

# Nitrogen Availability from Composts for Humid Region Perennial Grass and Legume–Grass Forage Production

D. H. Lynch,\* R. P. Voroney, and P. R. Warman

## ABSTRACT

Perennial forages may be ideally suited for fertilization with slow N release amendments such as composts, but difficulties in predicting N supply from composts have limited their routine use in forage production. A field study was conducted to compare the yield and protein content of a binary legume–grass forage mixture and a grass monocrop cut twice annually, when fertilized with diverse composts. In all three years from 1998–2000, timothy (*Phleum pratense* L.)–red clover (*Trifolium pratense* L.) and timothy swards were fertilized with ammonium nitrate (AN) at up to 150 and 300 kg N ha<sup>-1</sup> yr<sup>-1</sup>, respectively. Organic amendments, applied at up to 600 kg N ha<sup>-1</sup> yr<sup>-1</sup> in the first two years only, included composts derived from crop residue (CSC), dairy manure (DMC), or sewage sludge (SSLC), plus liquid dairy manure (DM). Treatments DM at 150 kg N ha<sup>-1</sup> yr<sup>-1</sup> and CSC at 600 kg N ha<sup>-1</sup> yr<sup>-1</sup> produced cumulative timothy yields matching those obtained for inorganic fertilizer. Apparent nitrogen recovery (ANR) ranged from 0.65% (SSLC) to 15.1% (DMC) for composts, compared with 29.4% (DM) and 36.5% (AN). The legume component (approximately 30%) of the binary mixture acted as an effective “N buffer” maintaining forage yield and protein content consistently higher, and within a narrower range, across all treatments. Integrating compost utilization into livestock systems that use legume–grass mixtures may reduce the risk of large excesses or deficits of N, moderate against potential losses in crop yield and quality, and by accommodating lower application rates of composts, reduce soil P and K accumulation.

APPLICATION TO SOIL IS increasingly seen as an option for management of organic wastes and by-products from municipal and industrial sources. Composting is the technology most widely used for pretreatment of these organic feedstocks (Muchovej and Pacosvsky, 1997). Of the 5 million Mg of municipal organic waste annually produced in Canada, more than one-quarter is now composted (Kelleher, 2001). There has been increasing interest in research focusing on the response of annual crops to application of agricultural, municipal, and industrially derived composts when compared with manures and mineral fertilizers (Schlegel, 1992; Paul and Beauchamp, 1993, 1994; Warman, 1995; Wen et al., 1995, 1997; Eghball and Power, 1999a, 1999b; Gagnon et al., 1997; Rodd et al., 2002). Poor recovery of N from composts by annual crops, however, has resulted in recommendations that they be considered solely as soil amendments in crop production (Gagnon et al., 1997). Gagnon et al. (1997), in Quebec, found apparent recov-

ery of compost N by wheat (*Triticum aestivum* L.) ranged from –14% (net N immobilization) to +15%, compared with 56% for ammonium nitrate. Brinton (1985) found that composting reduced N recovery from fresh dairy cattle manure from 28.5 to 9.2%. The reduction in inorganic N content during composting through immobilization as organic N, together with volatilization or leaching of N, often reduces inorganic N levels in compost to less than 15% of the total N. Paul and Beauchamp (1993, 1994, 1995) demonstrated greater <sup>15</sup>N immobilization in soils amended with solid or composted beef cattle manure when compared with an inorganic N fertilizer. N'Dayegamiye et al. (1997) and Kirchmann (1990) found that composted manures mineralized N at a slower linear rate compared with the exponential release of N from fresh manures.

Perennial grasses require sustained, season-long N availability, and may be ideally suited for fertilization with slow N release organic amendments such as composts. Composts may also provide residual plant-available N to perennial forages during early spring and fall, when soil conditions can limit fertilizer application in many regions, as shown for food waste composts (Sullivan et al., 1998) and biosolids and manure (Sullivan et al., 1997). DeLuca and DeLuca (1997) claim that composted manure can only be considered an effective primary fertilizer “once the cumulative N mineralization from previous applications reach steady state,” although this may occur within a relatively short period. As demonstrated for some manures (Beauchamp, 1986, 1987) and composts (Mamo et al., 1999), net N immobilization can occur in the first crop season, followed by net N mineralization under the second crop. In the year following application, Beauchamp (1987) and Paul and Beauchamp (1993) found no difference in crop yield response between inorganic fertilizer N and liquid poultry manure, liquid dairy cattle manure, or composted manure. While the effectiveness of repeated applications of sewage sludge (municipal biosolids) in enhancing forage supply has been demonstrated (Cogger et al., 1999; Zebbarth et al., 2000), with some exceptions (Warman and Cooper 2000a, 2000b), the benefits of repeat applications of composts to perennial forage crops remain largely untested.

Predicting availability of N from organic amendments is difficult (Gilmour et al., 1985; Janssen, 1996; N'Dayegamiye et al., 1997; Qian and Schoenau, 2002) and both the quality of the compost and climatic conditions can influence N dynamics in compost-amended soil (Gagnon et al., 1997). Attempts to meet crop N requirements

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**Abbreviations:** ANR, apparent nitrogen recovery; CSC, corn silage compost; DM, dairy manure; DMC, dairy manure compost; SSLC, sewage sludge compost.

by combining fertilizer inputs with compost applications (Wen et al., 1995; Gagnon et al., 1997; Sullivan et al., 1998; Eghball and Power, 1999b; Rodd et al., 2002) have yet to be consistently demonstrated as an effective and efficient approach. An alternative approach involves providing an optimal level of legume in the crop to act as an “N buffer” against the variable (or negative) N release from composts. The ability of legumes to fix atmospheric N during periods of low soil or input-derived plant-available N could potentially mitigate against crop yield losses and N deficiencies, and allow for reduced inputs of organic amendments.

The main objective of the study was to assess the crop response and N recovery of perennial forages following application of three composts produced from contrasting feedstocks (sewage sludge, dairy manure, plant residue), when compared with liquid manure and mineral fertilizer, under the humid Maritime conditions of Atlantic Canada. A secondary objective was to assess the efficacy of inclusion of a legume in the forage mixture to act as an N buffer, mitigating against losses in crop yield and quality when fertilized with materials of variable N supplying ability.

## MATERIALS AND METHODS

### Site Description and Experimental Design

The experiment was conducted over two forage production years (1999–2000) at Marshwind Farm, Masstown (45°22' N, 63°23' W) near Truro, Nova Scotia, on a field site previously maintained continuously in pasture. The soil type is a rapidly drained Hebert gravelly loam (Orthic Humo-Ferric Podzol). The site was sequentially plowed, disked, and harrowed, soil samples were recovered, and the experiment seeded in May to early June 1998 (Table 1). The experimental design consisted of a randomized complete block (RCBD) split-plot with four replicates. Main plot units consisted of a 5.5- × 48-m strip seeded to either forage crop: ‘Champ’ timothy alone or a timothy and ‘AC Charlie’ red clover mixture. Twelve fertilizer and organic amendment (manure and composts) treatments applied to 4- × 5.5-m plots of each crop formed the subplot units. Seeding rates were 10 kg ha<sup>-1</sup> for the timothy monoculture and 12 kg ha<sup>-1</sup> (with 60% clover by weight) for the timothy–clover mixture. Stand population counts one month after seeding indicated that clover comprised approximately 30% of the binary mixture. Weed control [primarily lambsquarters (*Chenopodium album* L.) and plantain (*Plantago major* L.)], in the year of forage establishment, was pro-

vided through application of 2,4-D (2,4-dichlorophenoxyacetic acid) to all timothy plots and hand-weeding of all mixed forage plots.

### Compost Preparation and Characterization of Organic Amendments

The physical and chemical characteristics of the manure and composts applied are presented in Table 2. The sewage sludge compost (SSLC) is a commercial product (Fundy Compost Unlimited, Brookfield, NS, Canada) produced by combining sewage sludge solids with horse manure and bulking agents such as bark or wood chips, and composting and curing in open windrows over a one-year period. The high ash content of this compost is attributable to the inclusion of the soil base to the windrows during compost turning at the commercial composting site. The dairy manure compost (DMC) used was produced on-site using heifer manure and sawdust bedding as feedstock. Approximately 20 Mg was windrowed in October 1998 and composted for 8 mo with frequent turning (monthly) using a skidsteer bucket loader. For the initial application a dairy manure compost from a nearby farm, also produced from heifer manure and sawdust bedding, was used. A third compost (CSC) was produced from corn (*Zea mays* L.) silage obtained from the farm. Commencing in April 1998, a total of 30 Mg of this material was composted for 8 to 12 mo and turned frequently (monthly). Both the CSC and DMC were produced and stockpiled under cover. Windrow temperatures during composting of the DMC and CSC composts were monitored at turning using a manual compost thermometer (data not shown). The liquid dairy manure (DM) was obtained from the Ruminant Animal Research Center manure storage lagoon at the Nova Scotia Agriculture College, Truro.

Four replicate composite ( $n = 7$ ) 10-L samples from all stockpiled composts were obtained and stored at 6°C before analysis, within 7 d before treatment application. Manure samples were obtained during transfer from the storage lagoon. The dry weight of the manure and compost samples was determined by drying (400–500 g) at 105°C for 24 h. A 1-kg subsample of each organic amendment was dried at 65°C for chemical analysis. The dairy manure was acidified to pH 4 to 5 by addition of 1 M H<sub>2</sub>SO<sub>4</sub> to prevent NH<sub>3</sub> losses during drying (Derikx et al., 1994). All dried compost and manure samples were ground to pass a 0.5-mm screen. The total N content of the composts was determined by dry combustion (CNS-1000; LECO Corp., St. Joseph, MI). Application rates of manure and composts were based on total N content after adjustment for moisture content. Ash content of dried compost samples was determined after 5 h at 600°C (Cambardella et al., 2001). Dried samples were also subjected to nitric acid digestion and inductively coupled plasma (ICP) analysis to determine the P, K, Ca, Mg, S, B, Fe, Mn and Zn content (Zheljazkov and Warman, 2002). Water-soluble extracts of the fresh composts were obtained using a modification of the method of Chefetz et al. (1998). Approximately 500 g (fresh weight) compost sample was extracted in deionized water (1:2 compost to water, w/v) by shaking (125 rpm) for 1 h on a reciprocal shaker in a 2-L plastic bottle. The suspension was centrifuged (30 min at 10 000 × *g*) and the supernatant filtered at 0.45 μm (#42; Whatman, Maidstone, UK) before analysis for mineral N content by steam distillation with magnesium oxide (NH<sub>4</sub>) and Devarda's alloy + magnesium oxide (NO<sub>3</sub>) (Keeney and Nelson, 1982).

### Fertilizer and Organic Amendment Application Rates

A full description of fertilizer and organic amendment treatments is presented in Table 3. Treatments included an unfertil-

**Table 1. Initial soil characteristics (0–15 cm).**

Characteristic	Value†
Soil type	Hebert loam
pH	5.3 ± 0.2‡
Sand, g kg <sup>-1</sup> soil	362 ± 4§
Silt, g kg <sup>-1</sup> soil	463 ± 47§
Clay, g kg <sup>-1</sup> soil	175 ± 28§
P, mg kg <sup>-1</sup> soil	39.3 ± 7.9¶
K, mg kg <sup>-1</sup> soil	131.8 ± 50.3¶
Ca, mg kg <sup>-1</sup> soil	1135.5 ± 155.7¶
Mg, mg kg <sup>-1</sup> soil	358.8 ± 74.8¶
S, mg kg <sup>-1</sup> soil	17.6 ± 3.5¶

† Values are means ± standard deviations ( $n = 8$  composite samples).

‡ In 0.01 M CaCl<sub>2</sub>.

§ By the pipette method of Sheldrick and Wang (1993) on 2-mm sieved soil.

¶ By Mehlich-3 extraction and inductively coupled plasma.

**Table 2. Physical and chemical characteristics† of manure and compost amendments applied in 1998 and 1999.‡**

Parameter	Dairy manure (DM)			Sewage sludge compost (SSLC)			Dairy manure compost (DMC)			Corn silage compost (CSC)		
	Sept. 1998	June 1999	Sept. 1999	Sept. 1998	June 1999	Sept. 1999	Sept. 1998	June 1999	Sept. 1999	Sept. 1998	June 1999	Sept. 1999
Dry matter, g kg <sup>-1</sup>	88.8	71.0	71.0	335.5	350.6	346.3	359.3	276.0	229.2	276.1	364.9	355.5
Ash, g kg <sup>-1</sup>	13.8	22.5	26.9	31.7	50.8	53.5	29.0	25.8	30.3	39.8	15.8	22.5
C to N ratio	9.5	5.4	ND	21.7	23.7	24.8	16.3	23.4	21.3	10.6	10.9	7.9
Total N, g kg <sup>-1</sup>	40.9	52.9	52.9	16.5	11.0	9.9	23.0	16.7	17.0	31.0	39.8	49.2
Total P, g kg <sup>-1</sup>	6.1	6.8	5.4	7.1	5.1	4.6	8.3	4.9	5.1	6.3	6.1	9.5
Total K, g kg <sup>-1</sup>	16.1	30.4	28.9	5.7	4.7	4.3	33.0	22.7	20.1	26.3	32.8	45.3
NH <sub>4</sub> + NO <sub>3</sub> , mg N kg <sup>-1</sup>	ND§	ND	ND	246.2	130.5	106.3	30.5	67.1	69.6	108.0	111.3	129.6

† With the exception of DM, all analyses are expressed on a dry matter basis.

‡ Values are means with  $n = 4$ .

§ Not determined.

ized control, plus the recommended rate ( $N_{rec}$ ) and a high rate ( $N_{high}$ ) of mineral fertilizer N for forage in the region containing grass alone (150 kg N and 300 kg N ha<sup>-1</sup> yr<sup>-1</sup>, respectively) or 30% legume (40 kg N and 150 kg N ha<sup>-1</sup> yr<sup>-1</sup>, respectively), applied as ammonium nitrate (NH<sub>4</sub>NO<sub>3</sub>). An additional mineral fertilizer treatment ( $N_{rec} + PK$ ) included the recommended N rate plus P (0–46–0) and K (0–0–60) supplied according to regional recommendations for forages at 40 kg P<sub>2</sub>O<sub>5</sub> ha<sup>-1</sup> yr<sup>-1</sup> and 120 kg K<sub>2</sub>O ha<sup>-1</sup> yr<sup>-1</sup> (Atlantic Provinces Agricultural Services Committee, 1991). Organic amendments included treatments of liquid dairy manure (DM), dairy heifer manure compost (DMC), and sewage-sludge compost (SSLC) applied to supply a total annual input of either 150 kg or 300 kg N ha<sup>-1</sup> yr<sup>-1</sup> to both forage crops. As the research was also designed to assess the dynamics of compost carbon and nitrogen in soil, the higher N content (and lower C to N ratio) corn–silage compost (CSC; Table 2) was applied to supply 300 kg and 600 kg N ha<sup>-1</sup> yr<sup>-1</sup> to ensure similar total C inputs for all compost treatments. All treatments were applied as split applications, with 50% of the annual N input rate applied after each of two forage cuts per year, commencing with an initial split in September 1998 in the year of forage establishment. All mineral fertilizer treatments ( $N_{rec}$ ,  $N_{rec} + PK$ ,  $N_{high}$ ) were applied throughout the duration of the experiment (1998–2000). The organic amendments (manure and composts) were applied from September 1998 to September 1999 only (i.e., three applications). As such, the crop response to these latter treatments in 2000 is attributable solely to the residual or carryover benefits of these prior inputs. All treatments were surface broadcast to a 3.0-m strip within each 4 × 5.5-m experimental unit, to maintain a 1-m unfertilized buffer between plots.

### Forage Harvesting and Analysis

In each of the forage production years, 1999 and 2000, the crop was harvested twice per year (June and September). For yield determination a 8.0-m<sup>2</sup> swath was cut from within the center of each plot and the fresh weight was determined using a J. Haldrup (Logstor, Denmark) forage harvester. A representative subsample was dried at 60°C to determine dry matter content, and ground to pass a 0.5-mm screen. The remaining standing forage was cut in bulk and removed from the site. Forage C and N content was determined by dry combustion (LECO CNS-1000). Forage tissue from the June 2000 harvest was digested with nitric acid and analyzed for P, K, Ca, Mg, S, B, Fe, Mn, and Zn content by ICP (Zheljzakov and Warman, 2002).

### Estimation of Apparent Recovery of Nitrogen from and Fertilizer Nitrogen Equivalency of Organic Amendments

The apparent nitrogen recovery (ANR) of treatment N by the timothy crop was calculated for each cut, and cumulatively over the course of the experiment, by difference as:

$$ANR (\%) = [(N \text{ uptake for treatment} - N \text{ uptake for unfertilized control})/N \text{ applied}] \times 100$$

Because the apparent crop recovery of N from organic amendments may underestimate the actual mineralization of the N from these materials, the fertilizer N equivalency (FNE) was calculated for each organic amendment as:

$$FNE = (ANR\%_{org}/ANR\%_{IF}) \times 100$$

where ANR%<sub>org</sub> is the cumulative apparent N recovery for organic amendments, and ANR%<sub>IF</sub> is the cumulative apparent N recovery for inorganic N fertilizer applied at the recommended rate ( $N_{rec}$ ) (Cogger et al., 1999; Zebarth et al., 2000).

### Estimation of Apparent Contribution of Legume Nitrogen Fixation and Forage Botanical Composition

The apparent contribution of N derived from clover N<sub>2</sub> fixation (AN<sub>2</sub>) over the course of the experiment for each fertility treatment was calculated as:

$$AN_2 (\text{kg N ha}^{-1}) = N \text{ offtake by mixed crop for treatment}$$

**Table 3. Nitrogen and dry matter input rates for fertilizer and organic amendments.**

Treatment	Treatment	Annual N applied	Total N applied	Total dry matter applied
		kg N ha <sup>-1</sup> yr <sup>-1</sup>	kg N ha <sup>-1</sup>	Mg ha <sup>-1</sup>
Control	Control	—	—	—
Fertilizer	$N_{rec}$	150/40†	300/80†	—
	$N_{rec} + PK$	150/40†	300/80†	—
	$N_{high}$	300/150†	600/300†	—
Dairy manure	DM150	150	225‡	4.7
	DM300	300	450‡	9.3
Sewage sludge compost	SSLC150	150	225‡	18.7
	SSLC300	300	450‡	37.5
Dairy manure compost	DMC150	150	225‡	12.8
	DMC300	300	450‡	25.6
Corn silage compost	CSC300	300	450‡	11.8
	CSC600	600	900‡	23.7

† Rates as applied to timothy and timothy–clover mixture forage stands, respectively.

‡ All organic amendments applied by fall of first production year (i.e., fall 1999).

## – N offtake by timothy for treatment

where N offtake refers to the cumulative crop N recovered ( $\text{kg N ha}^{-1}$ ) from all sources, including  $\text{N}_2$  fixation, calculated as the sum of the products of dry matter yield and N content.

To assess fertility treatment affects on forage botanical composition, the percent legume content in each plot of the mixed forage was assessed by two independently conducted visual ranking methods in July 2000: (i) as the average of the percent legume content assessed for each of the four quadrats of the whole plot or (ii) as the average of the percent legume content in five 0.25-m<sup>2</sup> quadrats placed equidistantly across a diagonal transect of the plot.

**Determination of Soil Residual Inorganic Nitrogen**

Timothy has a shallow rooting biomass, with more than 80% of the root biomass in the top 0 to 15 cm of soil (Belanger et al., 1999), and soil inorganic N to this depth may be considered plant-available. In October 2000, after the final forage harvest, soil samples to a depth of 15 cm were recovered using a split core sampler (i.d. = 4.8 cm). To avoid sampling bias due to the potentially uneven plot distribution of amendments, samples were recovered from 10 fixed locations within each plot. The cores were cut into segments and combined to form one composite sample per depth increment (0–5, 5–10, and 10–15 cm). Shoots and crowns were removed and samples were passed through a 6-mm sieve to remove gravel and large roots, followed by storage at 4°C. Samples from 24 plots (timothy plots only; three replicates of eight treatments [control,  $\text{N}_{\text{rec}}$ ,  $\text{N}_{\text{high}}$ , DM300, DMC300, SSLC300, CSC300, and CSC600]) were extracted for inorganic N content ( $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N) within six weeks of sampling. Thirty grams fresh weight of soil was extracted by shaking for 1 h in 2 M KCl (5:1 solution to soil ratio) and filtered (Whatman #42), and soil  $\text{NH}_4^+$ -N

and  $\text{NO}_3^-$ -N were determined by molecular absorption spectroscopy in a segmented flow system (Technicon Industrial Systems Corp., Tarrytown, NY). Soil moisture content was determined by drying a 20-g soil subsample for 24 h at 105°C.

**Statistical Analyses**

Statistical analysis of the data was conducted using the general linear model of SAS software (SAS Institute, 1999). Least square (LS) means were used to separate significant main and interaction effects, following a protected ( $p = 0.05$ ) *F* test.

**RESULTS****Forage Dry Matter Yield**

In 1999 and 2000, average annual air temperatures of 8.0 and 7.8°C, respectively, were well above 30-yr average mean annual temperature of 5.8°C for the Truro region. Growing season (April–August) monthly mean precipitation of 65.0 mm (1999) and 71.0 mm (2000) was below the seasonal monthly mean of 88.0 mm. These unusually warm, dry conditions will have impacted negatively on the yield of the second cut in particular, in both seasons. For both harvests in the first forage production year (1999) fertility treatment alone significantly affected forage dry matter yield (Table 4). There was no significant yield response to compost treatments throughout 1999. In Cut 1 in 1999, the highest rate of N fertilizer treatment alone ( $\text{N}_{\text{high}}$ ) produced crop yields ( $6.03 \text{ Mg ha}^{-1}$ ) significantly greater than the unfertilized control ( $5.57 \text{ Mg ha}^{-1}$ ) when averaged across both forage crops. For the second cut in 1999, while all forage

**Table 4. Crop dry matter yields as affected by forage crop and fertility treatment.**

Treatment†	Dry matter yield							
	1999				2000			
	Mg ha <sup>-1</sup>							
	Cut 1		Cut 2		Cut 1		Cut 2	
Clover–timothy	5.26		0.94		6.57a		1.53	
Timothy	5.76		1.03		5.62b		1.23	
	Fertility§							
	Clover–timothy	Timothy	Clover–timothy	Timothy	Clover–timothy	Timothy	Clover–timothy	Timothy
Control	5.39ab¶	5.75ab	1.10ab	0.54a	5.92a	3.60a	1.43abc	0.45a
$\text{N}_{\text{rec}}$	5.56ab	6.07ab	1.17ab	1.39c	5.93a	6.30c	1.58bcd	2.27g
$\text{N}_{\text{high}}$	5.85b	6.21b	1.36b	1.10b	6.95ab	6.98c	2.01cd	2.10fg
$\text{N}_{\text{rec}} + \text{PK}$	4.94a	5.71ab	0.95a	1.12b	6.24a	7.13cd	1.77bcd	1.99efg
DM150	5.49ab	5.71ab	1.07ab	1.25c	6.31a	6.29c	1.35abc	1.48def
DM300	5.48ab	5.99ab	1.00a	1.07bc	6.22a	6.14bc	0.77a	0.81abc
DMC150	4.99a	5.79ab	0.98a	0.84a	6.92ab	4.41a	1.26ab	1.16bcd
DMC300	5.07a	5.75ab	0.95a	0.76a	6.52ab	4.57ab	1.60bcd	1.52def
SSLC150	5.10a	5.49a	0.94a	0.72a	6.07a	3.55a	1.35abc	0.69abc
SSLC300	4.91a	5.48a	0.87a	0.70a	6.44a	3.79a	1.64bcd	1.00abcd
CSC300	5.06a	5.72ab	0.99a	0.90b	7.19a	6.15c	1.44bc	0.66ab
CSC600	5.27ab	5.45a	1.03ab	0.94b	8.10b	8.56d	2.12d	1.34cde
	ANOVA							
Crop	NS		NS		*		NS	
Fertility	*		***		***		***	
Crop × fertility	NS		NS		**		*	

\* Significant at the 0.05 probability level.

\*\* Significant at the 0.01 probability level.

\*\*\* Significant at the 0.001 probability level.

† See Table 3 for treatment descriptions.

‡ Values are means with  $n = 48$ .

§ Values are means with  $n = 4$ .

¶ Within each column, values followed by different letters are significantly different at the 0.05 probability level.

yields were greatly reduced (averaging  $<1.0 \text{ Mg ha}^{-1}$ ), yields for the fertilizer ( $N_{\text{rec}}$ ,  $N_{\text{high}}$ ,  $N_{\text{rec}} + \text{PK}$ ) and liquid manure treatments (DM150, DM300) differed significantly from the control. A significant crop by fertility treatment interaction was obtained for forage yield at both harvests in 2000 (Table 4). All treatments applied to the clover–timothy crop, except the highest rate of corn silage compost (CSC600), failed to improve yields significantly compared with the unfertilized control. In contrast, all treatments applied to the timothy crop increased yields compared with the control, with the exception of DMC and SSLC in the first cut, and SSLC150 and SSLC 300, CSC300, and DM300 in the second cut (Table 4). A similar trend was evident for cumulative dry matter yields over both years (Fig. 1). Only the CSC600 ( $16.52 \text{ Mg ha}^{-1}$ ) and the  $N_{\text{high}}$  ( $16.16 \text{ Mg ha}^{-1}$ ) treatments produced yields significantly greater than the control ( $13.83 \text{ Mg ha}^{-1}$ ) in the mixed forage stand. In contrast, in the grass monocrop, all treatments except the sewage sludge compost (SSLC150, SSLC300) and low rate of dairy manure compost (DMC150) produced cumulative yields greater than the unfertilized control ( $10.34 \text{ Mg ha}^{-1}$ ). Among the composts, the CSC600 ( $16.29 \text{ Mg ha}^{-1}$ ) treatment alone matched the cumulative timothy yields

obtained for the fertilizer treatments  $N_{\text{rec}}$  ( $16.03 \text{ Mg ha}^{-1}$ ),  $N_{\text{high}}$  ( $16.40 \text{ Mg ha}^{-1}$ ), and  $N_{\text{rec}} + \text{PK}$  ( $15.94 \text{ Mg ha}^{-1}$ ).

### Forage Nitrogen Concentration

Crop alone significantly affected forage tissue N concentration in each of the first forage cuts in 1999 and 2000, with the legume–grass forage of higher quality (Table 5). For the second cuts in each year, a crop by treatment interaction determined N content. All treatments applied to the clover–timothy crop failed to differ from the unfertilized control with respect to forage N content throughout the duration of the experiment (Table 5). In contrast, for the timothy monocrop, the fertilizer ( $N_{\text{rec}}$ ,  $N_{\text{high}}$ , and  $N_{\text{rec}} + \text{PK}$ ) and CSC treatments produced a significantly greater crop N content than the control in September 1999, while in September 2000, treatments  $N_{\text{high}}$  and  $N_{\text{rec}} + \text{PK}$  alone produced gains in timothy N content.

### Forage Nitrogen Offtake

With the exception of the first cut in 1999, crop N offtake was characterized by a significant crop by treatment interaction (Table 6). In June 1999, more N was

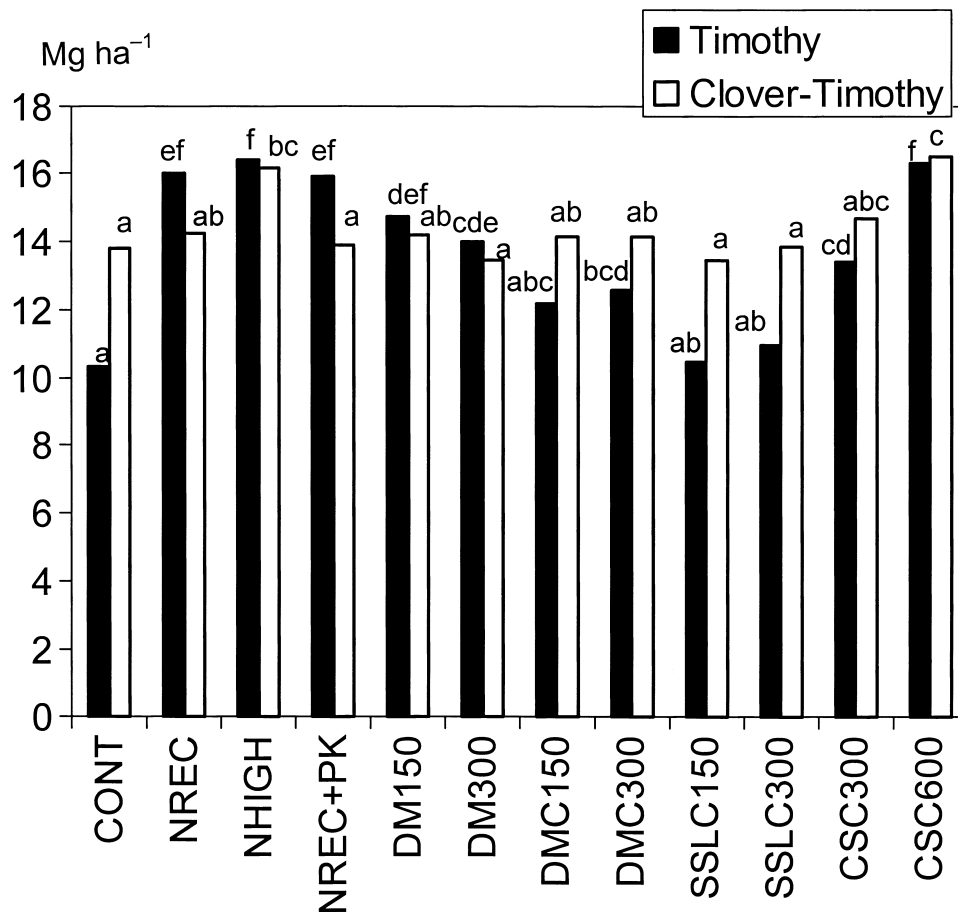


Fig. 1. Cumulative forage dry matter yields as affected by forage crop and fertility treatment. The term CONT is control; NREC and NHIGH are inorganic N fertilizer at recommended and high rates, respectively; DM is dairy manure; and DMC, SSLC, and CSC are compost produced from dairy manure, sewage sludge, and corn silage, respectively. Units in treatment title refer to annual application rates in  $\text{kg total N ha}^{-1} \text{ yr}^{-1}$ . Within each crop, columns with different letters are significantly different at the 0.05 probability level.

Table 5. Crop nitrogen concentration as affected by forage crop and fertility treatment.

Treatment†	N concentration							
	1999				2000			
	g N kg <sup>-1</sup>							
	Crop‡		Fertility§		Crop‡		Fertility§	
	Cut 1	Cut 2	Cut 1	Cut 2	Cut 1	Cut 2	Cut 1	Cut 2
Clover–timothy	19.7a	33.1a	15.1a	17.4a	15.1a	17.4a	15.1a	17.4a
Timothy	15.4b	23.8b	13.3b	16.0b	13.3b	16.0b	13.3b	16.0b
	Clover–timothy	Timothy	Clover–timothy	Timothy	Clover–timothy	Timothy	Clover–timothy	Timothy
Control	19.3	14.1	33.5abc¶	20.1ab	14.5	12.7	16.9abcd	17.3ab
N <sub>rec</sub>	19.7	14.9	31.7ab	29.8d	15.0	13.8	15.8a	17.2ab
N <sub>high</sub>	19.6	17.6	34.3bc	35.1e	15.6	15.6	17.9cd	22.4d
N <sub>rec</sub> + PK	19.3	14.9	33.1abc	31.5d	14.7	12.9	17.4abc	20.0cd
DM150	19.4	14.9	32.7abc	17.7a	16.0	13.1	18.1abcd	15.0a
DM300	19.7	16.3	35.6c	22.4bc	12.6	13.5	16.1ab	16.0ab
DMC150	20.5	14.9	34.1bc	20.0ab	16.1	12.8	20.0d	17.7bc
DMC300	20.7	14.6	30.7a	21.3bc	16.8	13.8	17.1abc	16.4ab
SSLC150	20.7	14.1	32.5abc	20.0ab	15.1	13.0	18.5cd	15.8ab
SSLC300	19.3	15.1	32.8abc	20.3ab	14.9	12.3	17.4abc	15.0a
CSC300	19.7	15.0	33.8abc	23.3c	14.6	12.6	17.2abc	15.7ab
CSC600	18.9	17.9	32.8abc	23.9c	15.3	13.6	16.7ab	16.3ab
	ANOVA							
Crop	***		**		*		*	
Fertility	NS		***		NS		***	
Crop × fertility	NS		***		NS		*	

\* Significant at the 0.05 probability level.

\*\* Significant at the 0.01 probability level.

\*\*\* Significant at the 0.001 probability level.

† See Table 3 for treatment descriptions.

‡ Values are means with  $n = 48$ .§ Values are means with  $n = 4$ .

¶ Within each column, values followed by different letters are significantly different at the 0.05 probability level.

recovered in the clover–timothy forage than the grass only forage and among treatments, only N<sub>high</sub> produced gains in crop N recovery. The data for the mixed forage

crop for the remaining three cuts (Table 6), or combined over all four cuts (Fig. 2), indicated that only two treatments, N<sub>high</sub> (Fig. 2) and CSC600 (June 2000; Table 6),

Table 6. Crop nitrogen offtake as affected by forage crop and fertility treatment.

Treatment†	N offtake							
	1999				2000			
	g N kg <sup>-1</sup>							
	Crop‡		Fertility§		Crop‡		Fertility§	
	Cut 1	Cut 2	Cut 1	Cut 2	Cut 1	Cut 2	Cut 1	Cut 2
Clover–timothy	103.4a	33.9a	99.1a	26.3	99.1a	26.3	99.1a	26.3
Timothy	87.5b	22.9b	75.4b	22.4	75.4b	22.4	75.4b	22.4
	Clover–timothy	Timothy	Clover–timothy	Timothy	Clover–timothy	Timothy	Clover–timothy	Timothy
Control	103.9ab¶	81.6ab	36.3ab	10.8a	85.8ab	47.2a	24.4b	7.7a
N <sub>rec</sub>	108.6ab	90.4ab	36.8ab	42.1c	88.45ab	86.6cde	25.0b	38.4e
N <sub>high</sub>	114.8b	109.3c	45.5b	37.3c	107.5bc	108.0ef	35.0b	44.7e
N <sub>rec</sub> + PK	95.0a	85.8ab	31.3a	35.4c	90.8ab	91.9def	30.3b	39.8e
DM150	106.1ab	85.0ab	34.7a	22.1b	102.1abc	84.1cde	24.6b	22.2cd
DM300	107.7ab	97.3bc	35.8ab	23.6b	78.8a	83.3bcde	12.4a	12.9abcd
DMC150	101.8ab	86.4ab	32.6a	16.9ab	109.8bc	57.4ab	25.2b	20.7bcd
DMC300	104.5ab	83.9ab	28.9a	15.4ab	108.5bc	63.1abc	27.2b	24.2d
SSLC150	105.4ab	77.3a	30.1a	14.4ab	91.6ab	46.1a	24.5b	11.0abc
SSLC300	93.8a	82.5ab	28.3a	13.9ab	95.2ab	44.0a	27.7b	14.9abcd
CSC300	99.9ab	86.8ab	33.7a	20.7ab	106.0bc	77.8bcd	24.3b	10.3ab
CSC600	99.5ab	96.7ab	33.1a	22.4b	124.3c	114.6f	34.9b	21.5bcd
	ANOVA							
Crop	*		*		*		NS	
Fertility	**		***		***		***	
Crop × fertility	NS		**		**		**	

\* Significant at the 0.05 probability level.

\*\* Significant at the 0.01 probability level.

\*\*\* Significant at the 0.001 probability level.

† See Table 3 for treatment descriptions.

‡ Values are means with  $n = 48$ .§ Values are means with  $n = 4$ .

¶ Within each column, values followed by different letters are significantly different at the 0.05 probability level.

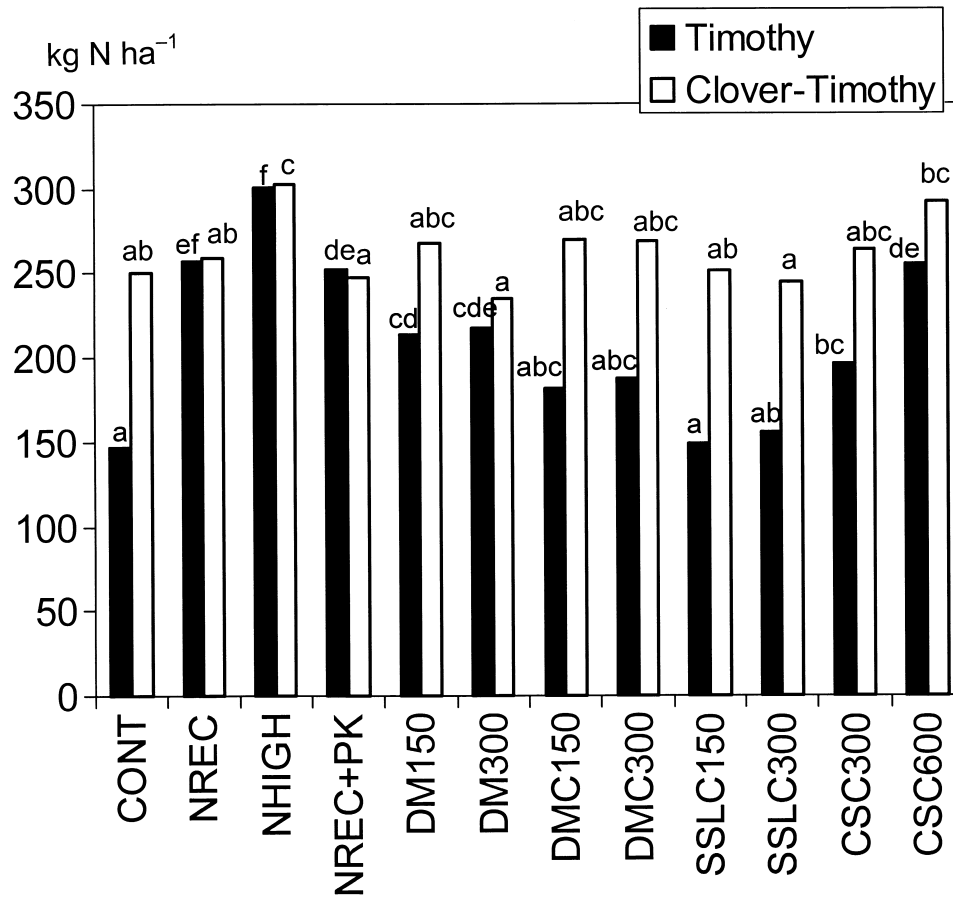


Fig. 2. Cumulative crop nitrogen offtake as affected by forage crop and fertility treatment. The term CONT is control; NREC and NHIGH are inorganic N fertilizer at recommended and high rates, respectively; DM is dairy manure; and DMC, SSLC, and CSC are compost produced from dairy manure, sewage sludge, and corn silage, respectively. Units in treatment title refer to annual application rates in kg total N ha<sup>-1</sup> yr<sup>-1</sup>. Within each crop, columns with different letters are significantly different at the 0.05 probability level.

resulted in greater N offtake than the unfertilized control, primarily due to greater dry matter yields. In addition, total N offtake for all treatments applied to the clover-timothy crop spanned a narrow range of 245.0 kg N ha<sup>-1</sup> (SSLC300) to 302.2 kg N ha<sup>-1</sup> (N<sub>high</sub>) (Fig. 2). Differences in cumulative N offtake between CSC600 (291.8 kg N ha<sup>-1</sup>) and the two N fertilizer rates, N<sub>rec</sub> (258.8 kg N ha<sup>-1</sup>) and N<sub>high</sub> (302.2 kg N ha<sup>-1</sup>), for this crop were not significant. In contrast to the mixed forage crop, cumulative N offtake for all treatments applied to the timothy crop spanned a relatively wide range, with the highest N offtake (300.6 kg N ha<sup>-1</sup>) more than double that of the unfertilized control (147.3 kg N ha<sup>-1</sup>) (Fig. 2). Cumulative timothy N offtake was greatest for N<sub>high</sub> (300.6 kg N ha<sup>-1</sup>), followed by N<sub>rec</sub> (256.8 kg N ha<sup>-1</sup>), N<sub>rec</sub> + PK (252.6 kg N ha<sup>-1</sup>), and CSC600 (255.2 kg N ha<sup>-1</sup>). Intermediate N recovery rates were obtained for the two liquid manure treatments DM150 (213.4 kg N ha<sup>-1</sup>) and DM300 (217.5 kg N ha<sup>-1</sup>), while all application rates of DMC and SSLC failed to produce N offtake values significantly different from the unfertilized control (147.3 kg N ha<sup>-1</sup>). This ranking of the treatments with respect to timothy N offtake was consistently observed through the last three timothy harvests (Table 6).

### Apparent Recovery of Fertilizer and Amendment Nitrogen, Contribution of Legume Nitrogen Fixation, and Forage Botanical Composition

Cumulative ANR in the timothy crop averaged 36.5% for the inorganic N fertilizer applied at the recommended rate, N<sub>rec</sub> (Table 7), and 25.6% for the N<sub>high</sub> treatment.

Table 7. Apparent recovery of fertility treatment N in the harvested timothy crop.

Treatment†	N applied kg N ha <sup>-1</sup>	1999‡		2000		1998–2000 Cumulative
		Cut 1	Cut 2	Cut 1	Cut 2	
N <sub>rec</sub>	300	11.7 (2.9)	20.4 (10.2)	13.1	10.2	36.5
N <sub>high</sub>	600	18.5 (4.6)	9.3 (4.6)	10.1	6.2	25.6
N <sub>rec</sub> + PK	300	5.6 (1.4)	16.3 (8.2)	14.9	10.7	35.1
DM150	300	4.6 (1.5)	7.5 (5.0)	16.4	6.5	29.4
DM300	450	10.5 (3.5)	4.4 (2.9)	8.0	1.2	15.6
DMC150	300	6.4 (2.1)	4.0 (2.7)	4.5	5.8	15.1
DMC300	450	1.6 (0.5)	1.8 (1.2)	3.5	3.7	8.9
SSLC150	300	-5.7 (-1.9)	2.3 (1.6)	-0.5	1.5	0.7
SSLC300	450	0.6 (0.2)	1.1 (0.7)	-0.7	1.6	1.8
CSC300	600	3.5 (1.2)	3.4 (2.3)	6.8	0.6	10.8
CSC600	900	5.0 (1.7)	1.9 (1.3)	7.5	1.5	12.0

† See Table 3 for treatment descriptions.

‡ Based on total N applied before this cut (or total N applied over the course of the experiment) for each treatment.

**Table 8. Apparent contribution of N derived from N<sub>2</sub> fixation to total N offtake in the timothy–clover crop (1999–2000).**

Treatment†	Total N applied	Cumulative apparent N derived from N <sub>2</sub> fixation	Apparent N derived from N <sub>2</sub> fixation
	kg N ha <sup>-1</sup>	kg N ha <sup>-1</sup>	% of total N offtake
Control	0	103.1	41.2
N150	300	46.0‡	15.2
DM150	300	54.1	20.2
DM300	450	17.1	7.3
DMC150	300	88.0	32.7
DMC300	450	81.8	30.4
SSLC150	300	102.9	40.9
SSLC300	450	89.4	36.5
CSC300	600	68.0	25.8
CSC600	900	36.6	12.6

† See Table 3 for treatment descriptions.

‡ Determined by subtracting cumulative N offtake for timothy treatment N<sub>rec</sub> from N offtake for clover–timothy treatment N<sub>high</sub>, which both received N applied at 150 kg N ha<sup>-1</sup> yr<sup>-1</sup>.

The lower input rate of liquid dairy manure (DM150) produced the second highest ANR over all harvests combined, at 29.4%. The cumulative ANR for compost treatments ranged from a low of less than 2% for the sewage sludge compost (SSLC150 and SSLC300) to 15.10% for the lower application rate of heifer manure compost (DMC150). Negative ANR values for both SSLC treatments at some harvests indicated that net N immobilization had occurred. An average of 73% of the total cumulative ANR for all of the organic amendments (manure and composts) was obtained from carryover N released in the year following final application, 2000.

The order of treatments for apparent N derived from N<sub>2</sub> fixation (AN<sub>2</sub>) (Table 8) was the inverse of the order of treatments for timothy crop N offtake. Apparent N<sub>2</sub> fixed N contributed 44 kg N ha<sup>-1</sup> (7–26% of total N offtake) for the inorganic fertilizer, liquid manure, and CSC treatments. In contrast, for the two composts of lower plant-available N (DMC and SSLC), N<sub>2</sub> fixation contributed an average of 91 kg N ha<sup>-1</sup> (33–41% of total crop N offtake), close to the 103.1 kg N ha<sup>-1</sup> (41% of total crop N offtake) obtained for the unfertilized control. Visual estimates of percent legume content in the mixed forage stand in July 2000 (Table 9) indicated a general trend of reduced clover content compared with the unfertilized control for all treatments, except DMC150, with loss of legume content greatest at the highest input rates.

**Table 9. Effect of fertility treatment on forage mixture composition.**

Treatment	Visual ranking method†	
	Plot quadrat	Transect quadrat
	% clover	
Control	23.0	26.0
N <sub>rec</sub>	14.0	12.0
N <sub>high</sub>	19.0	16.0
N <sub>rec</sub> + PK	20.0	18.0
DM150	17.0	9.0
DM300	9.0	6.0
DMC150	26.0	28.0
DMC300	20.0	18.0
SSLC150	18.0	19.0
SSLC300	20.0	12.0
CSC300	20.0	15.0
CSC600	16.0	10.0

† Conducted in July 2000. Values are means with *n* = 4.

**Table 10. Effect of fertility treatment on timothy forage tissue macronutrient content in June 2000.**

Treatment†	Concentration‡			
	Ca	Mg	K	P
	g kg <sup>-1</sup>			
	Fertility			
Control	1.97	1.31	15.98abc§	2.09bc
N <sub>rec</sub>	1.79	1.21	14.12a	1.79a
N <sub>high</sub>	1.86	1.26	14.73ab	1.84a
N <sub>rec</sub> + PK	1.58	1.03	17.52cd	1.98ab
DM150	1.58	1.14	17.67cd	2.20bc
DM300	1.50	1.03	17.94cd	2.14bc
DMC150	1.73	1.14	18.01cd	2.16bc
DMC300	1.63	1.19	18.51d	2.26c
SSLC150	1.65	1.06	17.01bcd	2.17bc
SSLC300	1.39	1.00	17.59cd	2.09bc
CSC300	1.61	1.17	18.66d	2.17bc
CSC600	1.47	1.21	21.13e	2.30c
	ANOVA			
Fertility	NS	NS	***	**

\* Significant at the 0.05 probability level.

\*\* Significant at the 0.01 probability level.

\*\*\* Significant at the 0.001 probability level.

† See Table 3 for treatment descriptions.

‡ Results of inductively coupled plasma analyses of forage from timothy plots only. Values are means with *n* = 4.

§ Within each column, values followed by different letters are significantly different at the 0.05 probability level.

### Forage Tissue Calcium, Phosphorus, Potassium, and Magnesium Content

Significant differences between treatments with respect to P and K content, but not Ca and Mg, were obtained for timothy forage plant tissue obtained at June 2000 (Table 10). Tissue P content was significantly lower for the N<sub>rec</sub> and N<sub>high</sub> than the control and all other treatments. Treatments CSC300, CSC600, and DMC300 produced tissue K levels greater than the control. Higher application rates of all composts tended to increase tissue P and K contents, but not Ca and Mg.

### Soil Residual Inorganic Nitrogen

Fall soil nitrate concentrations were very low for all treatments (<5 mg kg<sup>-1</sup>) at both subsurface depths (5–10 and 10–15 cm). Differences between treatments, however, were apparent at the surface depth (0–5 cm), with nitrate N levels of 21.9 and 26.0 mg kg<sup>-1</sup> for the CSC300 and N<sub>high</sub> treatments, respectively; significantly greater than the 7 to 13 mg kg<sup>-1</sup> range obtained for the remaining treatments (data not shown).

## DISCUSSION

In the present study there was no response to increasing N fertilizer inputs beyond 150 kg N ha<sup>-1</sup> (N<sub>rec</sub>) with respect to cumulative DM yields. Long-term (>35 yr) fertilization studies of timothy in Atlantic Canada produced maximal DM yields of 6.84 Mg ha<sup>-1</sup> yr<sup>-1</sup> at a fertilizer rate of 180 kg N ha<sup>-1</sup> (Belanger et al., 1999). The timothy yields of 8.20 Mg ha<sup>-1</sup> yr<sup>-1</sup> obtained for treatments N<sub>high</sub> and CSC600 are partly attributable to a decision to delay harvests beyond the optimum stage for forage quality, an approach that permitted adequate discrimination between results for the amendments and the relatively high yields for the unfertilized timothy

control. The average yields and N offtake obtained for the unfertilized control ( $5.17 \text{ Mg DM ha}^{-1} \text{ yr}^{-1}$  and  $73.7 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ ) reflect high levels of apparent net soil N mineralization during the first production year. In long-term studies in eastern Canada, yields and N offtake for unfertilized timothy controls have averaged from 2.2 to 4.1  $\text{Mg DM ha}^{-1} \text{ yr}^{-1}$  and 25 to 60  $\text{kg N ha}^{-1} \text{ yr}^{-1}$  (Kline and Broersma, 1983; Belanger et al., 1999).

In assessing the crop response to treatments, it bears restating that while all fertilizer treatments were applied in all years of the experiment (1999–2000), the response in the second year (2000) to organic amendments is solely a function of residual nutrient benefits from their prior application. A supply of 140  $\text{kg N ha}^{-1}$  in spring and 120  $\text{kg N ha}^{-1}$  in summer is required to provide maximal nonlimiting conditions for shoot growth of timothy varieties under Atlantic Canada conditions (Belanger and Richards, 1999), although when fertilizer is applied at 200  $\text{kg N ha}^{-1} \text{ yr}^{-1}$  and above herbage nitrate concentrations can reach levels detrimental to livestock health (Warman 1986a, 1986b; Bittman and Kowalenko, 1998). The large cumulative yields over two forage production years obtained for treatment CSC600 (Fig. 1), which was matched only by the  $N_{\text{high}}$  treatment in the mixed forage crop and all fertilizer treatments and one liquid manure treatment (DM150) in the timothy crop, indicate that composts can provide sufficient in-season and residual plant-available N to support high forage crop yields. These results, given the nature of the CSC feedstocks, also demonstrate that composts effective in supporting crop growth can be produced in the absence of livestock manure or municipal biosolids in the compost feedstocks. Nitrogen surpluses (treatment inputs – outputs of N by crop removal) of up to 800  $\text{kg N ha}^{-1}$  for some of the compost treatments (Table 7) may be of concern. Fall residual nitrate levels for all treatments (0- to 15-cm sampling depth) were less than 10  $\text{mg kg}^{-1}$ , however. In addition, the CSC compost appeared to be mineralizing slowly ( $k = 0.06 \text{ yr}^{-1}$ ) with between 82 and 87% of applied compost retained in surface soil (0–5 cm) two years after application as determined by carbon balance and stable isotope techniques (data not shown). Sullivan et al. (1998) and Bittman and Kowalenko (1998) found that whether N was supplied to perennial forages through composts or as inorganic fertilizer, residual soil inorganic N levels in the fall were typically very low ( $<5 \text{ mg kg}^{-1}$ ; 0- to 30-cm depth) due to efficient crop utilization of nitrate and/or immobilization of applied N in soil organic matter.

The cumulative ANR by the timothy crop ranged from 25.6% ( $N_{\text{high}}$ ) to 36.5% ( $N_{\text{rec}}$ ) (Table 7), which is lower than the 47 to 85% ANR of fertilizer N by forage grasses reported in previous studies (Kiemnec et al., 1987; Sullivan et al., 1997; Cogger et al., 1999). The application of 50% of the annual N inputs for all treatments immediately following the second cut in the fall will probably have reduced the efficiency of fertilizer N in this study. Soil conditions in early spring can restrict the application of fertilizer to perennial grass stands, however, and the availability of residual plant-available N from organic amendments for early season forage growth has been

shown to be a particular benefit of their use (Sullivan et al., 1997). The cumulative ANR for the dairy manure treatment (DM150) of 29.4% (Table 7) is slightly below that for fertilizer ( $N_{\text{rec}}$ ) applied at equivalent annual N input rates. By comparison, Paul and Beauchamp (1993) obtained 28% N recovery from liquid dairy manure applied over three years to corn. Manure slurries have typically large inorganic N contents, while the contribution of mineralized N from the organic fraction is usually negligible (Van Kessel et al., 1999). The inorganic N in liquid dairy manure appears to be 75 to 80% as plant-available as inorganic fertilizer N since a fraction of the N is lost due to volatilization after application (Beauchamp, 1986). The low timothy forage N content (Table 5) and reduction in apparent N recovery for both liquid manure treatments by the second cut in year 2000 (Table 7) compared with the DMC treatment, indicates little residual benefit from the previous applications of liquid dairy manure in comparison with a composted dairy manure. This result is in agreement with that of Paul and Beauchamp (1993).

The cumulative ANR range obtained for the three composts (Table 7) of 0.7 to 15.1% falls within the range of N recovery found for different composts in previous studies. Gagnon et al. (1997), in Quebec, applied four dairy manure and commercial composts to spring wheat at up to 360  $\text{kg total N ha}^{-1}$  and obtained ANR for composts ranging from –14% (net N immobilization) to 15%, compared with 24 to 56% ANR for ammonium nitrate applied at up to 180  $\text{kg N ha}^{-1}$ . Eghball and Power (1999a, 1999b) obtained a high of 15% ANR for a beef manure compost in the first year of application (compared with 40% for uncomposted manure), followed by 8% compost N recovery in the second year. Averaged over four years, 12% of compost N was recovered by corn compared with 45% for fertilizer N. The multiple applications of the inputs per year make determination of recovery of N from a single compost application difficult. The ANR for the first cut in 1999 (Table 7), taken 10 mo after the first split application (September 1998), provides an estimate of the annual ANR, ranging from –5.7% (SSLC) to 6.4% (DMC) for the three compost treatments. The lack of a crop DM (Table 4) and N offtake (Table 6) response for the first cut in 1999 to most treatments, however, suggests that cultivation of the pre-existing pasture was followed by a large flush of soil mineral N and soluble organic N (Bhogal et al., 2000), which masked the actual ANR for compost treatments over this period. Also, a significant proportion of amendment N mineralized in this first year may have been immobilized by the decay of pasture leaf litter and root residue. Concentrations of N in the stubble and roots of perennial grass swards have been found to increase with increasing N inputs (Whitehead et al., 1990) and N immobilized in macroorganic matter and nonharvested portions of the crop represents a significant pool of potentially mineralizable N in grasslands (Hassink, 1994; Patra et al., 1999).

Because the crop recovery of N may underestimate the actual mineralization from organic amendments, the fertilizer N equivalency (FNE) of organic inputs is often

reported. Cogger et al. (1999) and Zebarth et al. (2000) reported that FNEs for raw or activated sewage sludges typically fall within a 40 to 60% range, across a wide range of environments. In the present study, the greatest FNE (80.5%) was obtained for the liquid dairy manure (DM150) while the FNE obtained for the compost treatments was 1.8% (SSLC150), 29.6% (CSC300), and 41.4% (DMC150).

Nitrogen deficiencies influence timothy sward structural characteristics by reducing leaf extension and persistence and total leaf area per tiller. As a result the livestock feed quality of the forage is reduced (Belanger, 1998). At matched annual N input rates (CSC300, DMC300, SSLC300), the CSC compost outperformed the DMC and SSLC composts with respect to timothy crop cumulative yield, N offtake, and percent N recovery (Fig. 1 and 2, Table 7), and thus appears to be a higher-quality compost with respect to plant-available N content. For equally decomposable materials, the fraction of mineralized organic N is linearly related to the C to N ratio of the material (Janssen, 1996). The average C to N ratio of the three composts was 23.4 (SSLC), 20.3 (DMC), and 9.8 (CSC). Qian and Schoenau (2002) obtained short-term immobilization for manures with C to N ratio of 15:1 while Janssen (1996) reported negligible net N mineralization for composts with C to N ratio greater than 22:1. The ranking of the composts with respect to N mineralized is also consistent with models positively correlating percent N mineralized with total N content and inversely to lignin to N ratio (Cabrera et al., 1994). The temporary N immobilization for SSLC apparent from the N offtake data (Table 7) is attributable to the addition of bark during SSLC composting, which contributed to a higher C to N ratio and lignin content and further diluted total N content (<1.25% N). Balkcom et al. (2001) found that sewage sludges composted with wood chips, in contrast to raw sewage sludges, do not mineralize N rapidly, and often promote immobilization. In humid regions, avoiding leaching losses by producing and storing composts under cover is an important means of reducing losses of N and K (Ulen, 1993; Eghball et al., 1997; Gagnon et al., 1999). As both the CSC and DMC composts were maintained under cover before application, the lower labile N content of the SSLC material may be a result of leaching of soluble N during composting and curing. For all three composts, inorganic N levels at application of less than 3% of total N (Table 2) were relative low compared with the 5 to 10% range obtained elsewhere (Wen et al., 1995; Gagnon et al., 1997). The DMC and CSC composts probably contained a higher content of more readily mineralizable soluble organic N and labile N forms from microbial products. Nitrogen mineralized from raw sewage sludge is mainly derived from catabolism of the protein pool, rather than decomposition of the material as a whole. Thermophilic temperatures, which are maintained during composting of sludges, reduce the quantity of labile organic matter present (Rowell et al., 2001).

Imbalances in timothy P and N concentrations will negatively affect timothy productivity (Belanger and Richards, 1999). For all organic amendments, tissue P con-

tent was only marginally (approximately 5%) below the critical P concentration relative to N content ( $P = 1.46 + 0.0695N$ ) recommended as optimum for timothy by Belanger and Richards (1999). The high initial soil test P levels (Table 1) and lack of a yield response to P and K when supplied together with N ( $N_{rec} + PK$ ) suggest that P was also not limiting to forage production for all fertilizer treatments. Phosphorus surpluses (treatment inputs – outputs of P by crop removal) generated for the higher application rates of organic amendments were 32.0 kg P ha<sup>-1</sup> (liquid manure), 185.5 kg P ha<sup>-1</sup> (SSLC300), 127.3 kg P ha<sup>-1</sup> (DMC300), and 135.1 kg P ha<sup>-1</sup> (CSC600).

Potassium in composts has been shown to be as available as fertilizer K (Wen et al., 1997). The SSLC compost had the lowest K content of all organic amendments (Table 2), while the CSC and DMC composts matched the K content of the liquid manure on a dry matter basis. Chen et al. (1996) and Warman and Cooper (2000a) found that dairy and chicken manure composts, respectively, provided K so readily to perennial grasses as to recommend care in avoiding excess or luxury uptake and nutrient imbalances. In contrast, a sewage sludge compost promoted ryegrass (*Lolium perenne* L.) K deficiencies at all rates of addition (Chen et al., 1996). Sewage sludges characteristically contain little K due to losses in the effluent. Potassium budgets (treatment inputs – outputs of K by crop removal) for the higher application rates of organic amendments were +16.5 kg K ha<sup>-1</sup> (liquid manure), -10.4 kg K ha<sup>-1</sup> (SSLC300), +413.3 kg K ha<sup>-1</sup> (DMC300), and +478.6 kg K ha<sup>-1</sup> (CSC600).

In the unfertilized mixed forage crop, estimated N<sub>2</sub> fixation rates averaged 52 kg N ha<sup>-1</sup> yr<sup>-1</sup>, a figure well within regional estimates of N<sub>2</sub> fixation per hectare by clover in mixed stands (Atlantic Provinces Agricultural Services Committee, 1991). By the second forage production year, legume content in the mixed crop was reduced for most treatments, compared with the unfertilized control (Table 9). Liquid dairy manure (DM150 and DM300) impacted more negatively on sward legume content and nitrogen derived from N<sub>2</sub> fixation than all compost treatments, however (Tables 8 and 9). Legumes will preferentially use available soil and applied N, and nitrogen fertilization of legume-based forages has been a controversial practice (Hannaway and Shuler, 1993; Schmitt et al., 1994, 1996). Nitrogen inputs promote shifts in the species composition of grasslands (Wedin and Tilman, 1996), and in a mixed legume–grass system high N availability can shift species composition to a predominantly grass mixture (MacLeod et al., 1965; Yarrow and Penning, 1994). Interspecies competition can also have a negative impact on N<sub>2</sub> fixation by legumes present within a sward (Kerley and Jarvis, 1999). The lower N availability of compost, by reducing grass competition, may be of benefit in this regard. Warman and Cooper (2000a) found that N supplied as ammonium nitrate at the recommended rate resulted in nearly pure stands of grasses after three years of application to mixed grass–legume hayfields. In contrast, composted or uncomposted chicken manure, applied at equivalent

total N, maintained sward legume contents at levels matching that of the unfertilized control. Additional nutrients such as Ca and K supplied with some composts may also contribute to legume persistence (Warman and Cooper, 2000a, 2000b).

By including a legume in the sward, crop N offtake was consistently greater at all harvest dates and cumulatively for the mixed crop compared with the grass only crop (Table 6 and Fig. 2). This was the case even though much higher rates of fertilizer N were applied to the grass only crop. In fact, the very similar cumulative N offtake values for the two crops for the  $N_{rec}$ ,  $N_{high}$ , and  $N_{rec} + PK$  treatments (Fig. 2) are somewhat remarkable given the differences in N input rates for these treatments in each crop. Second, and a more important indicator of the contrasting "N buffering" abilities of the two crops, the difference in total N offtake between all organic amendments and the highest N offtake obtained (approximately 300 kg N ha<sup>-1</sup> for the  $N_{high}$  treatment in both crops) was no greater than 55 kg N ha<sup>-1</sup> in the mixed crop, but ranged to as high as 152 kg N ha<sup>-1</sup> in the grass-only crop. The advanced maturity of the crop at some harvests diluted tissue N and P concentrations. Feed quality (protein content) of the mixed crop, however, irrespective of organic amendment applied, was consistently closer at all harvests to the optimum range for livestock feed for mature beef or dairy cattle (20–30 g N kg<sup>-1</sup>) (National Research Council, 1984, 1989) than that of the grass-only crop.

## CONCLUSIONS

The results presented here indicate that repeat applications of composts can provide sufficient plant-available N to sustain perennial forage grass yields. Because of the unfavorable N to P ratio in animal wastes and most composts relative to crop N and P uptake, however, the long-term use of composts for crop N requirements usually leads to agronomically excessive levels of soil P. This is also true for K for composts containing animal manures (Eghball and Power, 1999b; Reider et al., 2000). The surpluses and loading of soil P and K levels in excess of crop requirements associated with most higher compost application rates in this study provide additional support against routine use of composts as a sole N source for pure grass forage crops. A phosphorus-based approach to compost application, with additional crop N supplied as fertilizer, has been shown to produce annual crop yields similar to those received from an N-based compost or fertilizer approach but with reduced P buildup in surface soil and runoff DP concentrations (Eghball and Power, 1999b). Similarly, Reider et al. (2000) recommended applying composts of high P and K content based on crop P and K rather than N requirements, but suggest including a legume in the rotation as an additional N source. In either case, an accurate estimate of the potential N release from composts is required, or, to avoid crop N deficiencies, large N surpluses are often maintained. The approach taken here, of directly targeting the application of composts to a mixed legume–grass (or solely legume) crop,

permits "buffering" of crop N to reduce the risk of large N excesses or deficits. This in turn both minimizes potential losses in crop yield and quality if compost is applied and, by allowing smaller application rates of diverse composts, reduces soil P and K loading.

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