend on producer requirements for feed production and on site-specific requirements to remediate nitrate leaching and runoff of soil and nutrients from cropland.

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