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Fertilization and Mowing Effects on Unimproved Mixed-Species Hayfields in Quebec, Canada

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ABSTRACT

The objective of this experiment was to evaluate the response of two unimproved mixed-species hayfields in Quebec, Canada, to management regimes of high fertilization and intensive mowing. Dry matter and nutrient yields, tissue nutrient concentrations, and soil nutrient pools were determined in *Bromus–Poa* and *Pleum–Lolium* hayfields fertilized with inorganic fertilizer, liquid dairy manure, or no fertilizer and mown at different intensities (every 2 wk or unmown, during a 12-wk period). Dry matter and nutrient yields, and tissue nutrient concentrations were similar in plots receiving inorganic and dairy manure fertilizers, but the dry matter yield was 0.6 to 2.8 Mg ha^{-1} higher in fertilized plots than the unfertilized control. Repeated mowing reduced dry matter yield by 1.5 to 2.7 Mg ha^{-1}, however, tissue nutrient concentration and nutrient yield were greater in mown than unmown plots. The apparent N recovery in a mown, fertilized *Pleum–Lolium* hayfield was greater than 100%, as the nutrient yields (143 kg N ha^{-1}) were greater than the N fertilizer input of 75 kg N ha^{-1}. Soil NO_3^- and microbial biomass N concentration were significantly ($P < 0.05$, Tukey test) lower in fertilized plots that were mown every 2 wk than unmown during the study period. Frequent mowing may be a management option that can reduce soil residual N and thus limit NO_3^- leaching from mixed-species hayfields.

Perennial hayfields are an important component of livestock farming systems in eastern Canada covering up to 40% (2.3 million ha) of the agricultural land (Statistics Canada, 2001). They provide forage and bedding for cattle, primarily, and they make productive use of rocky and marginal soils that are unsuitable for field and vegetable crops. At least a third (800 000 ha) is defined as unimproved hayfields, not having had recent improvements such as cultivation, seeding, fertilization, or weed control (Statistics Canada, 2001). Over time, unimproved hayfields are gradually invaded by grass and weed species, which can lead to significant reductions in productivity. In eastern Canada, 50% of all crop production losses due to weed invasion occur in hay crops (Swanton et al., 1993). Currently, little information is available to producers on how to improve production in these unimproved mixed-species hayfields.

Fertilizer applications have a beneficial effect on hay production in swards with single-grass species (Cherney et al., 2002; Fairey, 1991; Willms, 1991; Lutwick and Smith, 1979; Reid, 1978; George et al., 1973), as well as in mixed-species swards (Griffin et al., 2002; Ziadi et al., 2000). A comparison of yield response of a mixed-species hayfield in Maine showed that greater yields were obtained from the inorganic fertilizers than the liquid dairy manure (Griffin et al., 2002). Unpredictable, weather dependent N losses from fertilizer and manure application can make N application rates difficult to estimate. Ziadi et al. (2000) showed that grass yield response to recommended fertilizer N varies significantly among sites throughout Quebec, and that optimum fertilizer N rates can be as much as 50 kg N ha^{-1} greater than recommended rates in cooler regions of the province.

Although fertilization may be inadequate in some cases, many unimproved hayfields still produce enough dry matter for two or more cuts per year. Besides nutrient availability, the frequency of hay harvests may influence the productivity of mixed-species hayfields. Many studies that have shown that defoliation of grass plants induces changes to the soil microbial community, which can subsequently lead to positive feedback effects on the grass, leading to greater nutrient concentration and growth (Ferraro and Oesterheld, 2002; Hamilton and Frank, 2001; Mikola et al., 2001; Bardgett et al., 1998). These compensatory mechanisms are plant specific and may not always be positive (Mawdsley and Bardgett, 1997; Guitian and Bardgett, 2000). How a mixed-species hayfield responds to defoliation is still unclear. Furthermore, since the complexity and heterogeneity of soil microbial communities can vary under grasslands of different management and age (Allison et al., 2005; Steenwerth et al., 2002; Grayston et al., 2001), diverse responses to defoliation are expected in hayfields due to the grass species present and fertilization practices (Macdonald et al., 2004; Bardgett et al., 1999).

The objectives of this experiment were: (i) to evaluate the manure and inorganic fertilizer recommendations for fertilizing a mixed-species hayfield; and (ii) to address the response of soil nutrient pools, plant yield, and plant nutrient uptake in mixed-species hayfields that were repeatedly defoliated by mowing under three fertilization regimes (no fertilizer, manure, or inorganic fertilizers). Two unimproved hayfields of different ages and different plant species composition were studied.

MATERIALS AND METHODS

The study was conducted from May to August in 2004 and 2005 on the research farm of Macdonald Campus of McGill University, QC, Canada (45°25′ N, 73°56′ W). Different fields were used in each year and their physical properties are described in Table 1. Legume cover in both fields was less than 5%. The field used in 2004 had been used for hay production for 10 yr and before that was cultivated for field crop produc-

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Abbreviations: CRAAQ, Centre de Reference en Agriculture et Agroalimentaire du Quebec; DM, dry matter; DON, dissolved organic N; MBN, microbial biomass N.

Table 1. Descriptions of the grasslands used in the each year of the study.

Soil characteristic	*Bromus–Poa* hayfield (2004)	*Pleum–Lolium* hayfield (2005)
Sand, g kg^{-1}	400	410
Silt, g kg^{-1}	450	380
Clay, g kg^{-1}	150	210
Organic C, g kg^{-1}	133	56
pH (H_2O)	7.2	7.2
Mehlich-3 P, kg ha^{-1}	190	46
Mehlich-3 K, kg ha^{-1}	601	224

tion. It was dominated by smooth brome (*Bromus inermis* Leyss.) and Kentucky bluegrass (*Poa pratensis* L.). The soil was a mixed, frigid Typic Endoquent, classified as a St-Zotique loam. The field used in 2005 had been used for hay production for 8 yr, and was formerly used as a grazing pasture for about 25 yr. It was dominated by timothy (*Pleum pratensis* L.), perennial ryegrass (*Lolium perenne* L.) and smooth brome (*B. inermis* L.) but had minor patches (<10%) of quackgrass [*Agropyron repens* (L.) P. Beauv.], common reed (*Phragmites communis* Trin.), yellow foxtail [*Setaria glauca* (L.) P. Beauv.], red clover (*Trifolium pratense* L.), barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.], reed canarygrass (*Phalaris arundinacea* L.) and tufted vetch (*Vicia cracca* L.). The soil was a mixed, frigid Typic Endoquent, classified as a Farmington loam. We used a different field in 2005 because at the end of 2004 farm management decided to plow under the *Bromus–Poa* field for maize production. The *Pleum–Lolium* hayfield was the nearest unimproved hayfield available and so was chosen for our experiment in 2005. Throughout this paper the fields will be referred to by the two dominant species present in each field; *Bromus–Poa* in 2004, and *Pleum–Lolium* in 2005.

The experiment was designed as a randomized complete block split plot with two mowing main treatments, three fertilizer subtreatments, and four blocks. Experimental plots measured 3 by 3 m. Buffer strips between main and sub treatments, and blocks were 1, 0.5, and 5 m, respectively. The two mowing treatments were a mown and unmown control. Grass in mown treatments was cut every 2 wk for 12 wk, and in the unmown control cut only once at 12 wk. The fertility treatments applied to subplots were an inorganic fertilizer blend, manure, and no fertilizer (control). The fertilizer recommendations, based on soil test P and K levels in the hayfields (Table 1) were 75–50–90 kg $N–P_2O_5–K_2O$ ha^{-1} in the *Bromus–Poa* hayfield, and 75–50–60 kg $N–P_2O_5–K_2O$ ha^{-1} in the *Pleum–Lolium* hayfield (CRAAQ, 2003). The inorganic fertilizer blend of calcium ammonium nitrate, triple super-phosphate, and potassium chloride was broadcast by hand at the rates recommended for each field. The manure was dairy cow slurry containing 3.1 g N kg^{-1}, 0.5 g P kg^{-1}, 2.9 g K kg^{-1} (wet basis), and 930 g H_2O kg^{-1} in the *Bromus–Poa* hayfield, and 3.2 g N kg^{-1}, 0.5 g P kg^{-1}, 3.3 g K kg^{-1} (wet basis), and 950 g H_2O kg^{-1} in the *Pleum–Lolium* hayfield. Slurry was weighed into buckets and surface applied at a rate of 80 m^3 ha^{-1}. This rate was chosen to supply 75 kg N ha^{-1}, based on the quantity of inorganic fertilizer-equivalent N in manure and N losses expected for surface application without incorporation of slurry in Quebec (CRAAQ, 2003). Manure applications provided an estimated 75–115–265 kg $N–P_2O_5–K_2O$ ha^{-1} in the *Bromus–Poa* hayfield, and about 76–90–299 kg $N–P_2O_5–K_2O$ ha^{-1} in the *Pleum–Lolium* hayfield.

In the *Bromus–Poa* hayfield, all plots were mowed and fertilized on 10 May. Beginning on 31 May 31, the plots were mown every 2 wk to a height of 5 cm using a hand-pushed lawnmower. A collection bag attached to the lawnmower collected the grass cuttings from each plot, which were then bagged and weighed fresh. A subsample of about 200 g was dried at 60°C for 72 h to determine the moisture content and calculate dry matter (DM) yield (Mg ha^{-1}) from each plot. The dried subsample was ground with a Wiley mill (<1-mm mesh) and stored at room temperature before nutrient analysis. Three to five handfuls of grass, sampled randomly with plots and weighing about 200 g fresh weight, were cut with shears every 2 wk from unmown plots, and similarly dried and ground for nutrient analysis. The final harvest was on 9 August. In the *Pleum–Lolium* hayfield, plots were mowed and fertilized during the week of 25 April, and grass samples were first collected on 10 May. Grass samples were collected and processed as described above every 2 wk thereafter until the final harvest on 18 July. Plant tissue was digested with H_2SO_4/H_2O_2 (Parkinson and Allen, 1975) and digests were analyzed colorimetrically for N and P using a Lachat Quick Chem autoanalyzer (Lachat Instruments, Milwaukee, WI), and for K using atomic absorption spectrometry. Nutrient yield (kg ha^{-1}) at each date was the product of dry weight yield and tissue nutrient concentration measured on that date. The nutrient yields from each harvest were summed to calculate total nutrient yield for the season. Apparent N recovery in the subplots that were mowed or received fertilizer was based on total N applied to each plot and calculated as: Apparent N recovery (%) = [N yield in treatment plot (kg ha^{-1}) − N yield in unfertilized, unmown control (kg ha^{-1})]/total N applied (kg ha^{-1}).

A composite soil sample consisting of four subsamples taken with a soil auger (2 cm internal diameter) from the 0- to 15-cm horizon was collected from each plot. Soil samples were kept at 4°C until analysis. Mineral N (NO_3–N + NH_4–N) was determined by extracting 5 g field-moist soil with 50 mL 2 *M* KCl (Maynard and Kalra, 1993). After shaking for 1 h and filtering, the extract was analyzed by colorimetry for NO_3–N and NH_4–N on a multichannel Lachat auto-analyser (Lachat Instruments, Milwaukee, WI). Available P and K were determined by extracting 2.5 g air-dry soil with 25 mL Mehlich-III solution (Tran and Simard, 1993). The P concentration in extracts was analyzed colorimetrically on a Lachat auto-analyser (Lachat Insturments, Milwaukee, WI) and K concentration was measured using atomic absorption spectrophotometer.

In 2005 only, we analyzed microbial biomass N (MBN) in soil samples using the chloroform fumigation-direct extraction method followed by persulfate digestion and calculated as: [(total extractable N after fumigation − total extractable N before fumigation)/0.54] (Brookes et al., 1985; Joergensen and Mueller, 1996). Dissolved organic N was calculated as the difference between the NO_3–N and NH_4–N concentrations in a persulfate digested soil extract and the original undigested soil extract (Cabrera and Beare, 1993).

The effect of fertilizer, mowing regime and mowing date on weekly DM yields, and tissue nutrient concentrations were evaluated using repeated measures analysis over time and for each time period using the PROC MIXED function of SAS software (SAS Institute, 2001). Total cumulative DM yield, nutrient yield, and soil nutrient concentrations were evaluated by split-plot analysis using the PROC MIXED function of SAS software. In the mixed model, a simple covariance structure was fitted according to the selection criteria outlined by Wang and Goonewardene (2004). The differences between least square means of significant treatment effects were evaluated using Tukey's means comparison test ($P = 0.05$).

RESULTS

Climate Data

The weather in 2004 was similar to the 30-yr mean, although minimum temperatures were slightly cooler.

However, more extreme temperature and precipitation events were observed in 2005 (Fig. 1). In 2005, above normal temperatures began in early June and continued for the next 12 wk with maximum and minimum daily temperatures of over 30 and 20°C being recorded. Although the total precipitation was high in 2005, compared to the 30-yr mean, the frequency of rainfall events was low but the average rainfall per event was greater. Weekly rainfall tended to be lower than long term averages in June and July of 2005, except for three above-average rainfall events (Fig. 1).

Grass Yields

Total grass DM yields were significantly affected by fertilizer ($P < 0.0001$ in both years) and mowing regime ($P = 0.0251$ in 2004, and $P < 0.0001$ in 2005) (Fig. 2). In the *Bromus–Poa* hayfield, unmown plots had greater yields than mown plots. Similarly, the unmown, fertilized plots in the *Pleum–Lolium* hayfield had greater yields than all other plots. When the same fertilizer treatment was applied, unmown plots had greater yields than mown plots except in the unfertilized control of the *Pleum-Lolium* hayfield (Fig. 2). The greatest biweekly yields were obtained 4 to 6 wk after fertilization (Fig. 3). While the grass yields at each harvest were not affected by fertilizer treatments in the *Bromus–Poa* hayfield, biweekly yields in the *Pleum–Lolium* hayfield were significantly greater ($P < 0.05$) in fertilized than unfertilized plots from Weeks 4 to 10 (Fig. 3).

Tissue Nutrient Concentration

The N concentration in the subsamples from the *Bromus–Poa* hayfield ranged from 12 to 37 g kg^{-1}, while subsamples from the *Pleum–Lolium* hayfield contained

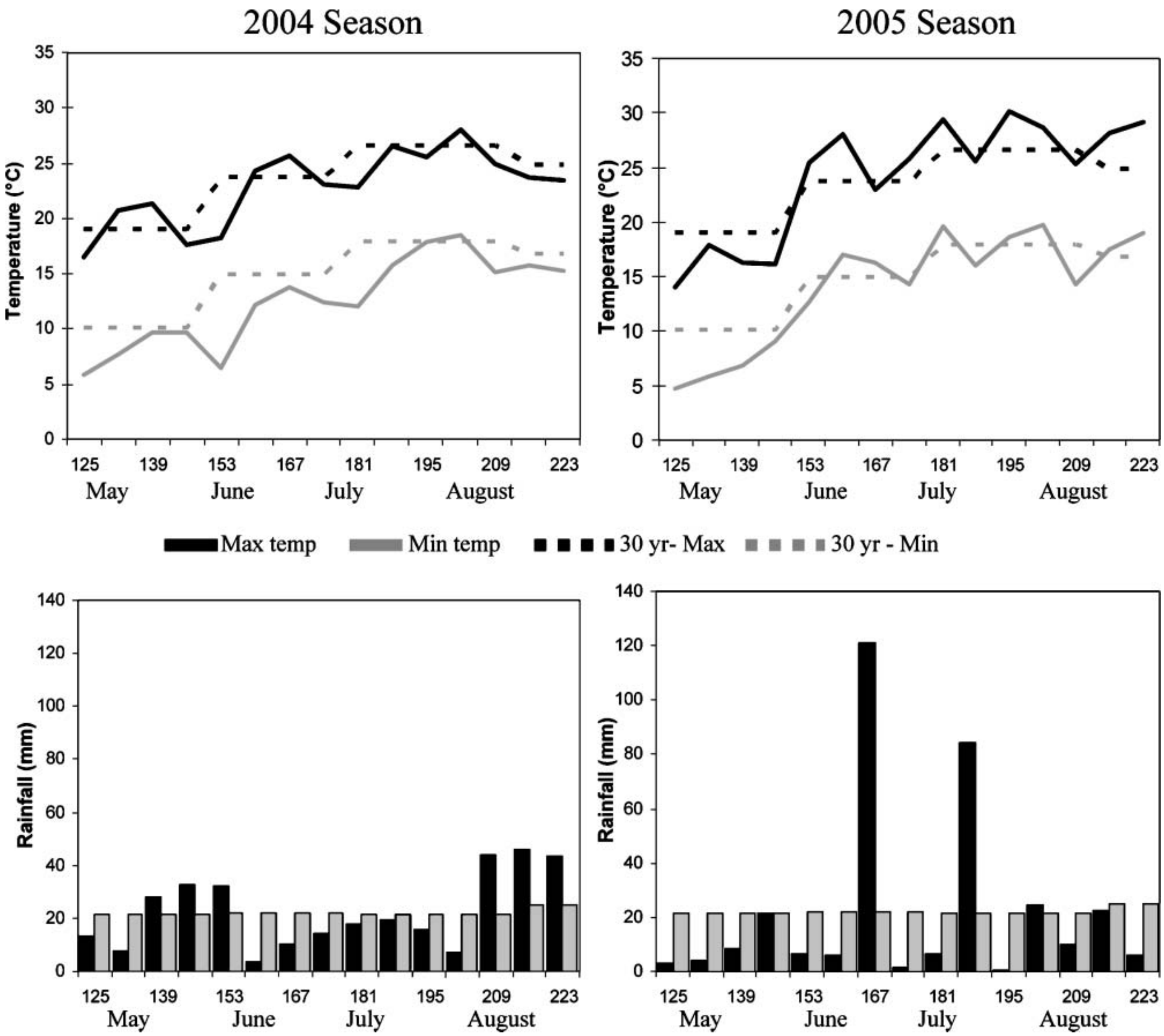

Fig. 1. Mean weekly maximum and minimum temperatures (solid lines) and weekly rainfall totals (dark-colored columns) for 2004 and 2005, and 30-yr mean maximum and minimum temperatures (dotted line) and rainfall totals (light-colored columns) at Macdonald Campus Research Farm. The calendar day and month are shown on the *x* axis.

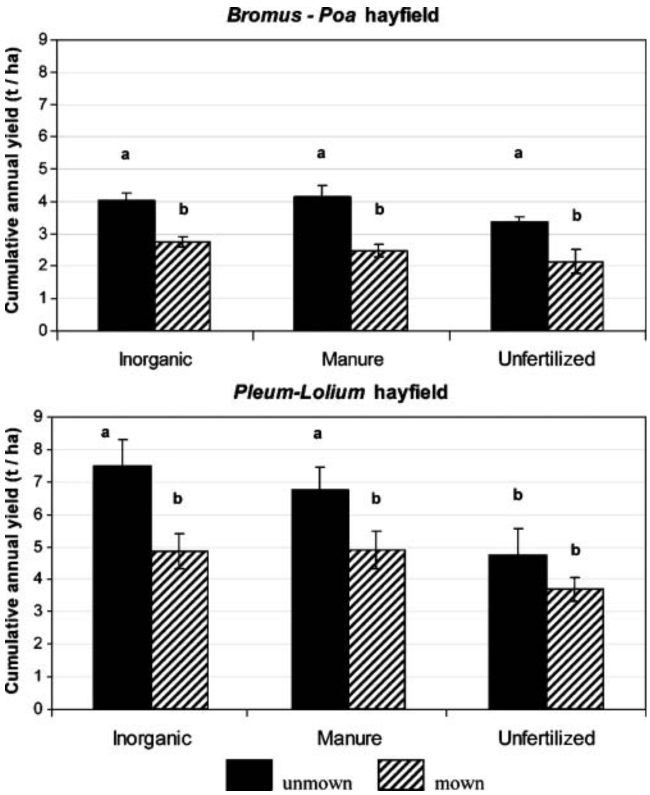

Fig. 2. Total grass dry matter (DM) yield (Mg ha^{-1}) for each fertilizer and mowing treatment in each year. Values shown as mean ± SE (n = 4). Columns with similar letters are not significantly different by Tukey's means comparisons test (P = 0.05).

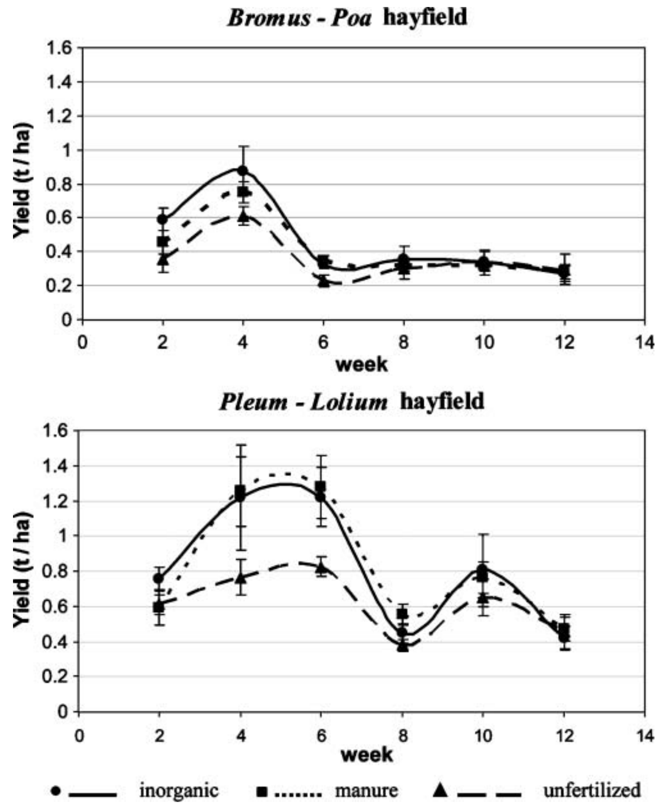

Fig. 3. Biweekly grass yields (Mg DM ha^{-1}) from mown plots. Values are the mean ± SE of four replicates for each fertilizer treatment. DM, dry matter.

between 12 and 40 g kg^{-1}. Tissue N concentration in both hayfields was significantly affected ($P < 0.0001$) by fertilizer source, mowing, mowing date, and the fertilizer × mowing × mowing date interaction. In the *Bromus–Poa* hayfield, tissue N concentrations were similar in inorganic and manure treatments during the growing season, although fertilized grass had a greater tissue N concentration ($P < 0.04$) than unfertilized grass until Week 8. From Week 6 onward, mown plots had greater tissue N concentration than unmown plots ($P < 0.0001$) (Fig. 4). In the *Pleum–Lolium* hayfield, tissue N concentration was greater ($P < 0.0001$) in fertilized grass than unfertilized grass during the first 6 wk, however the inorganic and manure fertilizer treatments during the growing season were not different. Tissue N concentration was greater in the unmown than mown plots in Week 2 ($P = 0.0085$). No differences were observed between mowing treatments in Week 4, but from Week 6 onward, tissue N concentration was greater in the mown than unmown plots ($P < 0.0001$) (Fig. 4). Phosphorus concentrations ranged from 1.9 to 3.8 g kg^{-1} in both hayfields, and K concentrations ranged from 9 to 28 g kg^{-1} in the *Bromus–Poa* hayfield and from 15 to 28 g kg^{-1} in the *Pleum–Lolium* hayfield. Generally, the tissue P and K concentrations followed the same trends as tissue N, with higher tissue P and K concentrations in fertilized plots early in the season (up to Week 6), and greater P and K concentrations in mown than unmown plots later in the season (after Week 6) (data not shown).

Nutrient Yield

Greater N and K yields were observed in the mown, fertilized plots than the unmown and unfertilized plots of the *Bromus–Poa* hayfield (Table 2). Similarly, the N, P, and K yields were greater in mown, fertilized plots than unmown, unfertilized plots in the *Pleum–Lolium* hayfield (Table 2). The apparent N recovery was 20 to 30% greater in the mown, fertilized plots than the unmown, fertilized plots in the *Bromus–Poa* hayfield, and 60 to 80% greater in the mown, fertilized plots than the unmown, fertilized plots in the *Pleum–Lolium* hayfield (Table 2).

Soil Nutrient Concentrations

Soil nutrient concentrations were generally unaffected by fertilizer or mowing treatment in the *Bromus–Poa* hayfield, with the exception of the P and K concentrations, which were greater in the manure-fertilized mown plots than in the inorganically fertilized, unmown plots (Table 3). Soil NH_4^+, dissolved organic N (DON), P, and K concentrations were unaffected by fertilizer or mowing treatment in the *Pleum–Lolium* hayfield. Soil NO_3^- concentrations were not different in 2004, regardless of the treatment. In 2005, soil NO_3^- concentrations were greater in inorganic fertilized unmown plots than most other treatments, but statistically equal to manure fertilized unmown plots, and was lowest in the manure fertilized mown plots (Table 3). Greater MBN was ob-

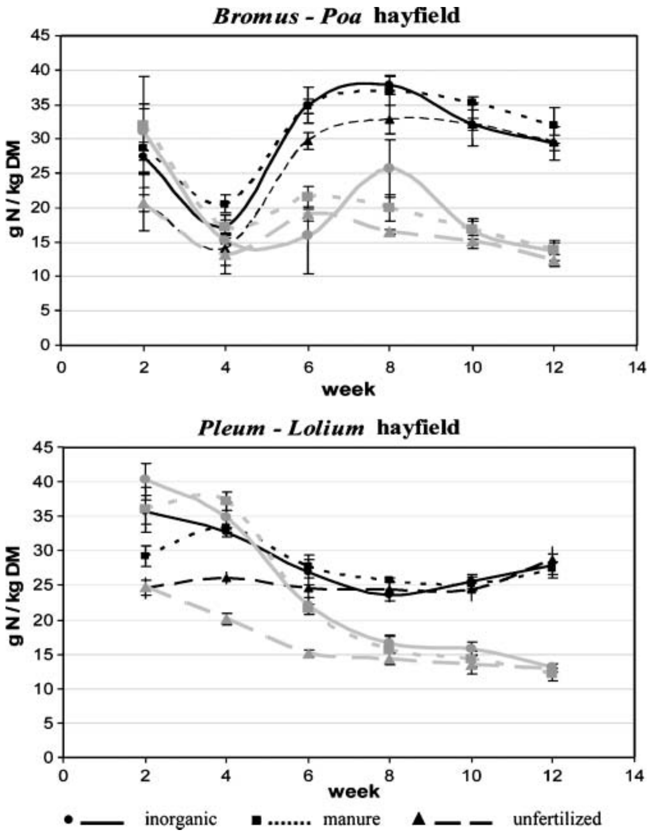

Fig. 4. Tissue N concentration (g N kg^{-1} DM) for each fertilizer and mowing treatment in each year. Mown treatments shown in dark lines and unmown treatment in lighter colored lines. Values shown as mean ± SE. DM, dry matter.

served in the unmown, fertilized plots than the mown, fertilized plots of the *Pleum–Lolium* hayfield (Table 3).

DISCUSSION

Fertilization of Mixed-Species Stands

The total DM yields obtained in fertilized plots after 12 wk (4.0–4.2 Mg ha^{-1} and 6.7–7.5 Mg ha^{-1} in the *Bromus–Poa* and *Pleum–Lolium* hayfields, respectively) is comparable with average yields (2.5–10 Mg ha^{-1}) obtained for other cool season perennial grasses in northeastern North America (Durr et al., 2005; Malhi et al., 2003; Cherney et al., 2002; Griffin et al., 2002; Ziadi et al., 2000; Madakadze et al., 1999). Although these hayfields were considered unimproved and under-utilized, they had moderate to high soil fertility and produced 3.4 to 4.7 Mg ha^{-1} in unfertilized plots, which is comparable to yields obtained in other fertilized fields in this region (Durr et al., 2005; Griffin et al., 2002). High residual N from previous fertilizer applications and mineralization of the organic matter may have contributed to the grass production observed in these unfertilized plots (Ziadi et al., 2000; Hansen et al., 2005). Reasonable hay yields can be obtained without adding fertilizers to soils that are moderately fertile, but a yield increase of 0.6–2.8 Mg ha^{-1} was obtained in 12 wk when the recommended amounts of N, P, and K nutrients were added. Grass yields were not different when inorganic or manure fertilizers were applied in both hayfields, suggesting that similar yields can be obtained when decomposition coefficients and N-loss factors are used to match inputs of manure N to inorganic N fertilizer. Our results are consistent with yields reported in grasslands that received the same N input from manure and inorganic fertilizer even though the P and K loadings differed (Min et al., 1999a, 1999b; Estavillo et al., 1996; Castle and Reid, 1987). The manure-fertilized plots increased the P and K concentrations slightly compared to unfertilized plots in the *Bromus–Poa* hayfield, but statistical differences were not found in the *Pleum–Lolium* hayfield. It is well documented that soil overloading with P and K from the long-term use of manure has important environmental consequences for waterways (Hooda et al., 2001; Bolinder et al., 2000; Simard et al., 1995). The potential for high P and K loadings with manure and past fertilization history of hayfields should be considered before choosing a fertilizer source.

Tissue nutrient concentrations in hay from fertilized plots (12–40 g N kg^{-1}, 1.8–3.8 g P kg^{-1}, 15–28 g K kg^{-1}) were slightly higher than the average nutrient concentrations reported for the first cut of hay in Quebec

Table 2. Total nutrient yields (kg ha^{-1}) for all mowing and fertilizer treatments in each hayfield.†

Mowing treatment	Fertilizer treatment	Nutrient yield N	P	K	Apparent N recovery‡
		kg ha^{-1} ± SE			% of N applied
***Bromus–Poa* hayfield**					
Unmown	**Unfertilized**	**41 ± 4 b**	**6 ± 0.4 a**	**28 ± 1 b**	**–**
	Inorganic	**54 ± 4 ab**	**7 ± 0.3 a**	**48 ± 2 a**	**72 b**
	Manure	**59 ± 10 ab**	**8 ± 1 a**	**46 ± 7 ab**	**79 ab**
Mown	**Unfertilized**	**53 ± 13 ab**	**6 ± 1 a**	**37 ± 8 ab**	**–**
	Inorganic	**77 ± 9 a**	**8 ± 1 a**	**55 ± 6 a**	**102 a**
	Manure	**73 ± 7 a**	**8 ± 0.6 a**	**52 ± 4 a**	**97 ab**
***Pleum–Lolium* hayfield**					
Unmown	**Unfertilized**	**62 ± 13 c**	**9 ± 2 c**	**72 ± 13 b**	**–**
	Inorganic	**97 ± 9 b**	**15 ± 3 ab**	**119 ± 11 a**	**129 b**
	Manure	**83 ± 13 bc**	**15 ± 3 ab**	**118 ± 21 a**	**110 b**
Mown	**Unfertilized**	**95 ± 15 b**	**11 ± 2 bc**	**76 ± 11 b**	**–**
	Inorganic	**143 ± 20 a**	**16 ± 3 a**	**108 ± 16 a**	**191 a**
	Manure	**143 ± 23 a**	**16 ± 3 a**	**111 ± 17 a**	**190 a**

† Values in each column for each hayfield followed by similar letters are not significantly different by Tukey's means comparison test (P = 0.05).
‡ Apparent N recovery % = N yield in treatment plot (kg ha^{-1}) − [N yield in unfertilized control (kg ha^{-1})/total N applied (kg ha^{-1})]. Calculated separately for each mowing regime and hayfield.

Table 3. Soil nutrient concentrations (mg kg^{-1}) for all mowing and fertilizer treatments in each hayfield.†

Mowing treatment	Fertilizer treatment	Soil nutrient concentrations: NO_3^-	NH_4^+	Microbial biomass N (MBN)	Dissolved organic N (DON)	P	K
		mg kg^{-1} ± SE					
Bromus–Poa **hayfield**							
Unmown	**Unfertilized**	**14 ± 1.7 a**	**2.4 ± 0.2 a**	**n.a.‡**	**n.a.**	**90 ± 14 ab**	**290 ± 34 ab**
	Inorganic	**12 ± 0.7 a**	**2.4 ± 0.4 a**	**n.a.**	**n.a.**	**70 ± 27 b**	**180 ± 68 b**
	Manure	**14 ± 1.0 a**	**2.6 ± 0.3 a**	**n.a.**	**n.a.**	**120 ± 17 ab**	**390 ± 65 ab**
Mown	**Unfertilized**	**15 ± 2.0 a**	**2.0 ± 0.3 a**	**n.a.**	**n.a.**	**140 ± 24 ab**	**330 ± 17 ab**
	Inorganic	**13 ± 1.3 a**	**1.8 ± 0.2 a**	**n.a.**	**n.a.**	**150 ± 15 ab**	**350 ± 46 ab**
	Manure	**15 ± 1.8 a**	**3.1 ± 0.5 a**	**n.a.**	**n.a.**	**180 ± 21 a**	**470 ± 39 a**
Pleum–Lolium **hayfield**							
Unmown	**Unfertilized**	**10 ± 1.2 bc**	**1.9 ± 0.2 a**	**63 ± 3.5 ab**	**7.5 ± 1.0 a**	**18 ± 5 a**	**200 ± 44 a**
	Inorganic	**17 ± 3.1 a**	**2.9 ± 0.8 a**	**66 ± 1.9 a**	**8.7 ± 1.5 a**	**22 ± 9 a**	**210 ± 67 a**
	Manure	**16 ± 1.1 ab**	**2.4 ± 0.5 a**	**65 ± 1.9 a**	**6.6 ± 1.0 a**	**24 ± 12 a**	**350 ± 110 a**
Mown	**Unfertilized**	**10 ± 1.0 bc**	**2.0 ± 0.3 a**	**62 ± 3.8 ab**	**6.8 ± 1.0 a**	**12 ± 5 a**	**160 ± 58 a**
	Inorganic	**9 ± 1.4 bc**	**2.3 ± 0.5 a**	**49 ± 3.2 b**	**10 ± 3.4 a**	**18 ± 13 a**	**230 ± 130 a**
	Manure	**9 ± 0.4 c**	**2.9 ± 0.6 a**	**51 ± 2.8 b**	**6.6 ± 1.1 a**	**20 ± 15 a**	**240 ± 150 a**

† Values in each column for each hayfield followed by similar letters are not significantly different by Tukey's means comparison test (P = 0.05).
‡ n.a., not available.

(15–23 g N kg^{-1}, 2.2–3.2 g P kg^{-1}, 14–26 g K kg^{-1}) (CRAAQ, 2003), and similar to values from other studies (13–33 g N kg^{-1}, 2.3–3.7 g P kg^{-1}, 10–26 g K kg^{-1}) (Elliott and Abbott, 2003; Griffin et al., 2002; George et al., 1973). There are conflicting reports in the scientific literature on how fertilizer sources affect tissue nutrient concentration and nutrient yields. No differences in nutrient concentration were observed in a timothy and Kentucky bluegrass hayfield when fertilized with inorganic fertilizer or dairy slurry, but nutrient yield was greater with the inorganic fertilizer (Griffin et al., 2002). Cherney et al. (2002) found more variable concentrations of tissue N from manure treatments than from inorganic fertilizer, however N yields were greater with the inorganic fertilizer. Similar to our findings, Mikhailova et al. (2003) reported that tissue P was sometimes greater with inorganic fertilization than manure, but that P yield was unaffected by fertilizer source. Apparent N recovery in unmown plots amended with inorganic and manure fertilizers (72–129%) are slightly greater than values for other cool-season grass species (Griffin et al., 2002; George et al., 1973). We expect that the apparent N recovery would be even greater had the experiment lasted longer.

Effect of Mowing on Mixed-Species Hayfields

Repeated defoliation of grass plants can have both positive and negative effects on growth and tissue nutrient concentration (Ferraro and Oesterheld, 2002). The decrease in functional tissue and photosynthetic ability from defoliation is thought to trigger plant responses that can either cause damage and reduced growth or lead to over compensation and increased growth in the plant (Ferraro and Oesterheld, 2002; Bardgett et al., 1999). These plant species specific responses have been examined in pure stands in greenhouse experiments (Beltran-Lopez et al., 2005; Guitian and Bardgett, 2000), however, information concerning responses in mixed species hayfields is lacking. Less frequent mowing regimes have been shown to increase yields for a variety of grass species in temperate climates (Elliott and Abbott, 2003; Madakadze et al., 1999; Willms and Fraser, 1992; Fairey, 1991; Willms, 1991). In our experiment, the DM yields after 12 wk were reduced by 1.5 to 2.7 Mg ha^{-1} by repeated mowing at 2-wk intervals. Similar reductions in yield were found in a smooth brome and Kentucky bluegrass grassland after 6 wk where yield was reduced by 0.7 Mg ha^{-1} when the cutting interval was reduced from 6 to 2 wk (Donkor et al., 2003).

Despite the yield reduction from repeated mowing, a positive compensatory response of the grasses increased tissue N (Fig. 4), P, and K concentrations. An increase in tissue nutrient concentrations arising from greater defoliation intensity has been shown for a variety of grasses (Durr et al., 2005; Donkor et al., 2003; Elliott and Abbott, 2003; Madakadze et al., 1999; Bardgett et al., 1998; Fairey, 1991). Although the underlying physiological mechanisms are unclear, it has been suggested that the soil microbial community, stimulated by root exudation from defoliated plants, increases the mineralization of nutrients from the soil organic matter, which subsequently increases nutrient availability for the plant (Bardgett et al., 1998). Differences in plant maturity at later weeks in the experiment may also partly explain differences in nutrient concentration arising from repeated mowing. At Week 12 the grass in unmown plots was at a later reproductive stage than in mown plots and contained a higher proportion of stem material with less N.

Another positive feedback from repeated mowing is the increase in N yields in 2005. Although the DM yields were less in the mown plots, the N yields were greater, largely due to the increases in tissue N concentration. The relationship between N yield and mowing intensity seems less clear than that between nutrient concentration and mowing intensity. A species-specific response was found between N yield and defoliation intensity for four grasses grown in Alberta, Canada (Fairey, 1991). Only meadow foxtail (*Alopecurus pratensis* L.) had greater N yield with more frequent mowing, while meadow bromegrass and timothy showed no difference between mowing regimes, and smooth bromegrass had less N yield with more frequent mowing. Furthermore, the response of N yield to defoliation intensity differed among grass species when grown alone or with different companion legumes (Fairey, 1991). In a mixed species (smooth brome and Kentucky bluegrass) grassland in Alberta, no differences in crude protein yield were observed when the mowing intensity was reduced from 6 to 2 wk (Donkor et al., 2003). Over a wide range of N rates, Reid (1978) showed that crude protein yield in a perennial ryegrass sward was greatest at an intermediate mowing schedule of 5 cuts as opposed to 3 and 10 cuts per year. These studies suggest that changes in N yield related to mowing intensity may be plant species specific. In both hayfields, the N yields were greater in the mown than unmown plots for all corresponding fertilizer regimes. Mowing more frequently to increase the N yield of forage may be a management option that could add value to unimproved hayfields dominated by brome, timothy, and perennial ryegrass in Quebec. However, as stated above, this relationship may not apply to all grasses in all temperate climates.

Soil Fertility as Influenced by Mowing and Fertilization

The average manure P (40 kg P ha^{-1}) and K (225–250 kg K ha^{-1}) loadings were high in both hayfields but had little effect on the soil P and K concentrations, except in the manure fertilized mown plots, which had greater P and K concentrations than inorganic unmown plots in *Bromus–Poa* hayfield. It is likely that the amounts of P and K added to the soil and removed with the harvested grass are relatively small compared to the total P and K pools, so changes due to fertilization were not observed. In contrast, Griffin et al. (2002) observed more soil P and K in fertilized plots than unfertilized controls of hayfields on a silt loam soil in a similar climate.

Soil N pools in mixed-species hayfields were generally not affected by fertilizer and mowing treatments, except in the *Pleum–Lolium* hayfield where the fertilizer × mowing treatment interaction had a significant effect ($P < 0.032$) on the NO_3^- and MBN concentrations. High N yields (>140 kg N ha^{-1}) in fertilized, mowed plots led to very high apparent N recovery of greater than 100% (Table 2), which coincided with a decrease in soil NO_3^- and MBN concentrations. High N yields from forages can induce a net field scale N deficit and lower the soil N concentration (Singer and Moore, 2003). This can lead to N deficiency in the following year's crop if sufficient N fertilizer is not applied. However, it may also be a useful management tool to remove excess soil N and prevent autumn and winter leaching of residual NO_3^- to water bodies. Pasture cutting management and growing of high N demanding grass species have been proposed as methods to reduce excess soil N and prevent NO_3^- leaching (Bedard-Haughn et al., 2005; Nevens and Rehuel, 2003; Singer and Moore, 2003). A comparative study of five defoliation systems on a German grassland demonstrated that mowing was more effective than rotational grazing and mixed grazing–mowing systems, at reducing residual soil N and preventing nitrate leaching (Wachendorf et al., 2003). Our experiment was not designed to find the optimum mowing intensity for nutrient removal and further research is warranted especially in grasslands at risk of nutrient leaching.

CONCLUSIONS

Unimproved mixed species hayfields with a low proportion of legumes are often considered to be marginally productive. Applying fertilizers and increasing the mowing frequency are simple management practices that affect DM yield and nutrient concentration in hayfield grasses. When applied on an inorganic fertilizer equivalent N basis, dairy manure slurry and inorganic fertilizers produced equally good DM yields with high tissue nutrient concentrations. Repeated mowing reduced DM yield, but increased tissue nutrient concentration and N yield of these hayfields. Using a more intensive mowing regime to increase the hay N yield might be an attractive management option for a marginal hayfield, however, the increased N yield must justify the extra expenditure from more frequent mowing. More frequent mowing decreased soil NO_3^- concentrations in a *Pleum–Lolium* hayfield, suggesting the mowing is a management option that can reduce soil residual N at the end of the growing season in some hayfields. Research is needed to determine the optimum mowing intensities on hayfields to reduce soil residual N and prevent NO_3^- leaching.

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