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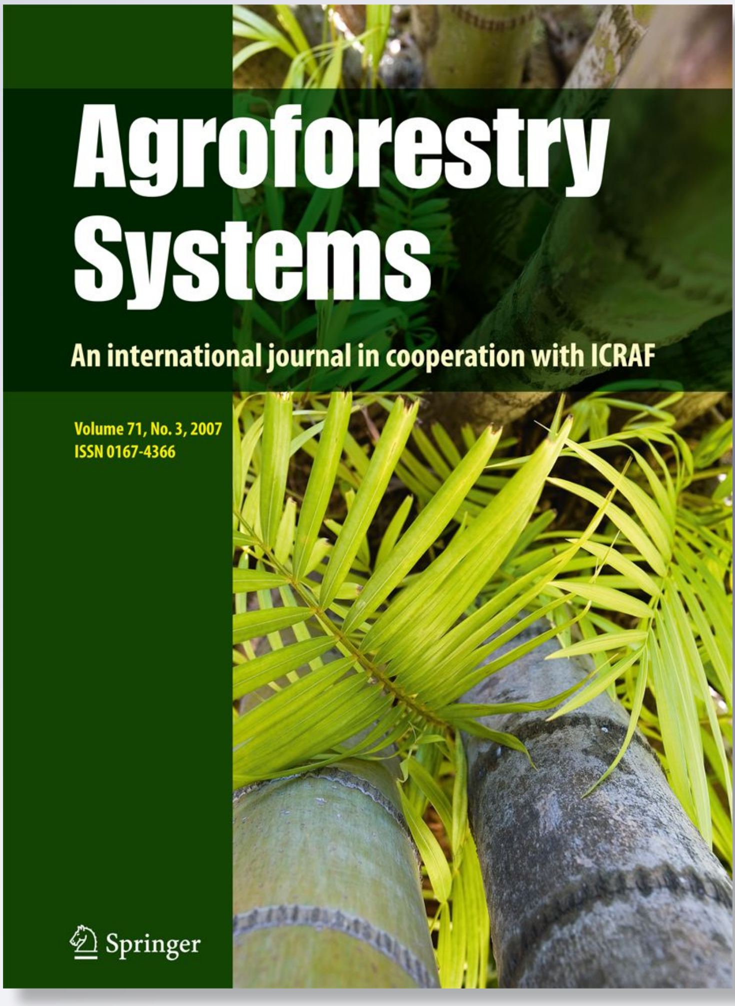

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Abstract Tree-based intercropping (TBI) systems, combining agricultural alley crops with rows of hardwood trees, are largely absent in Canada. We tested the hypothesis that the roots of 5–8 years old hybrid poplars, growing in two TBI systems in southern Québec, would play a "safety-net" role of capturing nutrients leaching below the rooting zone of alley crops. TBI research plots at each site were trenched to a depth of 1 m on each side of an alley. Control plots were left with tree roots intact. In each treatment at each site, leachate at 70 cm soil depth was repeatedly sampled over two growing seasons using porous cup tension lysimeters, and analyzed for nutrient concentrations. Daily water percolation rates were estimated with the forest hydrology model ForHyM. Average nutrient concentrations for all days between consecutive sampling dates were multiplied by water percolation rates, yielding daily nutrient leaching loss estimates for each sampling step. We estimated that tree roots in the TBI system established on clay loam soil decreased subsoil NO_3^- leaching by 227 kg N ha^{-1} and 30 kg N ha^{-1} over two consecutive years, and decreased dissolved organic N (DON) leaching by 156 kg N ha^{-1} year^{-1} in the second year of the study. NH_4^+ leaching losses at the same site were higher when roots were present, but were 1–2 orders of magnitude lower than NO_3^- or DON leaching. At the sandy textured site, the safety net role of poplar roots with respect to N leaching was not as effective, perhaps because N leaching rates exceeded root N uptake by a wider margin than at the clay loam site. At the sandy textured site, significant and substantial reductions of sodium leaching were observed where tree roots were present. At both sites, tree roots reduced DON concentrations and the ratio of DON to inorganic N, perhaps by promoting microbial acquisition of DON through rhizodeposition. This study demonstrated a potential safety-net role by poplar roots in 5–8 year-old TBI systems in cold temperate regions.

Keywords Agroforestry · Hybrid poplar · Lysimeter · Nutrient leaching losses · Trenching

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Introduction

Nitrogen (N) and phosphorus (P) are the two main growth limiting nutrients of many agricultural crops, and they are consequently applied as fertilizers in quantities often exceeding 100 kg ha^{-1} (CRAAQ 2003). Various studies on N use efficiency have estimated that only 30–50% of fertilizer-N is actually absorbed by the crops (Raun and Johnson 1999). Likewise, MacDonald and Bennett (2009) estimated that the average fertilizer-P application rate in nine watersheds of southern Quebec (Canada) exceeded crop requirements by 15–22 kg ha^{-1}. Fertilizer nutrients that are not absorbed by crops may be lost from the field through pathways such as volatilization, surface runoff or leaching to groundwater, causing economic losses and environmental pollution (Drury et al. 1996). Fertilization may also result in a net displacement of clay-adsorbed base cations into soil solution, where they may subsequently be leached from the soil profile (Lundell et al. 2001). Recently, the spread of noxious blue-green algae in southern Québec lakes (Giani et al. 2005) has created a public debate as to what measures and policies should be implemented to reduce the environmental pollution caused by current farming practices. There is a growing demand for better and new production systems that will result in a more efficient cycling of fertilizer nutrients.

Tree-based intercropping (TBI) systems that combine agricultural alley crops with rows of hardwood trees, have been implemented in Europe and in the US but are largely absent from the agricultural landscape of Canada. Bradley et al. (2008) recently proposed the implementation of TBI systems in eastern Canada, as a means of improving "soil quality". In this case, soil quality was defined using different criteria, one of which is the ability of the soil to mitigate groundwater pollution. In what has been labelled "the safety-net hypothesis" (van Noordwijk et al. 1996), we posited that the roots of trees grown in a TBI system can capture and help retain nutrients that would be leached below the rooting zone of the alley crops. The safety-net feature has already been confirmed in a mature cotton-pecan TBI system in Florida with 50 years old trees (Allen et al. 2004). It remains, however, uncertain whether a safety-net effect can be observed with much younger trees, especially in cold temperate climates where potential growth rates are intrinsically lower.

In this report, we will discuss the results from a study similar to the one conducted by Allen et al. (2004), to assess the effects of tree roots in 5–8 years old TBI systems in southern Québec on the leaching of mineral and dissolved organic N, total and ortho-P, and base cations such as Na^+, K^+, Ca^{2+}, Mg^{2+}. The study was performed on two pilot study sites with two contrasting soil textures. On each site, hybrid poplar (*Populus* sp.) was planted as the early-dominant tree species because of its high water uptake potential (Pallardy and Kozlowski 1981) and its ability to rapidly establish roots below the entire rooting zone of the alley crops (Friend et al. 1991).

Materials and methods

Study sites and experimental design

The first study site is located near the town of Saint-Rémi (45°16′N, 73°36′W), Québec. Mean annual temperature and precipitation are respectively 6.3°C and 844 mm (Environment Canada 2009). Monthly climate averages for the study period are shown in Fig. 1. A TBI system was established in the spring of 2000 using three hybrid poplar clones (*Populus trichocarpa* × *deltoids* TD-3230, *P. nigra* × *maximowiczii* NM-3729, *P. deltoids* × *nigra* DN-3308), which had attained an average height and diameter at breast height (DBH) of 8 m and 13.5 cm respectively in 2006. Rows of hybrid poplar alternated with rows of high-value hardwood species such as black walnut (*Juglans nigra* L.) and white ash (*Fraxinus americana* L.), which had attained an average height of 3.5 m in 2006. Tree rows were established atop a 1.5 m wide bed covered with plastic mulch (75 cm on either side) and oriented along a north–south axis. The spacing between tree rows was 6 m and trees within rows were spaced by 2 m. Soybean (*Glycine max* Merr.) was grown as the alley crop since 2004. Soil texture was clayey loam (35% clay, 30% silt, 35% sand), soil pH in 0.1 N KCl solution was 6.05, and soil organic matter content was 6.0%. We planned to sow wheat (*Triticum aestivum* L.) as the alley crop in 2006, therefore plots were fertilized prior to sowing (3rd week of May) with 100 kg N,

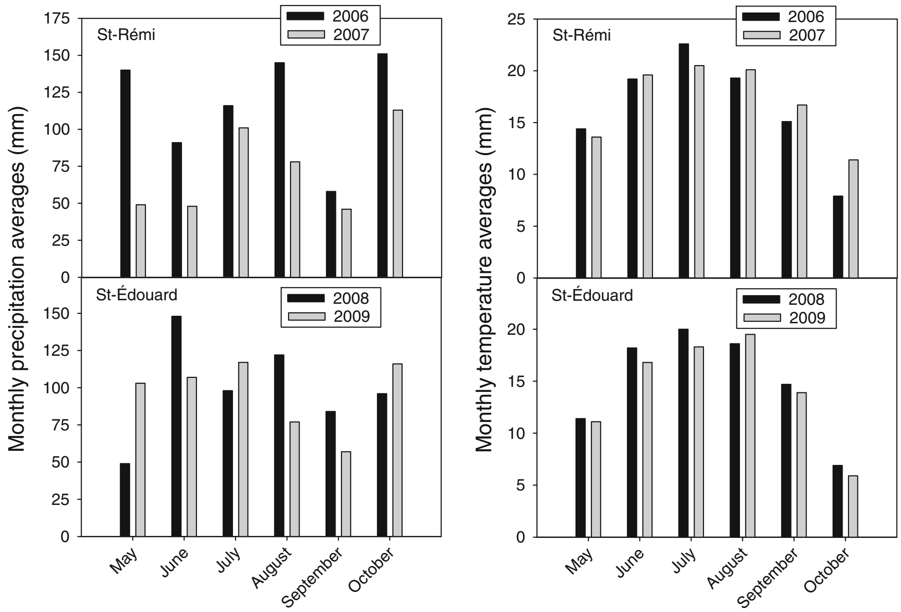

Fig. 1 Monthly climate averages for each experimental site during the study period

65 kg P_2O_5 and 60 kg K_2O ha^{-1}, as recommended for wheat by the Centre de référence en agriculture et agroalimentaire du Québec (CRAAQ 2003). Due to exceptionally high precipitation that spring and early summer (Fig. 1), the plots could not be tilled and sown until late June. For that reason, soybean was planted instead of wheat. It is reasonable to assume that the substantial growth of herbaceous vegetation and weeds that occupied the plots prior to sowing absorbed soil nutrients at least to the same extent as would a wheat crop. The year 2007 presented normal climate conditions, and the alleys were sown with soybean and fertilized with 33 kg N, 33 kg P_2O_5 and 33 kg K_2O ha^{-1} (CRAAQ 2003).

The second study site is located 150 km further north near the town of Saint-Édouard-de-Maskinongé (46°20′N, 73°09′W). Mean annual temperature and precipitation are respectively 4.7°C and 994 mm (Environment Canada 2009). Monthly climate averages for the study period are shown in Fig. 1. In spring of 2004, a TBI system was established using two hybrid poplars clones (*P. deltoides* × *nigra* DN3333, *P. deltoids* × *nigra* DN3570) alternating with rows of high-value hardwoods composed of red oak (*Quercus rubra* L.), red ash (*F. pennsylvanica* Marsh.) and white ash. Each tree row was established on a 2 m wide plastic mulch (1 m on either side) and trees within rows were spaced by 2 m. Poplars and high-value hardwoods had respectively attained an average DBH of 4.8 and 1.5 cm in 2008. Tree rows were oriented along a north-east axis and the spacing between rows was 8 m. Canola (*Brassica napus* L.) was grown as the alley crop in 2008, and white clover (*Trifolium repens* L.) in 2009. Soil texture was sandy (3% clay, % 10% silt, 87% sand), soil pH in 0.1 N KCl solution was 5.08, and soil organic matter content was 6.4%. In 2008, we broadcast applied 80 kg N, 80 kg P_2O_5 and 80 kg K_2O ha^{-1} prior to sowing, as recommended for canola (CRAAQ 2003). These fertilizer rates were halved in 2009, as recommended for white clover (CRAAQ 2003).

At St-Rémi, we established four plots (75 m × 8 m), each comprising one row of hybrid poplar, one adjacent row of high-value hardwoods, and the intercrop bound within both rows. In October 2005, a 1 m deep × 30 cm wide furrow was mechanically trenched at 75 cm distance from both tree rows, in two of the four plots. A double-ply polyethylene sheet (1.5 mm thick) was installed along the alley face of the trenches, and these were backfilled from the side closest to the trees, thereby causing minimal disturbance to the soil within the alley. These two trench plots were assumed, therefore, to be lacking tree roots for the next few years. In each plot, nine porous cup tension lysimeters, made of 1 m × 2.5 cm dia. PVC pipes fitted with high porosity ceramic cups (Soil Moisture Equipment Corp., Santa Barbara, CA) were installed 8 m apart and 2 m from the row of poplars, with porous cups at a depth of 70 cm. The top opening of each lysimeter was sealed with a plastic lid and left to overwinter (2005–2006) in order for soil particles to slake around the ceramic cups, as well as to allow the decomposition of fine roots that had been severed by the trenching (Lavoie and Bradley 2003). In October 2007, a similar setup was established at the St-Édouard site, this time using three trench and three non-trench plots, each equipped with six lysimeters.

Sampling and analysis of soil solution

Soil solution at St-Rémi was sampled from each lysimeter on 11 dates (11 May–8 Nov.) in 2006, and on 10 dates (16 May–Oct. 19) in 2007. Soil solutions at St-Édouard were sampled on 11 dates (13 May–16 Oct.) in 2008, and on 9 dates (6 May–19 Aug.) in 2009. Three drops of phenyl mercuric acetate were added to each sample to prevent microbial growth. Samples were kept frozen (–20°C) until they could be analyzed. All samples were analyzed colorimetrically for NH_4^+–N (nitroprusside–hypochlorite–salycilate) and NO_3^-–N (Cd reduction–sulphanilamide) concentrations (Mulvaney 1996) using a Technicon Auto-Analyzer (Pulse Instrumentations, Saskatoon, Canada). From onwards, the term DIN (i.e., dissolved inorganic N) is used to designate the sum of (NH_4^+–N + NO_3^-–N). Samples collected in 2007, 2008 and 2009 were also analyzed for dissolved organic nitrogen (DON), for ortho-P and total-P. DON was measured by subtracting initial mineral N (i.e., $NH_4^+ + NO_3^-$) concentrations from the total NO_3^- evolved from an alkaline persulfate digestion (Cabrera and Beare 1993). Ortho-P and total-P were measured colorimetrically by respectively reacting sampled solutions, and persulfate digested solutions, with an ammonium molybdate-ascorbic acid reagent (Murphy and Riley 1962). Samples collected in 2008 and 2009 were also analyzed for base cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) using a model AAnalyst 100 atomic absorption spectrometer (Perkin Elmer Corp., Norwalk, U.S.A.).

Estimating nutrient leaching losses

The rate of water percolating through the soil was estimated using the forest hydrology model ForHyM (Arp and Yin 1992). This is a spatially implicit model producing daily estimates of major water and heat flows in forested ecosystems based on local weather records (daily rain and snow amounts, and mean daily air temperature) and specifications concerning vegetation (amount and type of vegetation cover), topography (altitude, slope, aspect), soil conditions (soil class, depth, texture, organic matter, % coarse fragments, CEC), watershed location (longitude, latitude) and catchment area. This model is robust and has been used and cited in a number of published studies over the past 15 years (e.g., Houle et al. 2002; Balland et al. 2005; Murphy et al. 2009). The meteorological data used to calibrate the model was obtained from data published by the Government of Canada (Environment Canada 2009). We produced two model outputs, one ignoring the presence of tree roots (trenched plots) and another accounting for the presence of roots (non-trenched plots) at given tree age and density. For each lysimeter, average nutrient concentrations for all days between consecutive sampling dates were multiplied by the daily estimates of water percolation ($m^3\ ha^{-1}$) at 70 cm depth, yielding daily leaching loss estimates for each sampling step.

Statistical analyses

A linear mixed model was used to test the effects of sampling date, trenching, and their interaction term, on nutrient concentrations and estimated leaching losses. Data were log-transformed prior to analyses. Where significant ($P < 0.05$) sampling date x trenching interactions were found, the effect of trenching was tested at each sampling step using *t*-tests.

Results

At St-Rémi, average NH_4^+ concentrations and leaching losses in 2006 were significantly lower in trenched than in non-trenched plots (Fig. 2a, b). Conversely, average NO_3^- concentrations and leaching losses were significantly higher in trenched than in non-trenched plots in both 2006 and 2007 (Fig. 2c, d, e, f), as was DON in 2007 (Fig. 2g, h).

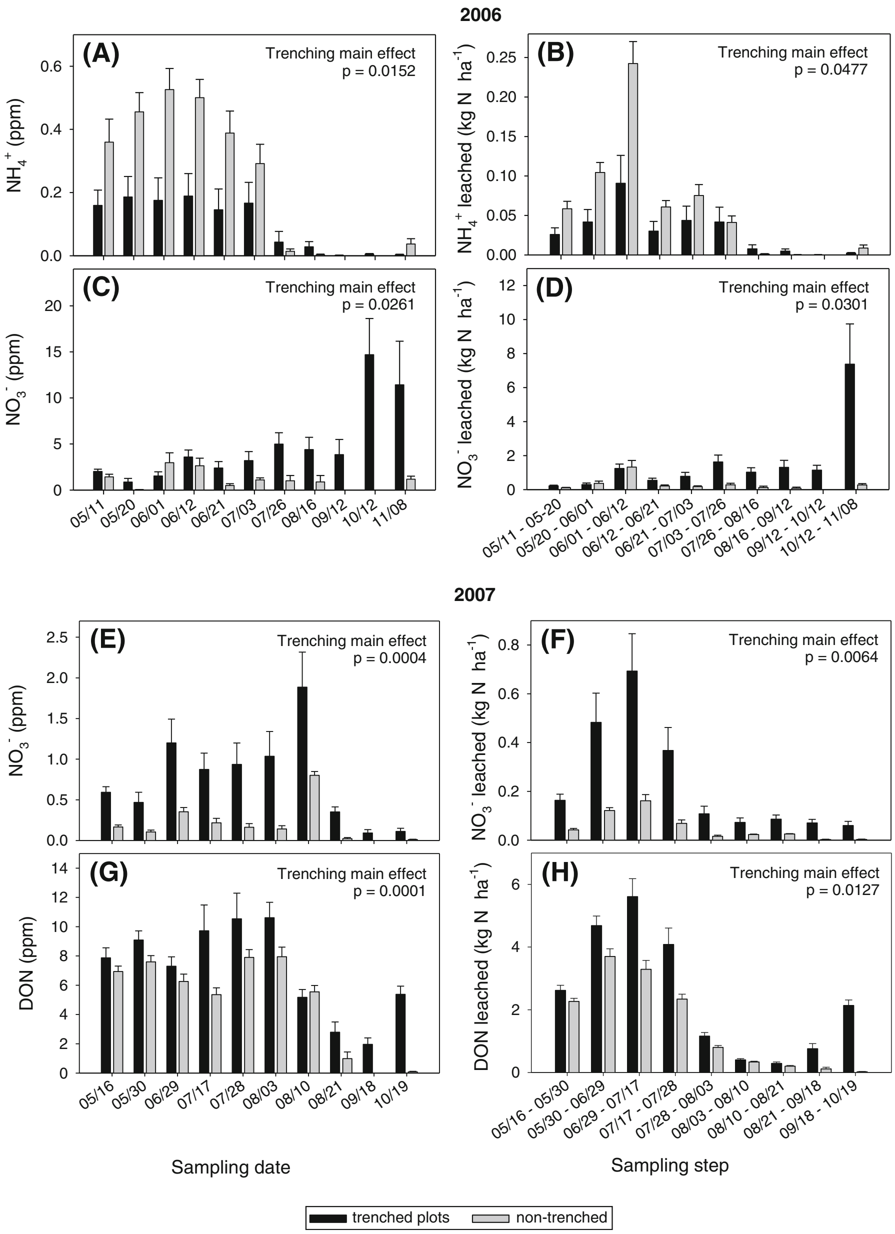

Fig. 2 Average NH_4^+–N, NO_3^-–N and DON concentrations at each sampling date, and average leaching losses per sampling step, in non-trenched versus trenched plots at St-Rémi (clayey loam soil) in 2006 and 2007; dates are denoted as month/day; *vertical lines* = 1 SE

Concentrations and estimated leaching losses of DON were approximately one order of magnitude greater than those of NO_3^-, which were one order of magnitude greater than those of NH_4^+.

At St-Édouard, trenching had no significant effect on nutrient concentrations or fluxes in 2008. In 2009, however, significant interactions were found between sampling date and trenching in controlling NH_4^+ and NO_3^- concentrations and leaching losses (Fig. 3a, b, c, d). More specifically, there were four sampling dates where concentrations and leaching losses of one or both mineral N forms were significantly higher in trenched than in non-trenched plots. Conversely, estimated NO_3^- leaching losses were about twice as

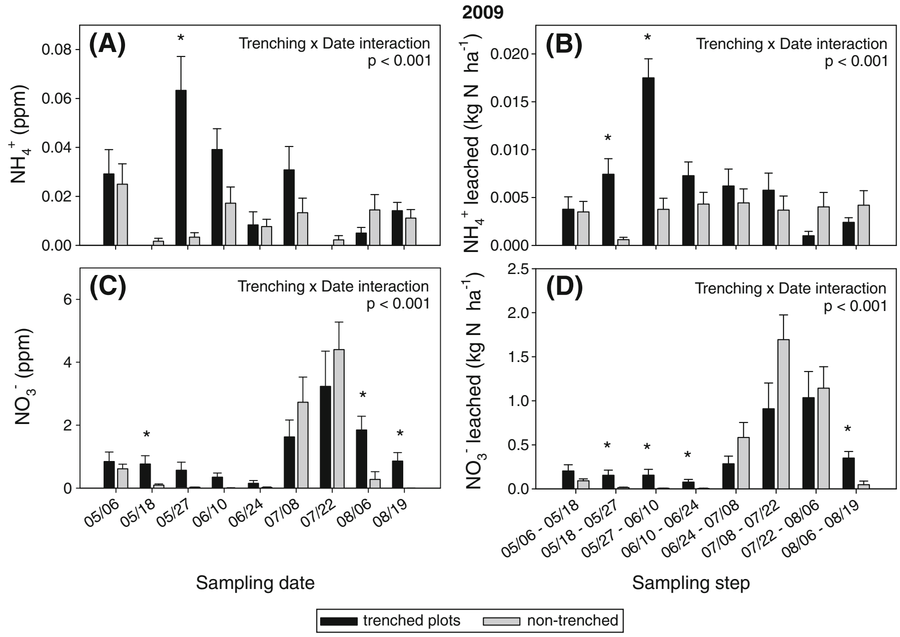

Fig. 3 Average NH_4^+–N and NO_3^-–N concentrations at each sampling date, and average leaching losses per sampling step, in non-trenched versus trenched plots at St-Édouard (sandy soil) in 2009; dates are denoted as month/day; *asterisks* denote sampling dates with significant trenching effects; *vertical bars* = 1 SE

high in non-trenched than in trenched plots during the period spanning June 24th to July 22nd, 2009. Although these differences were not statistically significant, the estimated amount of NO_3^- that was leached over this 4 weeks period was relatively high.

In both 2008 and 2009, concentrations and estimated leaching losses of Na^+ were significantly and substantially higher in trenched plots (Fig. 4a, b, c, d). As had been the case at St-Rémi, concentrations and estimated leaching losses of DON were one order of magnitude greater than those of NO_3^- (data not shown), which were one order of magnitude greater than those of NH_4^+. In 2007 (St-Rémi) and 2009 (St-Édouard), DON/DIN ratios were significantly lower in trenched than in non-trenched-plots (Fig. 5a, b). Over the 4 years, total-P and ortho-P were not detected in any of our samples.

Discussion

At the St-Rémi site, poplar roots reduced net N leaching losses, thereby confirming the "safety-net" effect in this young TBI system. By integrating our data over each growing season, we find that the presence of tree roots approximately reduced NO_3^- leaching by 227 kg N ha^{-1} in 2006 and by 30 kg N ha^{-1} in 2007, as well as DON leaching by 156 kg N ha^{-1} in 2007. Tree roots were more effective in reducing NO_3^- leaching in 2006 than 2007, because NO_3^- concentrations were higher (Fig. 2) and rainfall more sustained in 2006 (Fig. 1). The fact that hybrid poplar is a water-demanding tree species makes it especially suitable for reducing N losses in wet climates.

Our estimations of N leaching losses are based on the assumption that N concentrations measured in our lysimeters were representative of the entire alley, as though the distance from the tree row did not affect subsoil nutrient concentrations. We could not test this assumption because the need to operate small farm machinery within the alleys precluded the placement of lysimeters at different distances from the tree rows. There is, however, evidence from the literature that our assumption is acceptable. For example, Allen et al. (2004) found no significant differences in nutrient concentrations sampled from lysimeters placed at 1.5, 4.2 and 8.4 m from tree rows in a cotton-pecan TBI systems. Likewise, Friend et al. (1991) found that the lateral roots >2 mm in diameter of 2-year old hybrid poplar trees extended horizontally up to 4 m, resulting

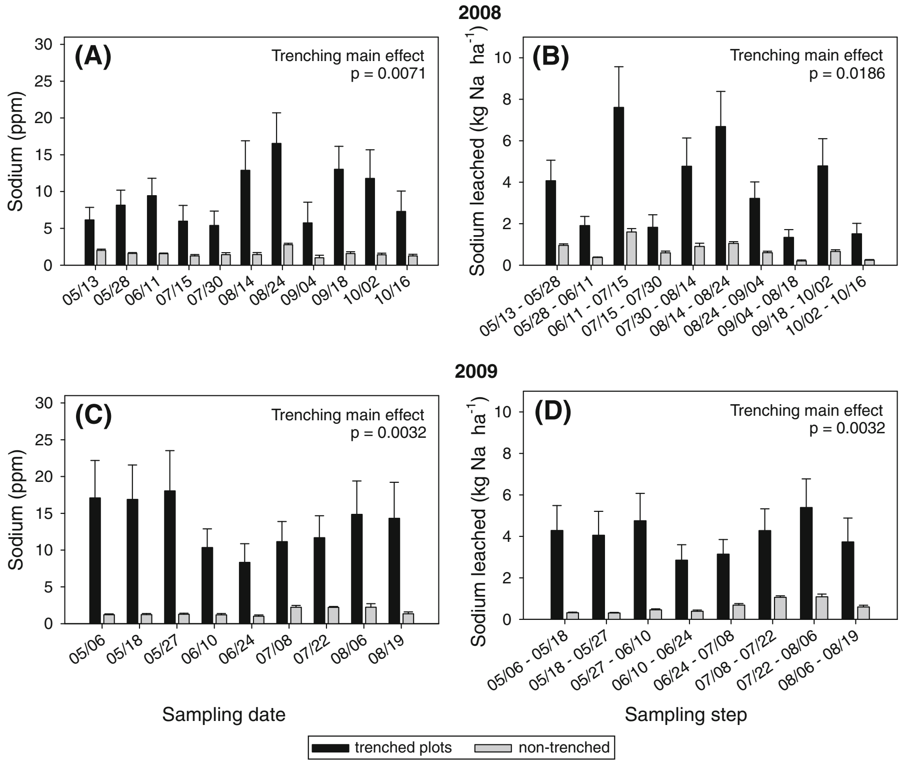

Fig. 4 Average sodium concentrations at each sampling date, and average leaching losses per sampling step, in non-trenched versus trenched plots at St-Édouard in 2008 and 2009; dates are denoted as month/day; *vertical bars* = 1 SE

in considerable overlap of root systems from adjacent tree rows. Furthermore, lysimeters were placed closer to the center of the alley than to the tree rows, suggesting that reductions of N leaching due to tree roots may, if anything, have been underestimated.

In 2006, we observed higher NH_4^+ concentrations and leaching losses in non-trenched plots. While these observations seem counterintuitive, they are nonetheless consistent with the results of Browaldh (1995) who found higher NH_4^+ concentrations (60 cm depth) at 1 m distance than at 5 m distance from poplar rows. The higher amount of NH_4^+ in non-trenched-plots may reflect favourable conditions for ammonification prevailing in the rhizosphere of poplar roots. For example, Bradley and Fyles (1995) demonstrated a positive relationship between root-derived available carbon from birch seedlings and net soil ammonification rates. Likewise, a trench plot study by Ehrenfeld et al. (1997) reported a positive effect of living roots on forest soil ammonification rates. The fact that poplars roots have a greater affinity for NO_3^- than for NH_4^+ (Choi et al. 2005) would explain why this excess NH_4^+ remained in soil solution in the presence of tree roots. We note, however, that the estimated increase in NH_4^+ leaching losses due to poplar roots was modest (5 kg N ha^{-1}) compared to the estimated reductions in NO_3^- and DON leaching.

At the St-Edouard site, the safety-net role of poplar roots with respect to NO_3^- leaching was not clearly demonstrated, as it was at the St-Rémi site. This may be due to better drainage on the coarser textured soil and to lower nutrient uptake by the younger poplar trees at St-Edouard. Consequently, nutrient leaching rates would likely exceed root N uptake rates by a wider margin at St-Edouard than at St-Rémi. Also in contrast to St-Rémi, we observed higher NH_4^+ leaching losses in trenched than in non-trenched plots at St-Édouard, although these losses remained relatively modest (0.76 kg N ha^{-1}) and were observed on only two occasions. Thus, compared to the St-Rémi site, poplar roots at the St-Edouard site absorbed more NH_4^+ relative to the amount that was mineralized. This greater absorption of NH_4^+ by poplars may result from the inherent low fertility of the coarser textured soil at

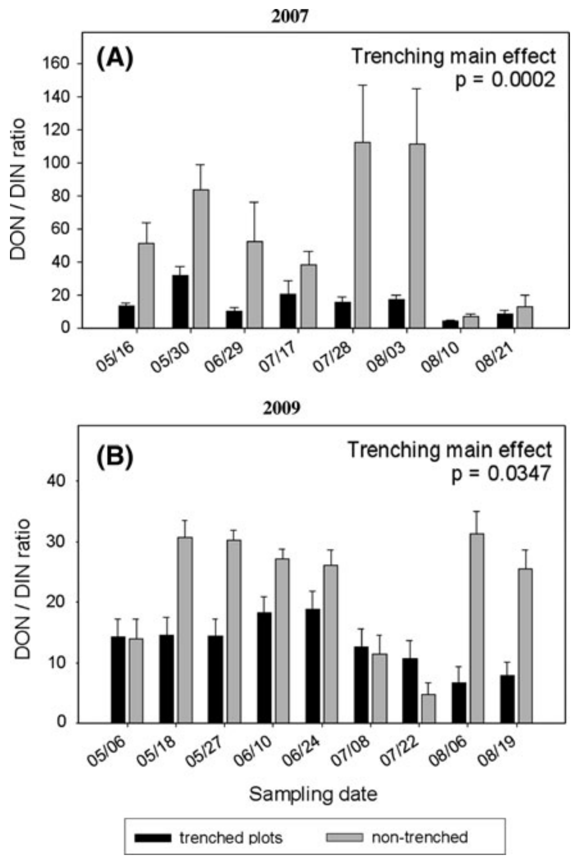

Fig. 5 Average DON:DIN ratio at each sampling date in non-trenched versus trenched plots at St-Rémi in 2007, and at St-Édouard in 2009; dates are denoted as month/day; *vertical bars* = 1 SE

St-Édouard. For example, Kronzucker et al. (1998) demonstrated a potential for roots to up-regulate membrane bound enzymes involved in NH_4^+ absorption when nitrogen is in limited supply.

At both sites, a substantial amount of nitrogen was leached in dissolved organic forms (DON). Although many plant species are capable of absorbing low molecular weight organic molecules such as amino acids (Nasholm et al. 1998), these labile molecules constitute a small proportion ($\sim$1%) of what is actually comprised in the DON pool (Hannam and Prescott 2003). Furthermore, it is likely that heterotrophic microorganisms are better competitors than plant roots for free amino acids in soil solution (Kahmen et al. 2009). Thus, it is unlikely that root uptake could alleviate leaching losses of DON to the same extent as NO_3^- or NH_4^+. It is notable, therefore, that poplar root systems did decrease DON leaching losses in 2007. This could not only have been due to poplar roots limiting water fluxes, as DON concentrations and DON/DIN ratios were also reduced in the presence of tree roots. We posit that poplar root systems promoted microbial acquisition of DON through rhizodeposition, as proposed by Bradley and Fyles (1995).

Among base cations, sodium was the only element to leach more abundantly in the trenched than in non-trenched plots at the St-Edouard site. Sodium's low atomic mass and single ionic charge result in this cation being adsorbed to negatively charged soil particles with lesser strength than other soil cations (Gardiner and Miller 2004). Sodium is thus the first cation to be leached, especially in a coarse textured soil with low cation exchange capacity. Our data suggest, therefore, a high sodium absorption potential for poplar roots, which makes this an interesting tree species in areas with repeated applications of high-salinity irrigation water (Zalesny et al. 2008), or for phytoremediation projects involving high salinity landfill leachate.

It cannot be assumed that the only effect of trenching was to eliminate the uptake of water and nutrients by trees. Among the "collateral effects" of trenching on soil nutrient dynamics, the elimination of poplar roots resulted in a loss of rhizodeposition products that drive nutrient acquisition by soil microbes (Bradley and Fyles 1995). For example, Lavoie and Bradley (2003) reported an increase in the NO_3^-:NH_4^+ ratio due to trenching that they attributed to a concomitant decrease in soil microbial biomass. Thus, the higher leaching losses of NO_3^- compared to NH_4^+ may not only be due to the greater mobility of NO_3^-, but may also reflect an artefact due to trenching. The elimination of poplar roots is also expected to reduce the amount of arbuscular mycorrhizal fungi colonizing the intercrop (Lacombe et al. 2009). This, in turn, could result in lower nutrient uptake by the intercrop and increase nutrient leaching.

In summary, our data suggest a safety-net role of poplar roots with respect to NO_3^-, DON and sodium leaching in 5–8 years old TBI systems of eastern Canada. Although poplar roots reduced N leaching to a greater extent on clayey loam than on sandy soil, the role of soil texture in controlling N interception by poplar roots still needs to be confirmed with studies comprising replicate sites of similar textural class. Future research should also test the safety-net role of poplar roots at greater tree row spacings, as TBI systems that have been proposed for eastern Canada comprise 12–20 m tree row spacings (e.g., Thevathasan and Gordon 2004), or about twice those used in our study.

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