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ARTICLE

A nutrient-based sustainability assessment of purpose-grown poplar and switchgrass biomass production systems established on marginal lands in Canada[1]

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Abstract: The sustainability of purpose-grown biomass production on marginal lands in Canada is uncertain. In this study, an assessment of biomass yield and sustainability was performed for two poplar clones (*Poplus deltoides* × *P. nigra*, DN-34—PDN, and *P. nigra* × *P. maximowiczii*, NM-6—PNM) and two switchgrass cultivars (*Panicum virgatum* 'Cave-in-Rock'—SGC, and *P. virgatum* 'Nebraska'—SGN) on three marginal lands in Guelph (ON), Kemptville (ON), and Nappan (NS) in Canada. The differences in stem biomass across sites were not significant; however, differences in stem biomass among plants were statistically significant between poplar and switchgrass ($p < 0.0001$) and between poplar clones ($p < 0.0001$). The 2-yr stem biomass yield in PNM (15.27 ± 1.28 t ha^{-1}) was significantly higher than those in PDN (7.02 ± 0.54 t ha^{-1}), SGC (2.57 ± 0.28 t ha^{-1}), and SGN (1.45 ± 0.22 t ha^{-1}). Two sustainability indices based on macronutrients (MBSI) and nitrogen (NBSI), were developed to assess sustainability. Both indices show that the biomass production system of high-yielding poplar clone PNM depicts nutrient loss and may require external nutrient inputs via fertilization during the establishment phase. Higher index values for switchgrass SGC (1.47 ± 0.22, 1.11 ± 0.15) and SGN (1.37 ± 0.16, 1.17 ± 0.12) for MBSI and NBSI, respectively, indicate that despite low stem biomass yields, switchgrass biomass production is sustainable. These findings suggest that, from a nutrient perspective, sustainable biomass production systems can be established on marginal lands in Canada; however, there is a trade-off between high yield and long-term sustainability in purpose-grown biomass production systems.

Key words: marginal lands, nutrient, poplar, sustainability, switchgrass.

Résumé : On ignore dans quelle mesure la production de biomasse sur les terres marginales du Canada serait une activité durable. La présente étude évalue le rendement de la biomasse et la pérennité de deux clones de peuplier (*Poplus deltoides* × *P. nigra*, DN-34 – PDN, et *P. nigra* × *P. maximowiczii*, NM-6 – PNM) ainsi que de deux cultivars de panic raide (*Panicum virgatum* cv. Cave-in-Rock – SGC et *Panicum virgatum* cv. Nebraska – SGN) sur trois terres peu productives situées à Guelph (ON), à Kemptville (ON) et à Nappan (NS), au Canada. La biomasse des tiges n'a pas varié de façon significative aux trois endroits, cependant, l'écart entre la biomasse des peupliers et celle du panic raide est statistiquement significatif ($p < 0,0001$), de même que l'écart entre la biomasse des deux clones de peuplier ($p < 0,0001$). Le rendement en biomasse de PNM au cours des deux années de l'étude ($15,27 \pm 1,28$ t par hectare) était sensiblement plus important que celui de PDN ($7,02 \pm 0,54$ t par hectare), de SGC ($2,57 \pm 0,28$ t par hectare) et de SGN ($1,45 \pm 0,22$ t par hectare). Les auteurs ont élaboré deux indices pour évaluer la pérennité d'après la concentration de macronutriments (MBSI) et celle d'azote (NBSI). Les deux indices révèlent que la production de

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biomasse par le clone de peuplier à rendement élevé PNM entraîne la perte d'oligoéléments, ce qui pourrait nécessiter un apport externe par fertilisation pendant la période où la culture s'établit. L'indice plus élevé obtenu pour le panic raide (1,47 ± 0,22 et 1,11 ± 0,15 pour SGC et 1,37 ± 0,16 et 1,17 ± 0,12 pour SGN avec le MBSI et le NBSI, respectivement) indique qu'en dépit du faible rendement des tiges, la production de biomasse par le panic raide serait une activité durable. Ces résultats laissent croire qu'on pourrait produire de façon durable de la biomasse sur les terres marginales du Canada, du moins sur le plan des oligoéléments. Un système de production spécifique de la biomasse nécessiterait néanmoins un compromis entre un rendement élevé et la pérennité. [Traduit par la Rédaction]

Mots-clés : terres marginales, oligoéléments, peuplier, durabilité, panic raide.

Introduction

The demand for biomass is increasing for renewable energy production. It is estimated that by 2030, biomass would be the single most important renewable energy resource, with 30% utilization in biofuel production and the contribution of biomass from purpose-grown crops, within the bioenergy mix, will increase up to 33%–39% (Nakada et al. 2014). However, achievement of this potential biomass from purpose-grown crops mainly depends on two highly uncertain factors: land availability and biomass yields derived from available lands (Bauen et al. 2009). The modest nutrient requirement of purpose-grown biomass crops make them suitable to be grown on marginal lands: lands that are otherwise unsuited for sustained agriculture production due to various geophysical and climatic limitations (CGIAR-TAC 2000; Aylott et al. 2010; Gelfand et al. 2013). In Canada, a land suitability rating system (LSRS) is used to assess the suitability of land for agriculture production. The LSRS uses soil, climate, and landscape information to classify land into seven discrete classes (1–7): class 1 being highly suitable and class 7 unsuitable. The intermediate classes (3–4) have some moderate to severe limitations that make them marginal lands for specific agriculture crop production (Agronomic Interpretation Working Group 1995). It is estimated that about 9.48 million hectares of marginal lands in Canada can be utilized for purpose-grown biomass (Liu et al. 2012).

The production of purpose-grown biomass heavily depends on the continued availability of nutrients (Hangs et al. 2014*a*). Frequent harvestings can lead to enhanced nutrient removal, which can reduce site productivity over time (Adegbidi et al. 2001; Palviainen and Finer 2012; Ge et al. 2015). Therefore, it is pivotal for a sustainable biomass production that nutrient input should compensate for nutrient loss via biomass harvest. Nutrient input can come from a variety of internal sources, such as leaf litter decomposition and root turnover, and external sources, such as dry deposition (dust) and wet deposition (precipitation) (Reynolds et al. 2001; Schroth et al. 2001; Liu et al. 2002). The nutrient inputs from leaf litter decomposition and root turnover have important roles in maintaining the nutrient budget for biomass growth and production. However, the type of nutrient input depends on the biomass crops. For instance, leaf litter in herbaceous crops is minimal as these crops undergo total aboveground biomass removal annually, whereas in woody crops almost all leaves shed as leaf litter and add nutrients to the soil via decomposition and nutrient mineralization. Generally, leaf litter of woody biomass crops contribute more potassium (K) and roots contribute more nitrogen (N) and phosphorus (P), whereas in herbaceous crops both leaf litter and roots provide N in addition to K (Holou et al. 2013; Amichev et al. 2014).

A complete understanding of nutrient cycling in terms of the type and amount of nutrient input and whether these nutrient inputs will offset nutrient removal via harvest is, therefore, essential to assess the long-term sustainability of purpose-grown biomass. From a nutrient perspective, even though biomass crop productivity is mainly driven by the availability of N, P, and K (Brown and Driessche 2005; Parrish and Fike 2005; Guillemette and DesRochers 2008), the role of N alone has been emphasised in several studies (McLaughlin and Kszos 2005; Rennenberg et al. 2010; Qin et al. 2015). This nutrient cycling aspect is poorly understood for purpose-grown poplar (*Populus* spp.) and switchgrass (*Panicum virgatum* L.) production on marginal lands in Canada. Accordingly, a research network was established in 2014 to quantify biomass production and nutrient cycling in purpose-grown poplar and switchgrass systems on marginal lands in Canada. In this study, we focus on leaf litter and root turnover as nutrient input sources to assess the potential sustainability of purpose-grown biomass crops on marginal lands. We developed two sustainability indices: one based on three macronutrients (N, P, and K) and the other based on only N nutrients (to account for the enhanced role of N in productivity).

Materials and Methods

Study sites and experimental design

This research is based on data from three study sites in Canada: two sites at the University of Guelph research stations in Guelph and Kemptville (ON), and one site at the Agriculture and Agri-Food Canada (AAFC) Research Farm in Nappan (NS). According to LSRS, these sites are class 3–4 lands. Specifically, class 3 lands have moderate limitations that reduce the choice of crops or require special conservation practices and class 4 lands have severe limitations that restrict the choice of crops or require special conservation practices and very careful management, or both (Agronomic Interpretation Working Group 1995).

Table 1. Baseline site characteristics of experimental plots.

	Nappan	Kemptville	Guelph
Geo-climate			
Latitude	45°45′42.6″N	45°00′24.6″N	43°32′28″N
Longitude	64°14′31.6″W	75°37′26.9″W	80°12′32″W
Elevation (m)	15	96	325
Frost-free days (d)	152	130	144
Mean annual precipitation (mm)	1155	868	904
Mean summer precipitation (mm)	273	325	338
Soil texture			
Sand (%)	60.33	60.00	49.67
Silt (%)	32.00	33.00	42.67
Clay (%)	7.67	7.00	7.67
Soil nutrient properties			
Soil N (g kg^{-1})	0.83	1.32	1.18
Total soil C (g kg^{-1})	18.69	20.71	19.72
Inorganic soil C (g kg^{-1})	0.71	0.73	3.62
Organic soil C (g kg^{-1})	17.97	19.97	16.10
Soil EC (μS)	72.52	118.25	84.67
Soil pH	6.70	6.59	7.50
Organic matter (g kg^{-1})	26.00	34.90	29.00
P (mg kg^{-1})	28.50	46.69	24.90
K (mg kg^{-1})	44.50	101.67	85.70
Ca (mg kg^{-1})	1167.40	1165.33	2134.80
Mg (mg kg^{-1})	76.00	219.08	218.30

Note: Data was collected in 2014 prior to the establishment of experimental plots. N, nitrogen; C, carbon; P, phosphorus; K, potassium; Ca, calcium; Mg, magnesium.

Geographic locations and baseline soil characteristics of the study sites are shown in Table 1. At each site, experimental plots of 200 m^2 (10 m × 20 m) were established in 2014 for two poplar clones (DN34—*Poplus deltoides* × *P. nigra* and NM6—*P. nigra* × *P. maximowiczii*; hereafter referred to as PDN and PNM, respectively) and two switchgrass cultivars (*P. virgatum* 'Cave-in-Rock' and *P. virgatum* 'Nebraska'; hereafter referred to as SGC and SGN, respectively) in a randomized complete block design (RCBD) with four replications. A 2-m buffer was set between plots to prevent any shading effect. Following the European double-row design, PDN and PNM cuttings were planted at a density of 16 500 cuttings per hectare in a double-row configuration with 1.5 m between a set of double rows (Cardinael et al. 2012). Within a double row, rows were 0.75 m apart and within a row each cutting was 0.60 m apart (Fig. 1). Plots of SGC and SGN were established by seeding in rows 0.18 m apart at rates of 30 and 25 kg ha^{-1}, respectively. The higher seeding rate was applied to compensate for the lower germination rate (<50%) and to cope with the low site fertility. The difference in seeding rate between the cultivars was mainly to compensate for differences observed in their respective germination rates.

Biomass yields

In this study, 2-yr (2015 and 2016) biomass yields are evaluated for leaf biomass, stem/woody biomass, and root biomass of poplar and switchgrass. As the focus of this research is nutrient-based sustainability assessment, the biomass samplings were carried out after senescence (late October–early November) to allow for nutrient translocation and to minimize nutrient harvest from the system (Gorlitsky et al. 2015; Ashworth et al. 2017). The nutrients in these biomass components were further analysed to assess potential sustainability of poplar and switchgrass biomass production across the study sites.

Stem/woody biomass

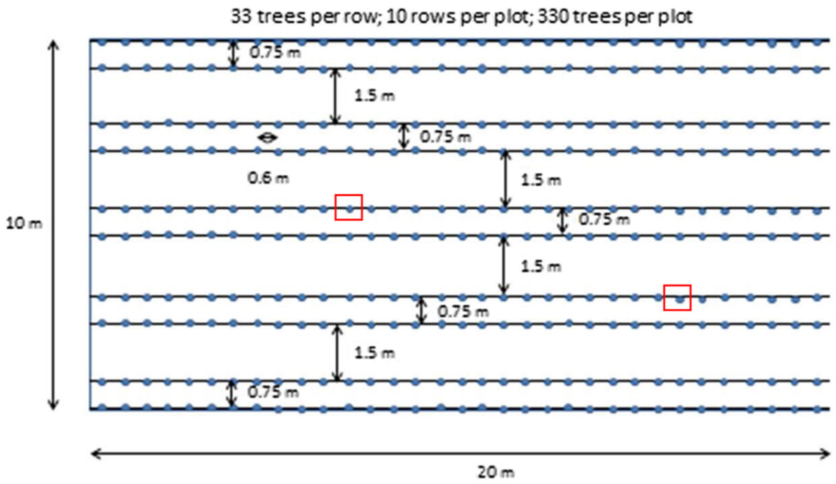
In energy crops, woody biomass is usually harvested once every 2–3 yr, whereas herbaceous biomass is harvested annually. In this study, annual yields of switchgrass biomass for 2015 and 2016 were consolidated to do a comparison with 2-yr poplar woody biomass yield.

In 2016, eight poplar plants from a randomly selected 2.25 m × 2.25 m area in the middle double rows in each poplar plot were harvested and weighed for their wet weight. A subsample was oven-dried at 65 °C until a constant mass was reached. After determining moisture content (eq. 1), woody biomass dry weight was calculated on a hectare basis.

$$(1) \qquad \text{Moisture content}\,(\%) = \frac{\text{Wet weight} - \text{Dry weight}}{\text{Wet weight}} \times 100$$

Switchgrass biomass samples were collected after the killing frost in late October/early November in 2015 and

Fig. 1. Layout of double row design used in poplar plots. Blue dots represent poplar cutting plantings at 0.6 m distance apart. Red boxes show how a sampling quadrant (60 cm × 60 cm) was laid out around each selected poplar plant. Actual location of sampling quadrants varied in each plot and depended on selected plants that represent the average crop condition. Distances shown are not to scale. [Colour online.]



2016. In each switchgrass plot, a 1-m^2 (1 m × 1 m) quadrant was used to collect samples. After harvest, all leaves were removed from stems. Leaves and stems were weighed separately for wet weight. Then, these samples were dried at 65 °C to achieve a constant weight. Moisture contents were determined using eq. 1 and dry weights for stem and leaf biomass were calculated on a hectare basis.

Leaf biomass

Leaf samples for both poplar and switchgrass were collected in 2015 and 2016. Traditionally, poplar leaf biomass samples are collected using leaf litter traps. However, the windy conditions at Nappan site made it difficult to collect samples using litter traps as leaves were blown away from the traps. So, a leaf plucking method was used to collect poplar leaves across all sites. In each poplar plot, all leaves from 10 randomly selected plants were picked and weighed for wet weight. To determine moisture contents, collected samples were dried at 65 °C for a few days until a constant mass was achieved. Finally, the dry weight of leaf biomass was calculated on a hectare basis based on plant density per hectare.

Switchgrass leaf biomass was measured from the leaves separated from the stems and a similar procedure executed for poplar leaves was applied to calculate dry weight on a hectare basis based on the sample area harvested.

Root biomass

Root biomass samples for both poplar and switchgrass were collected at the end of the 2016 growing season. In each polar plot, two plants were randomly selected for root samples. Then, a 60 cm × 60 cm quadrant was laid out around each selected plot in such a way that the plant stump was in the centre of the quadrant (Fig. 1). In each quadrant, soil with all roots was collected up to a 20-cm depth. For switchgrass root sampling, a quadrant of 30 cm × 30 cm was used to collect soils with roots up to a 20-cm depth. All soil samples were then rinsed on a 2 mm mesh screen to separate roots. Washed root samples were weighted for wet weight and then oven-dried at 65 °C until a constant mass was achieved. After determining moisture contents (eq. 1), root biomass dry weights were calculated on a hectare basis.

Assessment of sustainability

The sustainability of biomass crop production depends on the continued availability of nutrients through various internal and external sources. In this study, the potential total nutrient input through leaf litter and root turnover was used to assess the sustainability of poplar and switchgrass biomass production on marginal lands.

Nutrient analyses

Subsamples of all biomass samples (stem, leaves, and roots) of poplar (PDN and PNM) and switchgrass (SGC and SGN) for all plots were milled using a Wiley mill (Thomas Scientific, Swedesboro, NJ) and analyzed for N, P, and K at SGS Agri-Foods Laboratories Inc., Guelph, ON. The nutrients in senescing leaves were used in all analyses to account for nutrient translocation during leaf senescence in poplar leaves (McColl 1980; Cooke and Weih 2005).

Sustainability indices

Two nutrient input/output-based sustainability indices were developed: a macronutrient-based sustainability index (MBSI): the ratio of total N, P, and K input

Table 2. Significance level (p value) for the analysis of variance.

Source of variation	df	Leaf biomass	Stem biomass	Root biomass	MBSI	NBSI
Site	2	<0.0001	0.8289	0.0264	0.0669	0.0554
Block in site	9	0.1339	0.1583	0.8999	0.8215	0.7966
Plant[a]	3	<0.0001	<0.0001	<0.0001	0.0018	0.0010
Poplar vs. switchgrass	1	<0.0001	<0.0001	<0.0001	0.0102	0.0200
Poplar (PDN vs. PNM)	1	0.0001	<0.0001	0.8446	0.0016	0.0005
Switchgrass (SGC vs. SGN)	1	0.1354	0.1957	0.0003	0.8533	0.5766
Plant × site	6	<0.0001	0.1251	<0.0001	0.0030	0.5668
CV	—	38.21	33.32	39.03	37.55	39.74
R^2	—	0.8899	0.9340	0.8531	0.7798	0.6571

Note: Source of variations include site, plant, and their interaction as main effects on different biomass variables (leaf, stem, and root) and sustainability indices (MBSI and NBSI). The effects were tested on 2 yr data of two poplar clones (DN34 and NM6) and two switchgrass cultivars ('Cave-in-Rock' and 'Nebraska') from three experimental sites namely Guelph (ON), Kemptville (ON), and Nappan (NS) in Canada. df, degrees of freedom; MBSI, macronutrients-based sustainability index; NBSI, nitrogen-based sustainability index, CV, coefficient of variation.

[a]The partitioning of treatment (plant) sum of square was done using an orthogonal contrasts approach.

(via leaf litter and root turnover) to total N, P, and K output (via woody/stem biomass harvest) and a nitrogen-based sustainability index (NBSI): the ratio of total N input (via leaf litter and root turnover) to total N output (via woody/stem biomass harvest). A value of <1 for the developed sustainability indices indicates the system is undergoing a net loss of nutrients and will not be sustainable over the long term (Mohammadzade and Bazrgar 2014). However, actual sustainability will depend on additional factors such as the rate of nutrient release, atmospheric deposition, and nutrient leaching. These additional factors are beyond the scope of this study and are being investigated in a contemporary study.

Poplar is deciduous and shed all leaves by the end of growing season. Hence, in the case of poplar, 100% leaf biomass was considered as the nutrient input source in MBSI (eq. 2) and NBSI (eq. 3).

$$\text{MBSI}_{\text{P}} = \frac{\sum_{i=0}^{n}(\text{leaf}_{\text{N,P,K}} + \text{root}_{\text{N,P,K}})}{\sum_{i=0}^{n}(\text{stem}_{\text{N,P,K}})} \tag{2}$$

$$\text{NBSI}_{\text{P}} = \frac{\sum_{i=0}^{n}(\text{leaf}_{\text{N}} + \text{root}_{\text{N}})}{\sum_{i=0}^{n}(\text{stem}_{\text{N}})} \tag{3}$$

Complete leaf shed does not occur in switchgrass and leaves are harvested with stems and subsequently used for various purposes such as animal bedding and as mulch. In this study, it was observed that about 20% of leaves remained in plots after harvesting. Therefore, MBSI and NBSI indices for switchgrass were modified considering only 20% of leaf biomass as the nutrient input source. The MBSI and NBSI for switchgrass are expressed in eqs. 4 and 5, respectively.

$$\text{MBSI}_{\text{S}} = \frac{\sum_{i=0}^{n}(0.2\text{leaf}_{\text{N,P,K}} + \text{root}_{\text{N,P,K}})}{\sum_{i=0}^{n}(0.8\text{leaf}_{\text{N,P,K}} + \text{stem}_{\text{N,P,K}})} \tag{4}$$

$$\text{NBSI}_{\text{S}} = \frac{\sum_{i=0}^{n}(0.2\text{leaf}_{\text{N}} + \text{root}_{\text{N}})}{\sum_{i=0}^{n}(0.8\text{leaf}_{\text{N}} + \text{stem}_{\text{N}})} \tag{5}$$

Statistical analyses

All treatments were tested for statistical parameters using SAS 9.4 (SAS Institute Inc., Cary, NC). General linear procedures in SAS were used to perform statistical analyses. PROC GLM was used to perform partitioned analysis of the least squares means for site and plant interaction sliced by three experimental sites. To evaluate the planned comparison between plants, the treatment sum of square was portioned using an orthogonal contrast approach. Combined analysis was conducted as a RCBD in places for 2-yr data. A Shapiro–Wilk's test ($\alpha = 0.05$) was used to test whether residuals followed a normal distribution and, where necessary, log transformations were used to normalize residuals.

Results

Biomass yields

Results for 2-yr leaf biomass, stem biomass, and root biomass are presented in Tables 2–5 and Fig. 2. These results show that differences between overall leaf biomass and root biomass yields across sites are statistically significant, whereas stem biomass yields (woody and herbaceous) across sites are comparable (Table 2). Leaf biomass yield at Kemptville is significantly higher (5.60 ± 1.25 t ha^{-1}) than Guelph (3.26 ± 0.17 t ha^{-1}) and Nappan (2.53 ± 0.32 t ha^{-1}). The differences in combined (poplar and switchgrass) leaf biomass yields at Guelph (3.26 ± 0.17 t ha^{-1}) and Nappan (2.53 ± 0.32 t ha^{-1}) are non-significant. For root biomass, yields at Guelph (2.72 ± 0.42 t ha^{-1}) and Nappan (2.81 ± 0.63 t ha^{-1}) are significantly higher than Kemptville (1.86 ± 0.22 t ha^{-1}) (Table 3).

When compared among plants, the differences in leaf biomass, stem biomass, and root biomass all are

Table 3. Comparison of 2-yr means of leaf biomass, stem biomass, root biomass, and two sustainability indices (MBSI and NBSI) for Guelph (ON), Kemptville (ON), and Nappan (NS) in Canada.

Sites	Leaf biomass (t ha^{-1})	Stem biomass (t ha^{-1})	Root biomass (t ha^{-1})	MBSI	NBSI
Guelph	3.26 ± 0.17b	6.70 ± 1.26a	2.71 ± 0.42a	1.22 ± 0.14a	0.94 ± 0.07b
Kemptville	5.59 ± 1.25a	5.03 ± 1.89a	1.86 ± 0.22b	0.93 ± 0.16b	0.86 ± 0.12b
Nappan	2.53 ± 0.32b	6.47 ± 1.43a	2.81 ± 0.63a	1.41 ± 0.17a	1.21 ± 0.13a

Note: Within column, values (means and standard errors) with the same lowercase letter are not statistically different as determined by Duncan's new multiple range test at $\alpha = 0.05$. Data is for two poplar clones (DN34 and NM6) and two switchgrass cultivars ('Cave-in-Rock' and 'Nebraska'). MBSI, macronutrients-based sustainability index; NBSI, nitrogen-based sustainability index.

Table 4. Two-year means of leaf biomass, stem biomass, root biomass, and two sustainability indices (MBSI and NBSI) in two poplar clones (DN34 and NM6) and two switchgrass cultivars ('Cave-in-Rock' and 'Nebraska').

Plant	Leaf biomass (t ha^{-1})	Stem biomass (t ha^{-1})	Root biomass (t ha^{-1})	MBSI	NBSI
PNM	6.73 ± 1.26a	15.27 ± 15.27a	1.41 ± 0.21c	0.68 ± 0.06b	0.61 ± 0.05b
PDN	4.06 ± 0.80b	7.02 ± 0.54b	1.38 ± 0.25c	1.23 ± 0.17a	1.13 ± 0.11a
SGC	2.65 ± 0.27c	2.57 ± 0.28c	4.34 ± 0.61a	1.47 ± 0.22a	1.11 ± 0.15a
SGN	1.74 ± 0.30c	1.45 ± 0.22c	2.68 ± 0.44b	1.37 ± 0.16a	1.17 ± 0.12a

Note: Data is based on three experimental sites in Guelph (ON), Kemptville (ON), and Nappan (NS) in Canada. Within column, values (means and standard errors) with the same lowercase letter are not statistically different as determined by Duncan's new multiple range test at $\alpha = 0.05$. MBSI, macronutrients-based sustainability index; NBSI, nitrogen-based sustainability index.

Table 5. Significance level (p value) for partitioned analysis of the least square means for site and plant interaction for four plants (poplar, DN34 and NM6; switchgrass, 'Cave-in-Rock' and 'Nebraska') sliced by three experimental sites (Guelph, Kemptville, and Nappan) in Canada.

Site	df	Leaf biomass	Stem biomass	Root biomass	MBSI	NBSI
Guelph	3	0.5930	<0.0001	<0.0001	0.0003	0.0556
Kemptville	3	<0.0001	<0.0001	0.0563	0.0211	0.0667
Nappan	3	0.0180	<0.0001	<0.0001	0.0017	0.0109

Note: df, degrees of freedom; MBSI, macronutrients-based sustainability index; NBSI, nitrogen-based sustainability index.

statistically significant (Table 2). In general, leaf and stem biomass yields are significantly higher in poplar clones, whereas root biomass yields are significantly higher in switchgrass. Leaf and stem biomass yields are significantly higher in PNM (6.73 ± 1.26 t ha^{-1}, 15.27 ± 1.28 t ha^{-1}) than PDN (4.06 ± 0.80 t ha^{-1}, 7.02 ± 0.54 t ha^{-1}). In the case of switchgrass, the differences in leaf biomass and stem biomass between SGC (2.65 ± 0.27 t ha^{-1}, 2.57 ± 0.28 t ha^{-1}) and SGN (1.74 ± 0.30 t ha^{-1}, 1.45 ± 0.22 t ha^{-1}) are non-significant. Contrarily, root biomass yield in SGC (4.34 ± 0.61 t ha^{-1}) is significantly higher than SGN (2.68 ± 0.44 t ha^{-1}) and the differences between poplar clones (PNM—1.41 ± 0.21 t ha^{-1}, PDN—1.38 ± 0.25 t ha^{-1}) are non-significant (Table 4).

Comparison among plants shows that differences are highly significant (*i*) between poplar and switchgrass for leaf biomass (5.40 ± 0.80 t ha^{-1}, 2.20 ± 0.22 t ha^{-1}), stem biomass (11.14 ± 1.16 t ha^{-1}, 2.01 ± 0.21 t ha^{-1}), and root biomass (1.40 ± 0.17 t ha^{-1}, 3.51 ± 0.41 t ha^{-1}), (*ii*) between PDN and PNM for leaf biomass (4.06 ± 0.80 t ha^{-1}, 6.73 ± 1.26 t ha^{-1}) and stem biomass (7.02 ± 0.54 t ha^{-1}, 15.27 ± 1.28 t ha^{-1}), and (*iii*) between SGC and SGN for root biomass (4.34 ± 0.61 t ha^{-1}, 2.68 ± 0.44 t ha^{-1}) (Table 2). Results also show that sites exhibit different trends in producing leaf, stem, and root biomass (Table 5, Fig. 3). At Guelph, yield differences are significant (*i*) between poplar and switchgrass for root biomass (1.13 ± 0.19 t ha^{-1}, 4.30 ± 0.22 t ha^{-1}) and stem biomass (10.77 ± 1.43 t ha^{-1}, 2.63 ± 0.44 t ha^{-1}) and (*ii*) within poplar (PDN vs. PNM) for stem biomass (8.08 ± 0.77 t ha^{-1}, 13.47 ± 1.99 t ha^{-1}). At Kemptville, yield differences are significant (*i*) between poplar and switchgrass for leaf biomass (9.67 ± 1.43 t ha^{-1}, 1.52 ± 0.27 t ha^{-1}) and stem biomass (12.78 ± 3.08 t ha^{-1}, 1.15 ± 0.22 t ha^{-1}), (*ii*) within poplar (PDN vs. PNM) for leaf biomass (7.24 ± 1.37 t ha^{-1}, 12.09 ± 1.83 t ha^{-1}) and stem biomass (7.54 ± 1.13 t ha^{-1},

Fig. 2. Box-plots of leaf biomass across (*a*) sites and (*b*) plants; stem biomass across (*c*) sites and (*d*) plants; and root biomass across (*e*) sites and (*f*) plants. G, Guelph; K, Kemptville; N, Nappan; PDN, poplar DN34; PNM, poplar NM6; SGC, Switchgrass Cave in rock; and SGN, Switchgrass Nebraska. The *y*-axis units are t ha^{-1}. [Colour online.]

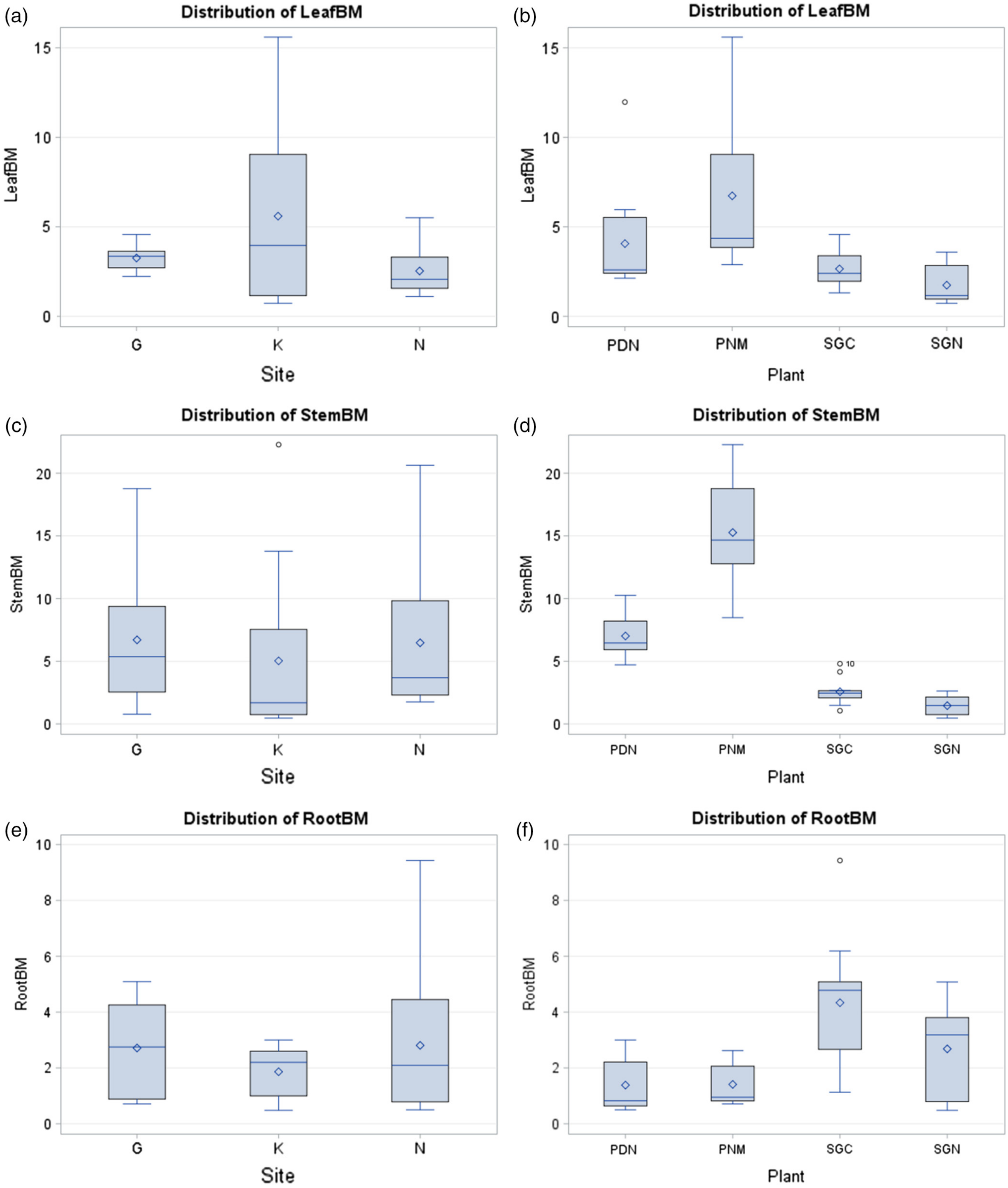
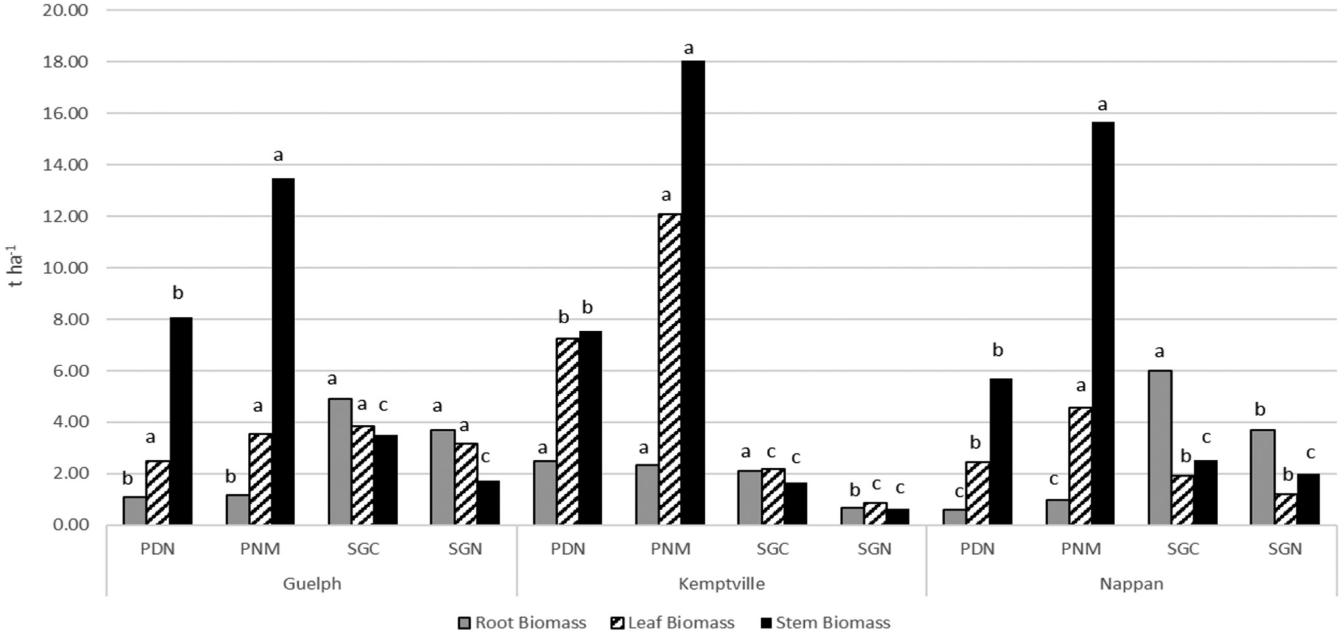


Fig. 3. Root, leaf, and stem biomass of different plants (poplar, PDN and PNM; switchgrass, SGC and SGN) in each experimental site (Guelph, Kemptville, and Nappan). Values are based on 2-yr data. Means in each site labeled with the same letter(s) are not significantly different as determined by least significant difference at $\alpha = 0.05$.



18.03 ± 3.01 t ha^{-1}), and (*iii*) within switchgrass (SGC vs. SGN) for root biomass (2.10 ± 0.32 t ha^{-1}, 0.66 ± 0.10 t ha^{-1}). At Nappan, yield differences are significant (*i*) between poplar and switchgrass for root biomass (0.77 ± 0.09 t ha^{-1}, 4.85 ± 0.73 t ha^{-1}) and stem biomass (10.69 ± 1.93 t ha^{-1}, 2.25 ± 0.11 t ha^{-1}), (*ii*) within poplar (PDN vs. PNM) for leaf biomass (2.45 ± 0.10 t ha^{-1}, 4.56 ± 0.28 t ha^{-1}) and stem biomass (5.69 ± 0.42 t ha^{-1}, 15.68 ± 1.49 t ha^{-1}), and (*iii*) within switchgrass (SGC vs. SGN) for root biomass (6.01 ± 1.11 t ha^{-1}, 3.68 ± 0.446 t ha^{-1}). Across all three sites, stem biomass yields are significantly higher in PNM (Guelph 13.47 ± 1.99 t ha^{-1}, Kemptville 18.03 ± 3.01 t ha^{-1}, and Nappan 15.68 ± 1.49 t ha^{-1}) than PDN (Guelph 8.08 ± 0.77 t ha^{-1}, Kemptville 7.54 ± 1.13 t ha^{-1}, and Nappan 5.69 ± 0.42 t ha^{-1}).

Sustainability

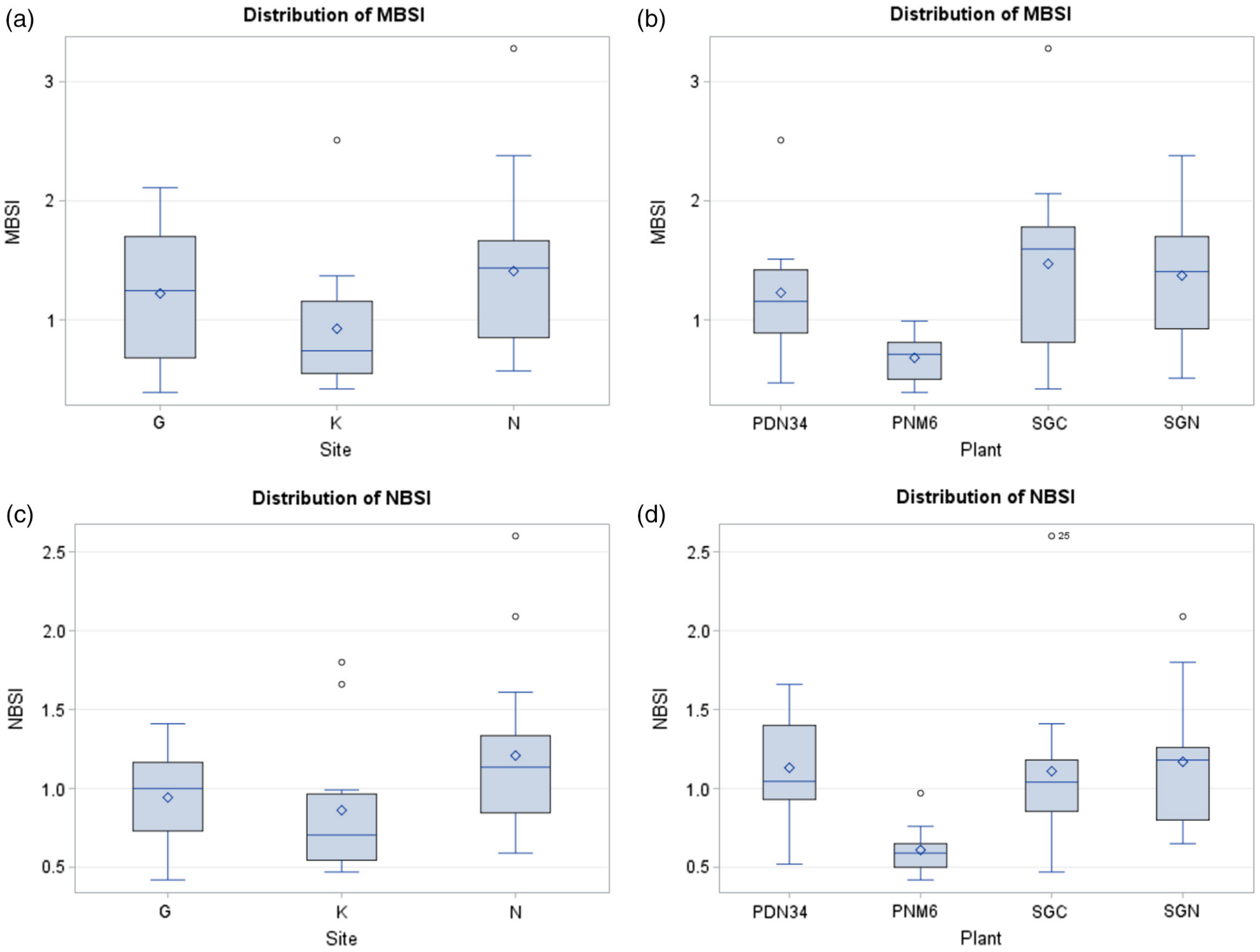
Results of nutrient analyses are presented in Table 6. The N and P nutrient concentrations for both plants (poplar and switchgrass) are the highest in leaf biomass (11.30 ± 0.82 g kg^{-1}, 2.13 ± 0.22 g kg^{-1}) followed by root biomass (6.60 ± 0.55 g kg^{-1}, 1.45 ± 0.16 g kg^{-1}) and stem biomass (5.87 ± 0.67 g kg^{-1}, 1.08 ± 0.06 g kg^{-1}), across all sites. Whereas, K nutrient concentration is the highest in root biomass (7.25 ± 0.55 g kg^{-1}) followed by leaf biomass (5.90 ± 1.31 g kg^{-1}) and stem biomass (4.24 ± 0.51 g kg^{-1}). Within plants, N nutrient concentration across all sites is highest in PDN leaves (15.38 ± 0.60 g kg^{-1}) followed by PNM leaves (11.18 ± 0.66 g kg^{-1}). At the site level, overall nutrient concentrations in stems and leaf biomass are higher at Kemptville, whereas nutrients in root biomass are higher at Guelph.

Results of MBSI and NBSI based on 2-yr nutrient dynamics are presented in Tables 2–5 and Figs. 4–5. The values for both indices are comparable for poplar (PDN and PNM) grown at Guelph and Nappan sites. At these two sites, switchgrass MBSI values (Guelph, 1.68 ± 0.15 and 1.70 ± 0.15; Nappan, 2.08 ± 0.35 and 1.67 ± 0.21, respectively, for SGC and SGN) are relatively higher than NBSI values (Guelph, 1.09 ± 0.10 and 1.11 ± 0.07; Nappan, 1.52 ± 0.31 and 1.44 ± 0.19, respectively, for SGC and SGN). However, the Kemptville site shows a different trend, where MBSI is relatively higher than NBSI for poplar (PDN, 1.94 ± 0.40 and 1.30 ± 0.26; PNM, 0.82 ± 0.01 and 0.50 ± 0.002, respectively, for MBSI and NBSI), but lower for switchgrass (SGC, 0.64 ± 0.10 and 0.72 ± 0.10; SGN, 0.75 ± 0.18 and 0.96 ± 0.24, respectively, for MBSI and NBSI). Analysis of variance results (Table 2) suggest that differences in MBSI and NBSI across sites are statistically non-significant, however, the respective p values (0.0669 and 0.0554) are close to the threshold of significant difference ($\alpha = 0.05$). At the plant level, statistically significant differences in sustainability indices (MBSI and NBSI) between poplar clones (PDN, 1.23 ± 0.17 and 1.13 ± 0.11, PNM, 0.68 ± 0.06 and 0.61 ± 0.05); and between poplar (0.96 ± 0.11 and 0.87 ± 0.08) and switchgrass (1.42 ± 0.14 and 1.14 ± 0.10) suggest that switchgrass production is sustainable. When considering overall biomass production, both indices (MBSI and NBSI) suggest nutrient sustainability at the Nappan site (1.41 ± 0.17 and 1.21 ± 0.13, respectively), whereas only MBSI (1.22 ± 0.14) suggests that Guelph site is sustainable. Overall, lower values of MBSI (0.93 ± 0.16) and NBSI (0.86 ± 0.12) at Kemptville

Table 6. Macronutrient concentrations (g kg^{-1}) in the stem, leaf, and root biomass of poplar (PDN and PNM) and switchgrass (SGC and SGN) across all three sites.

		Stem biomass			Leaf biomass			Root biomass		
Site	Plant	N	P	K	N	P	K	N	P	K
Guelph	PDN	7.80	1.13	4.10	16.48	1.65	5.74	10.30	2.70	9.88
	PNM	6.78	0.88	3.78	12.38	1.74	3.48	5.88	2.13	8.33
	SGC	3.25	0.78	3.30	7.16	1.01	1.03	6.13	1.20	8.90
	SGN	4.10	0.95	2.18	7.04	1.04	0.81	5.83	0.83	6.90
Kemptville	PDN	9.70	1.45	6.15	14.00	2.21	16.74	5.70	1.53	9.48
	PNM	10.35	1.35	5.75	9.63	2.05	13.28	4.70	1.35	8.83
	SGC	4.53	1.35	7.43	9.68	2.26	4.83	6.20	0.78	4.28
	SGN	5.18	1.25	6.98	10.63	1.58	2.35	10.65	1.15	3.95
Nappan	PDN	6.38	1.10	3.40	15.68	2.24	6.98	8.05	1.93	6.83
	PNM	5.60	0.95	2.70	11.53	3.01	6.55	4.75	1.75	5.58
	SGC	3.05	0.83	2.55	11.40	3.10	4.69	5.35	1.18	8.20
	SGN	3.73	1.00	2.55	9.99	3.63	4.39	5.63	0.95	5.83

Fig. 4. Box-plots of MBSI (macronutrients-based sustainability index) across (*a*) sites and (*b*) plants; and NBSI (nitrogen-based sustainability index) across (*c*) sites and (*d*) plants. G, Guelph; K, Kemptville; N, Nappan; PDN, poplar DN34; PNM, poplar NM6; SGC, Switchgrass Cave in rock; and SGN, Switchgrass Nebraska. The *y*-axis units are t ha^{-1}. [Colour online.]



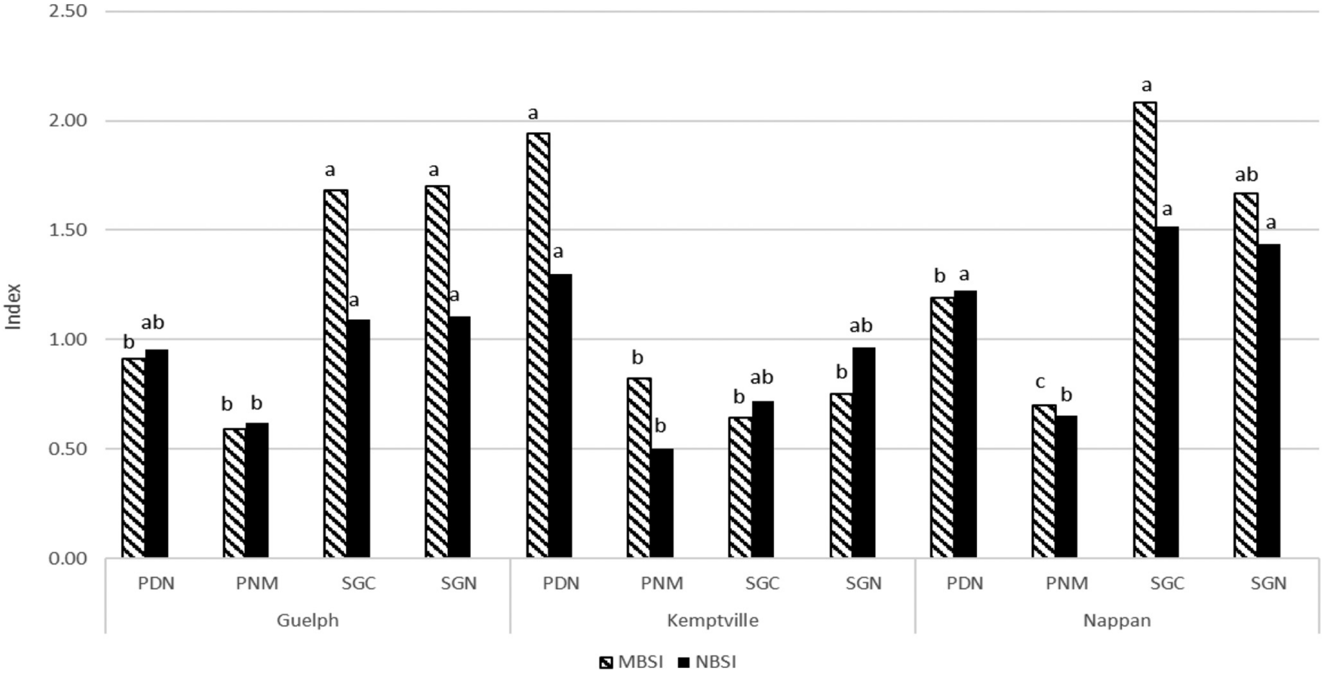


Fig. 5. Sustainability indices comparing the performance of different plants (poplar, PDN and PNM; switchgrass, SGC and SGN) in each experimental site (Guelph, Kemptville, and Nappan). MBSI and NBSI indicate input/output ratio of macronutrients (N, P, and K) and N, respectively. Values are based on 2-yr data. Means in each site labeled with the same letter(s) are not significantly different as determined by least significant difference at $\alpha = 0.05$.

show that biomass production is not sustainable at Kemptville (Table 3). When combined across all sites, all biomass plant production systems are sustainable except for PNM, which received index values of 0.68 ± 0.06 and 0.61 ± 0.05 for MBSI and NBSI, respectively (Table 4).

Discussions

There is growing interest to establish biomass crops to meet ever-increasing demand of bioenergy and to fulfil national and international obligations on reducing fossil fuel related carbon footprint. Studies suggest that nutrient requirements of purpose-grown biomass crops are relatively less and, hence, these crops can be successfully grown on marginal lands (Schmer et al. 2005). Although growing biomass crops on marginal lands is supported for many reasons such as it avoids conflict with food crop production and carbon emission from land use change and land reclamation (Tilman et al. 2009; Dillen et al. 2013), the key focus is on biomass production for biofuels and bioproducts (Qin et al. 2015). In Canada, herbaceous biomass crops are generally harvested once a year, whereas woody crops are harvested over a short rotation of 3–4 yr (Hangs et al. 2014*b*). Woody crops are considered better than herbaceous crops due to higher energy to mass ratio and lower overall ash contents, which are important considerations for industrial-scale biomass production and easy processing (Mann 2012). Woody crops also have the advantage of shedding their leaves every year, which adds nutrients to the soil (Hangs et al. 2014*a*). Studies on biomass yield comparison of woody and herbaceous species on marginal lands show that results are not consistent. For instance, Mann (2012) did not find any difference in biomass yield during the first two growing seasons of poplar and switchgrass in southern Ontario. Later, similar results were reported for the fifth growing season for the same crops on the same site by Marsal et al. (2016). Amaducci et al. (2017) compared the yield of six biomass crops including poplar and switchgrass and found that switchgrass biomass yield was significantly higher than poplar. Contrarily, our results show that stem biomass yields of poplar are significantly higher than switchgrass. The 2-yr poplar stem biomass yield ranges between 7.0 and 15.5 t ha^{-1}, with significant differences between the two studied clones. This yield range is consistent with poplar biomass yield reported in many studies (Aylott et al. 2008; Dillen et al. 2013; Marsal et al. 2016). Similarly, switchgrass harvestable biomass yield (stem and leaves) ranged from 1.6 t ha^{-1} (SGN) to 2.6 t ha^{-1} (SGC), which can be compared with the average yield of 3.5 t ha^{-1} yr^{-1} reported in other studies on marginal lands (Qin et al. 2015; Marsal et al. 2016). However, relatively lower SGC yields in this study can be attributed mainly to the following establishment issues at the Kemptville site: crop failure due to early frost during the establishment year (2014) and uncontrolled weeds during subsequent years.

Quantification of nutrients in leaf biomass and root biomass is important to assess biomass production system sustainability. We developed sustainability indices using macronutrients (MBSI) and N nutrient (NBSI) to assess biomass system sustainability. Lower values of MBSI (0.68 ± 0.06) and NBSI (0.61 ± 0.05) for a high-yielding biomass crop (PNM) suggest that the system is undergoing nutrient losses. This has implications for maintaining a high yield over successive rotations unless the system is fertilized. In poplar and many other woody crops, redistributions of nutrients, especially N, is a fundamental element of nutrient economy. During the growing season, poplar leaves store about 50% of total plant N (Cooke and Weih 2005). To maintain long-term productivity, some of this N is translocated (N-resorption) to the stem during leaf senescence. The N-resorption rates vary among poplar clones and clones with higher N-resorption rates exhibit increased growth rates (Cooke and Weih 2005). The higher N-resorption also affects nutrient quality of leaf litter, and thereby less N cycling through leaf litter decomposition. Our data (not presented in this paper) shows that the N-resorption rate in PNM is much higher than in PDN, which explains the higher yield in PNM as well as low-sustainability indices values. This also explains the lower NBSI (0.61 ± 0.05) than MBSI (0.68 ± 0.06) values, as the former is only an N-based index. These findings suggest a trade-off between high yield and long-term sustainability in purpose-grown woody biomass crops.

Higher index values for switchgrass (SGC, 1.47 ± 0.22 and 1.11 ± 0.15; SGN, 1.37 ± 0.16 and 1.17 ± 0.12) for MBSI and NBSI, respectively, suggest that despite low stem biomass yield, switchgrass biomass production systems are sustainable. Nutrient input and output allocations in switchgrass are different from poplar. Unlike poplar leaf litter, switchgrass leaves are harvested with the stem and thereby any nutrients in the leaves are ost at harvesting. Hence, the main nutrient input component is root biomass, which is rich in N. The sustainability of switchgrass production is mainly attributed to higher N concentration in switchgrass root biomass, which was significantly higher (SGC, 4.34 ± 0.61 t ha^{-1}; SGN, 2.68 ± 0.44 t ha^{-1}) than poplar (PDN, 1.38 ± 0.25; PNM, 1.41 ± 0.21).

Conclusion

The overall goal of this study is to assess the sustainability of purpose-grown biomass crops (poplar and switchgrass) on marginal lands in Canada. As these crops are mainly grown for biomass production, the common interest is to select high yield woody (clones) and herbaceous (cultivars) crops. Our results suggest that, from a nutrient perspective, sustainable biomass production systems can be established on marginal lands in Canada. However, during the establishment phase, high-yielding biomass crops (PNM) may require external nutrient inputs via fertilization to compensate for nutrients that are lost at harvest. Considering that, it should be mentioned that the results presented in this study were derived from young stands established only for 2 yr. As the stands mature, more nutrient inputs from aboveground and belowground plant components can be expected, with corresponding higher biomass yields and nutrient removals. Therefore, further investigation is warranted on these stands at the mature stage (five or more years after establishment) to be more conclusive.

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