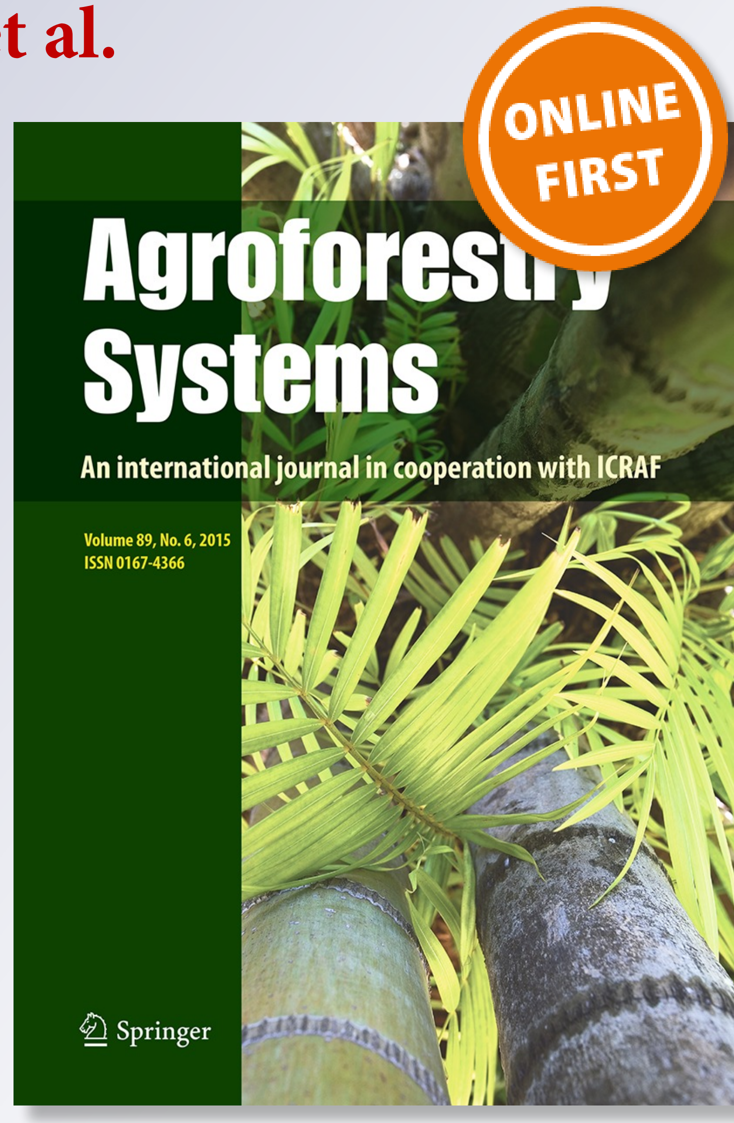
Biomass yield assessment of five potential energy crops grown in southern Ontario, Canada

Floriane Marsal, Naresh V. Thevathasan, Solène Guillot, John Mann, Andrew M. Gordon, Mahendra Thimmanagari, William Deen, et al.

Agroforestry Systems
An International Journal incorporating Agroforestry Forum

ISSN 0167-4366

Agroforest Syst
DOI 10.1007/s10457-016-9893-3



Agroforest Syst
DOI 10.1007/s10457-016-9893-3

Biomass yield assessment of five potential energy crops grown in southern Ontario, Canada

Floriane Marsal · Naresh V. Thevathasan · Solène Guillot · John Mann · Andrew M. Gordon · Mahendra Thimmanagari · William Deen · Salim Silim · Raju Soolanayakanahally · Derek Sidders

Received: 12 August 2015 / Accepted: 25 January 2016

Abstract Biomass yields of five commonly grown bioenergy crops, miscanthus, switchgrass, poplar (2293-19), willow (SX 67) and a mix of native grasses (polyculture) were assessed on a marginal land. When long-term yield responses were examined, miscanthus yield significantly increased from 5.96 ± 1.06 odt ha^{-1} y^{-1} in 2011 to 17.03 ± 8.1 odt ha^{-1} y^{-1} in 2014. Willow yield also increased from 3.21 ± 2.92 odt ha^{-1} y^{-1} in 2011 to 12.15 ± 4.94 odt ha^{-1} y^{-1} in 2014. However, for willow at this stage, we only compared the 1st year yields between 2011 and 2014, hence, three-year mature average yield in 2016 (mature stage) may not be much different from 12.15 odt ha^{-1} y^{-1}, as willow yield increase over time is not linear. Among all other tested biomass species; polyculture, switchgrass and poplar, they recorded numerically higher yields during the mature growth stage (2013/2014) but, failed to reach statistical significance ($p > 0.05$). In this study, we separated the growth stages as; early (2010/2011) and mature (2013/2014) stages. At the early stage, poplar and polyculture recorded significant yield differences ($p = 0.005$) and poplar biomass yield was significantly higher (7.71 ± 2. odt ha^{-1} y^{-1}) than polyculture (2.96 ± 0.43 odt ha^{-1} y^{-1}). At the mature stage (2013/2014), miscanthus biomass yield was significantly higher than the two other tested herbaceous species (polyculture and switchgrass). Miscanthus yield was 17.03 ± 8.10 odt ha^{-1} y^{-1}, which was almost three times higher than polyculture (5.64 ± 0.40 odt ha^{-1} y^{-1}) and switchgrass (5.99 ± 0.46 odt ha^{-1} y^{-1}) biomass yields. In relation to fertilization effect, miscanthus, polyculture and willow significantly and positively responded to fertilization.

F. Marsal · S. Guillot
AgroParisTech, 16 rue Claude Bernard, 75231 Paris Cedex 05, France

N. V. Thevathasan (✉) · J. Mann · A. M. Gordon
School of Environmental Sciences, University of Guelph, Guelph, ON N1G 2W1, Canada
e-mail: nthevath@uoguelph.ca

M. Thimmanagari
OMAFRA, 1 Stone Road East, Guelph, ON, Canada

W. Deen
Department of Plant Agriculture, University of Guelph, Guelph, ON N1G 2W1, Canada

S. Silim
Agri-Green Technologies Secretariat, Agri-Environment Services Branch Agriculture and Agri-Food Canada, Room 1136, K.W. Neatby Bld., 960 Carling Avenue Ottawa, Ottawa, ON K1A 0C6, Canada

R. Soolanayakanahally
Agroforestry Development Centre, Agriculture and Agri-Food Canada, P.O. Box 940, No. 2 Government Road, Indian Head, SK S0G 2K0, Canada

D. Sidders
Canadian Wood Fibre Centre, 5320 122 Street Northwest, Edmonton, AB T6H 3S5, Canada

Published online: 30 January 2016

The significant yield increases between unfertilized and fertilized treatments were: 12.06, 10.61, and 8.8 odt ha^{-1} y^{-1} for willow, miscanthus and polyculture, respectively. Miscanthus, willow and polyculture yields as influenced by fertilizer treatment were 23.81 ± 3.55, 21.80 ± 5.99, 12.13 ± 0.66 odt ha^{-1} y^{-1}, respectively.

Keywords Woody biomass · Herbaceous biomass · Fertilization · Marginal land · Bioenergy

Introduction

Increasing energy demands experienced worldwide coupled with fossil fuel use are contributing to increasing levels of CO_2 resulting in climate change. With the end of the use of coal to generate electricity by the Ontario Power Generation (OPG) in 2014, bioenergy from biomass is seen as a possible solution to replace coal. Unlike first generation bioenergy, which is derived from food crops, second generation bioenergy is produced from purpose-grown crops (Yue et al. 2014). Second generation bioenergy crops are able to grow on marginal lands, meaning land with poor to mediocre soil quality for food production based on Canadian Land Inventory classification. Furthermore, biomass crop production can also enhance soil and water quality and biodiversity, increasing the value of the land-base (Thevathasan et al. 2014; Sage 1998).

However, in order for biomass-based bioenergy to become economically and environmentally viable, management strategies related to sustainable biomass production should be thoroughly researched. This becomes more important in Ontario as the Ontario Power Generation (OPG) is looking into the development of biomass-based electricity production in the future. OPG is following up on their success they gained at the Atikokan generation plant, which is currently producing 200 MW generation from 100 % biomass as a renewable energy source (OPG 2014).

In order to address the above issue, since 2009, the University of Guelph (UG) and Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) are working on a comparative performance study of biomass production of five energy crops growing on marginal lands at their research site in Guelph, Ontario, Canada. Three herbaceous species are incorporated in this study, including Switchgrass (*Panicum virgatum*), Miscanthus giganteus (*Nagara*), and a polyculture (containing switchgrass, indiangrass (*Sorghastrum nutans*), big bluestem (*Andropogon gerardii*) and little bluestem (*Schizachyrium scoparium*) in a 25:25:25:25 mix. Additionally, two woody species are also being studied, including hybrid willow (*Salix spp*) and poplar (*Populus spp*). Short rotation woody crops (SRWC) and perennial grass (herbaceous) crops have a short establishment phase and are fast growing, and also able to re-sprout after multiple harvests over 18 years or more (Lemus and Lal 2005). Unlike herbaceous species, SRWC are harvested every 3 years instead of annually. As bioenergy production systems are dynamic, complex and long-lived in nature, a long-term study was required to monitor the yield potential trends for the five aforementioned species. Therefore, the principal aim of this study is to help Ontario landowners to decide on the most suitable (environmentally and economically) energy crops that could be grown on non-agricultural lands/marginal lands in Ontario. This study examines the long-term yield potential of five biomass crops commonly grown in Ontario, as well as the influence of fertilization on biomass yields.

Material and method

Field design and establishment

The Experimental field site is located at the UG, Guelph, Ontario (Latitude 43°32′60″N, longitude 80°12′30″W). The soil is a gray brown luvisol with a fine sandy loam texture (composed of 56 % sand, 34 % silt and 10 % clay) and is classified as class 4 (limited by slope and stoniness) based on Canadian Land Inventory (CLI) classification and hence is not recommended for field crops. However, the site was under corn (*Zea mays*), bean (*Glycine max*) and wheat (*Triticum vulgare*) rotation until 2008, and as the crop yields were very low, the field was converted to biomass research endeavours and was established in 2009. In 2009, the land was rototilled to a depth of 15 cm in order to prepare the 10 × 10 m test plots. Among the five test biomass species that were integrated into this study, three are herbaceous species (all seeds purchased from a commercial grower in Ontario) including, Switchgrass (*Panicum virgatum*), *Miscanthus giganteus* (var. Nagara), and a polyculture (containing switchgrass, indiangrass (*Sorghastrum nutans*), big bluestem (*Andropogon gerardii*) and little bluestem (*Schizachyrium scoparium*) in a 25:25:25:25 mix, and the two woody species are hybrid willow clone SX 67 (*Salix miyambeana*) [Source: State University of New York (SUNY) nursery, contact: Dr. Tim Volk] and poplar (*Populus spp*) clone 2293-19 [Source: the Canadian Wood Fibre Centre, contact Mr. Derek Sidders]. The five selected biomass crop species, the main treatment, were arranged in a Randomized Complete Block Design (RCBD) with four replications on 100 m^2 plots; in total 20 experimental plots (Fig. 1). Woody species (poplar and willow) planting density was 15,000 stools ha^{-1}, planted in a double row configuration with 1.5 m between double rows (European design) using 25 cm long cuttings. Within a double row, rows were 0.75 m apart and within a row each stem/cutting was 0.6 m apart. The miscanthus was planted in a grid pattern all spaced 0.75 m apart (within and between rows), while the herbaceous grasses (switchgrass and polyculture) were seeded at 45 kg ha^{-1} (Mann 2012). The seeding rate used in the establishment of herbaceous crops is the common rate used by the growers in southern Ontario, Canada (Urs Eggimann, Vice-President, Ontario Biomass Producers Co-op, pers. Comm., 2015).

In spring 2010, miscanthus nagara and willow SX67 were planted to replace miscanthus M1 and willow SV1, respectively, as these two biomass species failed to survive during the first growing season (2009). Unlike poplar, willow was coppiced after the first growing season in winter 2010 (Fig. 2).

The overall goal of this study is to test the short-term and long-term yield potentials of five (5) commonly recommended purpose-grown biomass species in Ontario. In this context, the unique feature of this experiment is that the study incorporated both herbaceous and woody species under same soil and environmental conditions in order to test yield potentials of these contrasting species. To-date, in the province of Ontario, there are no studies of this nature and therefore results from this study should provide useful information to the Ontario growers who want to diversify biomass production in their respective farms.

Biomass yields

To evaluate long-term biomass yields by species, data from years 2010, 2011, 2013 and 2014 are used in this study. Herbaceous biomass yields are reported on an annual basis as they are harvested at the end of each growing season. However, woody biomass yields are harvested every 2 to 3 years and therefore in order to calculate the annual yield, for comparison with herbaceous yields, accumulated yield was divided by number of years of growth. In this context, it should be noted that only poplar yields derived in 2011 and 2014 were divided by 3, representing 3 growth years of the 1st rotation (2011) and the 3 growth years of the 2nd rotation (2014). For willow, the comparison is made between 2011 and 2014 yields, which represents the 1st growing season of the 1st rotation (2011) and the 1st growing season of the 2nd rotation (2014). Therefore, yields are reported as annual yields as the growing year was only one. Similarly, for the fertilized and unfertilized experiment, the willow yield was not divided by the number of growth years because the willow was harvested in 2013 at the end of the 1st rotation (Fig. 3). More explanation related to willow yields reported in this study is given in the discussion section. We had to rely on existing data for poplar and willow, but at the same time compare yields at the same growth stages of the tested woody biomass species. Within herbaceous species, annual biomass yields were compared between the second (2010) and the fifth growing (2013) seasons. However, as miscanthus was replanted in 2010, the yield data were compared between 2011 and 2014 in order to compare 2nd and the 5th growing season yields. To enhance the understanding of the reader detailed harvest regime diagrams are given in Figs. 2, 3.

It should also be stated that one of the management practices that is recommended for willow biomass production is to coppice the 1st year growth in order to enhance multiple stems production (coppicing). Therefore, as the willow was re-replanted in 2010, the stand was coppiced during winter 2010 (Fig. 2), and stools were allowed to coppice and re-grow in 2011. First year biomass yields therefore were derived at the end of 2011 (1st year of the first rotation) and then at the end of 2014 (1st year of the second rotation (Fig. 3). There are limitations with respect to willow yields reported in this study as willow yield increase over the 3 growing years is not linear. Further discussion on this aspect is given under the discussion section based on climatic data, height and diameter data measured for the tested clone, SX 67, taken from an adjacent (50 m away) experiment.

A garden pruner was used to sample herbaceous crops and they were cut at 5 cm aboveground in the spring following the growth year. The sample location (1 m^2) within a plot was randomly selected in the middle of the plot. However, woody biomass samples were taken from an area of 2.25 m^2 with the use of a pruning saw. The sample area was relatively larger compared to herbaceous crop sample area as the space (1.5 m) between a double-row had to be accounted for (European planting configuration). Samples were oven dried at 65 °C for 8 days to calculate dry biomass, and biomass yields were then converted to oven dry tonnes per hectare per year. All samples were collected from the middle of the plots, leaving a 1 m buffer area around the experimental plots.

Fertilization effect

In 2014, each plot was divided into two parts to assess fertilization effects by changing the design from RCBD to a RCBD split plot. One part was fertilized in the spring 2014 at the rates N–P–K: 75–42–62 kg ha^{-1} and the other part was not fertilized (Figs. 1, 2). A 3 m buffer was set between plots to prevent fertilizer seepage or runoff. The fertilization rate was decided by the researchers as a test rate and also to keep the N level low. No particular recommendation rate was followed.

In order to assess the influence of fertilization on biomass yields, only 2014 yield data were used and also only 3 replications were used. We had to leave one replication untouched due to a separate ancillary study (nutrient cycling) that was in progress and we could not access those plots (Block C) for biomass sampling as we could not harvest the crops.

Statistical analysis

All data were analyzed using the statistical package 'R' version 0.98.1103-©2009–2014 using ANOVA for RCBD. Two way ANOVA was used to compare yields over the time period studied (Factors "Production year" and "Species"). The means were compared using Tukey Honestly Significant Difference (HSD) test (with $\alpha = 0.05$). Multiple pairwise comparison was performed after checking for any significant interactions between the tested factors. The authors are aware that the use of ' "Production year" (field season)' as a factor has some confounding effects as all growing seasons are not the same (please see Table 1, for rainfall and ambient temperature); see additional discussion on this in the discussion section.

There were no notable variations between rainfall and ambient temperature, the two most governing climatic conditions that influence biomass yields, during the comparison years (2010 and 2013 and 2011 and 2014). Due to the fact that biomass crops generally increase their yield potentials with maturity, it was decided to analyze the data having 'production year' as a factor in order to show biomass yield increases over time. It should be understood that this paper is exploring the yield dynamics associated with commonly grown bio-fuel crops in Ontario over a period of time. As these crops are grown on marginal lands or low fertile lands that are not suitable for field crop production, biomass yields associated with early growth stages (2010 and 2011) are generally significantly lower than biomass yields derived during the latter growth stages (2013 and 2014). Growers and landowners who own marginal lands are not so enthusiastic growing these biomass crops due to discouraging yields during the first 2 to 3 years after establishment even though yields significantly increase over the years. Therefore, we used the growth year harvest yields as a variable to compare significant increases in biomass yields among the tested species. Biomass crop growth is significantly influenced by climatic factors such as rainfall and ambient temperature. We have provided these climatic variables in Table 1. The tested herbaceous species are all C4 warm season grasses and therefore ambient temperature also can influence the herbaceous grass growth. Having said the above, it should be noted that yield comparisons are made between 2010 and 2013, where growing season rainfall was 473 and 573 mm for both years, and the ambient temperature was 16.8 and 16.6 °C, respectively. In 2011 and 2014, the rain fall was 474 and 539 mm for both years, and the ambient temperature was 16.8 and 16.9 °C, respectively. Therefore, yield comparisons were made between above given growth years, with confidence, as there were not much of differences in rainfall and ambient temperature.

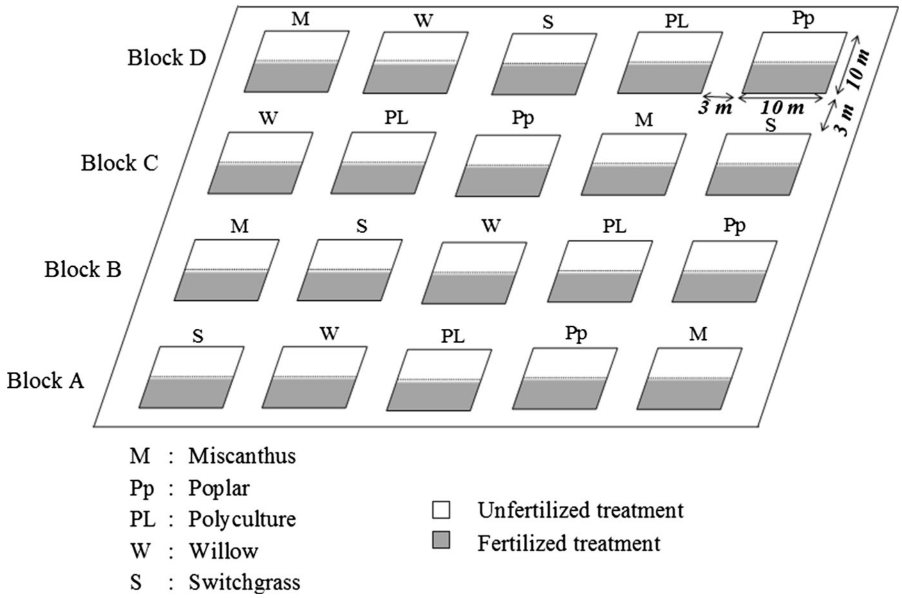


Fig. 1 Schematic diagram showing RCBD split plot design at the research site, University of Guelph, Guelph, Ontario, Canada

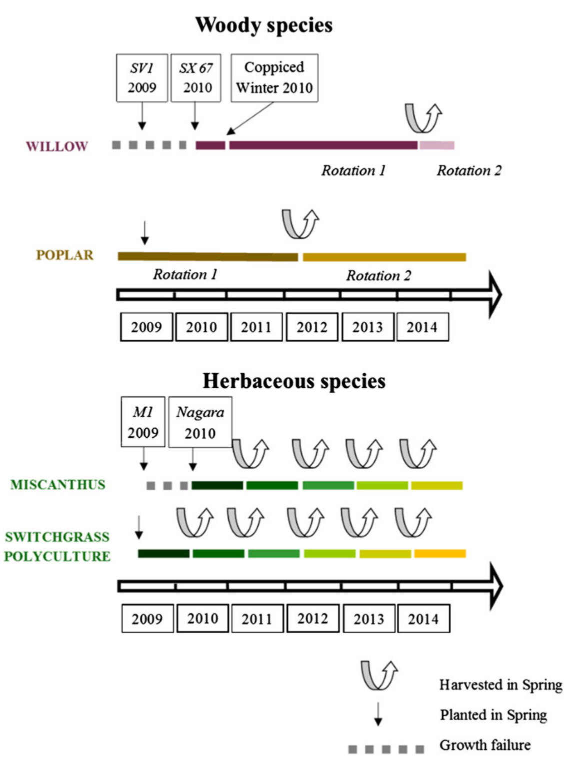


Fig. 2 Schematic diagram showing calendar (2009–2014) events: planting, coppicing and harvest of tested biomass crops at the research site, University of Guelph, Guelph, Ontario, Canada

Table 1 Climatic conditions during the growing seasons (March-September) at the research site, University of Guelph, Ontario, Canada

Years	Precipitations (mm)	Mean temperature (°C)
2010	473	16.8
2011	474	16.8
2012	299	17.3
2013	573	16.6
2014	539	16.9

In order to test the fertilization effects, the RCBD split plot was performed to analyze the 2014 fertilization effects on biomass yields, species was used as the main factor and fertilizer was used as the split-plot. There is a slight slope in the field towards the NE side and therefore fertilizer treatments were assigned to the lower side of the plot in order to avoid leaching of fertilizer into the unfertilized portion of the plot. The randomization had to be 'stratified' in this experiment.

The assumption of homoscedasticity was tested by performing Bartlett's test and the normality was verified with Shapiro test. Root (square) or logarithm transformation was used to adjust the models, when required. Outliers that did not fit within the Cook's distance were removed from statistical analyses.

Results

Biomass yields

Aboveground biomass yields were compared between early and latter growth stages among all tested biomass species and the results are presented in Table 2.

Within herbaceous species, the only significant difference observed was for miscanthus between the second and fifth growing seasons ($p = 0.01$). Poplar yields between the third year of the first and second rotations were not significantly different. Willow yields between the first year of the first rotation and the first year of the second rotation were significantly different ($p = 0.005$). In Table 2, soon after establishment (2010 and 2011), polyculture yield was significantly lower than all tested herbaceous species and poplar had the highest numerical yield compared to all tested species. Further analysis was carried out to compare woody species (results not presented) at the same stage (third year of growth from the first rotation for both, meaning at the end of 2011 and 2013 for poplar and willow, respectively; Fig. 3). This comparison showed that poplar yield was still significantly higher, at 7.71 odt ha^{-1} y^{-1}, when compared to willow yield at 2.03 odt ha^{-1} y^{-1} (willow data derived from a previous study). In order to derive per year yield, the total yield (3 growth years; 2009, 2010 and 2011 for poplar and 2011, 2012 and 2013 for willow—Fig. 3) was divided by 3 for both, poplar and willow.

In Table 2, the comparison of latter growth stage biomass yields indicated that miscanthus yield increased as the stand matured and it was comparable to woody yields and also statistically similar. However, only miscanthus yield was significantly higher than other tested herbaceous species.

Fertilization effect on biomass yield

The results are presented in Table 3.

The two-way split-plot ANOVA analysis indicated significant interaction between fertilizer and the tested species ($p = 0.02$). Simple effect analyses revealed that miscanthus significantly yielded the highest biomass yield (odt ha^{-1} y^{-1}) of 23.8 ($p = 0.02$) under fertilized treatment followed by willow at 21.8 ($p = 0.03$), and polyculture at 12.1 ($p = 0.0005$). More explanation on willow yield is given in the discussion section. The rest of the tested biomass species, switchgrass and poplar, were not influenced by the fertilizer application and yielded 14.8 ($p = 0.07$) and 10.1 ($p = 0.27$) odt ha^{-1} y^{-1}, respectively.

Table 2 Mean biomass yields (odt ha^{-1} y^{-1}) from all tested species at the early and mature growth stages (rows) and also within a growth (columns) stage across all tested species recorded at the research site, University of Guelph, Guelph, Ontario, Canada

Species	Early growing seasons (2010 and 2011)		Mature growing seasons (2013 and 2014)		P value
	Date	Yield	Date	Yield	
Miscanthus	2nd growing season (2011)	5.96 (±1.06)ab	5th growing season (2014)	17.03 (±8.10)a	0.01*
Polyculture	2nd growing season (2010)	2.96 (±0.43)a	5th growing season (2013)	5.64 (±0.40)b	0.28
Switchgrass	2nd growing season (2010)	3.43 (±0.23)ab	5th growing season (2013)	5.99 (±0.46)b	0.54
Poplar	3rd year of the 1st rotation (2011)	7.71 (±2.39)b	3rd year of the 2nd rotation (2014)	12.16 (±0.26)ab	0.7
Willow	1st year of the 1st rotation (2011)	3.21 (±2.92)ab	1st year of the 2nd rotation (2014)	12.15 (±4.94)ab	0.005*

P values that are presented in the above table refer to significance across rows. Low case letters within a column refer to statistical analyses of all tested biomass species within a growth stage. Same low case letters within a column are not statistically different at $p = 0.05$, between all tested species. Note: Due to crop failure in miscanthus in 2009, the second growing season for miscanthus was in 2011, and for all other herbaceous crops tested in this experiment the second growing season was in 2010. Similarly, for willow, clone SV1 failed in 2009, and SX 67 was replanted in 2010 and was coppiced in winter 2010 (Figs. 2 and 3), so the first year growth was in 2011, whereas for polar the first year growth was in 2009, and the 3rd year growth in 2011 is presented in the table above

Discussion

There are several studies in Europe that have reported on potential biomass crops and associated yields that can be derived from marginal lands (McKendry 2002; Lewandowski et al. 2003). However, all these studies have reported short-term yields under given climatic and site conditions. As biomass crops are long-lived and biomass is harvested over a period of 15 to 20 years, biomass yields derived from a single experimental site but over multiple harvest cycles, as in this study, need to be researched and reported to determine economic and environmental sustainability of these production systems. In this context, this study obtained yields from 5 different biomass crops, over a period of 2009 to 2014 (6 years), which can potentially be grown on Canadian marginal lands.

Biomass yields

Biomass yields from five tested species were analyzed at different growth stages (2-way ANOVA; species and growth stages (production year) as factors). For herbaceous species (miscanthus, switchgrass and polyculture), annual biomass yields were compared at two growth stages; early growth stages (2010 and/or 2011) and latter growth stages (2013 and/or 2014). Results suggest that miscanthus is the most productive perennial species among all tested biomass crops. Miscanthus yield significantly increased almost 3 times by 2014 from 5.96 (±1.06) odt ha^{-1} y^{-1} in 2011 to 17.03 (±8.10) odt ha^{-1} y^{-1} in 2014 ($p = 0.01$; Table 2). Other studies have also shown that miscanthus can reach maximum production as early as 3 years after establishment (Engbers 2012; Oo et al. 2012). At the mature growth stage, polyculture and switchgrass yielded significantly lower quantities of biomass, at 5.64 odt ha^{-1} y^{-1} and 5.99 odt ha^{-1} y^{-1} respectively, when compared to miscanthus yield (17.03 odt ha^{-1} y^{-1}). Therefore, these two species may require further investigation before being recommended to the Ontario biomass growers. Among the tested woody biomass species, poplar and willow, there were no significant differences in biomass yields within the growth stages, 2011 or 2014 (Table 2). However, the early stages of poplar growth (2011) resulted in a higher yield of 7.71 odt ha^{-1} y^{-1} (2009, 2010 and 2011 growth years mean yield—Table 2 and Fig. 3) but, failed to result in significantly higher yield at the latter stage, 2014 (12.16 odt ha^{-1} y^{-1}, Table 2). For poplar, as the yields were divide by 3 as they grew over a period of 3 years, 2012 to 2014, climatic data over a period of 3 years could have influenced the poplar yields reported in this study. In this context, 2012 was a very dry year (Table 1) and the rainfall received was only 58 % (299/515 mm) of the average annual rainfall (2010, 2011, 2013 and 2014). Poplar was harvested in 2011(1st rotation; Fig. 3) and a dry year (2012) following the harvest (2011) of poplar could have negatively impacted the poplar biomass yield in 2014, resulting in non-significant yield differences (Tables 2, 3). Our experience with woody crops, willow (SX 67), from a study initiated in 2006 is that the rainfall received immediately proceeding the harvest year or coppice year is vital as most of the growth in woody crop occurred in the year proceeding the coppice or harvest year. For example, the percentage increase in average height and diameter between years 1 (2013; 3rd cycle, data not reported) and 3 (2015), after harvest (2012) in willow, from a different study but just adjacent (50 m) to this study site, were only 31 and 23 %, respectively. Initial mean height and diameter in 2013, the year after harvest, were

Table 3 Influence of fertilization on biomass yields (2014) derived from the respective species at research site, University of Guelph, Guelph, Ontario, Canada

	Yields on unfertilized plot (odt ha^{-1} y^{-1})	Yields on fertilized plot (odt ha^{-1} y^{-1})	Significant difference
Miscanthus	13.2 ± 3.44	23.81 ± 3.55	0.02
Polyculture	3.33 ± 1.36	12.13 ± 0.66	0.0005
Switchgrass	5.94 ± 5.18	14.79 ± 3.51	0.07
Poplar	12.07 ± 0.31	10.14 ± 2.60	0.27
Willow	9.74 ± 1.27	21.80 ± 5.99	0.027

323.02 ± 6.96 and 1.18 ± 0.22 cm, respectively and the final mean height and diameter in November, 2015 (harvest year) were 466.72 ± 9.44 and 1.53 ± 0.38, respectively. Similar trends were observed since establishment (2006, data not presented). Therefore, the year proceeding the poplar harvest, 2012 (Fig. 3), could have negatively influenced the poplar biomass yield and resulted in non-significant yield increase even in the latter growth stages, 2012 to 2014, Tables 2, 3.

Between 2011 and 2014, willow biomass yield increased significantly from 3.21 to 12.15 odt ha^{-1} y^{-1} ($p = 0.005$; Table 2). This implies that willow has the ability to enhance their yield potentials as they mature. However, for willow at this stage, we only wanted to compare the 1st year yields between 2011 and 2014, which is the 1st year growth of the first rotation and the 1st year growth of the 2nd rotation, respectively (Fig. 3). Hence, three-year mature average yield in 2016, end of 2nd rotation (mature stage) for willow, may only be slightly higher than 12.15 odt ha^{-1} y^{-1}, as willow yield increase over time is not linear (Labrecque and Teodorescu 2005), and also as mentioned above height and diameter increment between year 1 and 3 was only 31 and 23 %, respectively. But, the first year growth in the 2nd rotation of willow crop and associated yield increase of 12.15 odt ha^{-1} is what should be emphasized in relation to potential biomass yield increase in woody crops as the stand mature. It should also be noted that the 1st year yield obtained in 2014 (2nd rotation) is certainly higher than the yield that was derived at the end of the first rotation in 2013 (2011, 2012 and 2013; Fig. 3) for willow at the same site, which was only 2.09 odt ha^{-1} y^{-1} (from a previous study). Therefore, the authors are comfortable in reporting the first year willow growth yield in the 2nd rotation, as it is, and the overall final yield in 2016, after one more growing season, should be just around 12.15 odt ha^{-1} y^{-1}. In a study conducted by Cardinael et al. (2012) at the same site, the author also reported a low willow biomass yield of 2.31 odt ha^{-1} y^{-1} (2009) after 3 years of establishment, but the yield subsequently increased to 11 odt ha^{-1} y^{-1} in 2012 (Thevathasan, pers. Comm, 2015). However, from a landowner perspective and also to obtain early economic returns from biomass yields, poplar may be a more suitable woody biomass crop as it yielded almost 8 odt ha^{-1} y^{-1} in 2011 at the end of the first three-year growth—first rotation (Table 2; Fig. 3).

Similar yield results that are reported in this study have also been reported by other investigators for willow and poplar. Kauter et al. (2003) and Keoleian and Volk (2005) have stated that willow reaches the maximum mean annual increment faster than poplar at age 3–5, whereas poplar takes up to age 4–10. Another long-term study on poplar and willow from the state of New York suggests that trees reached their maximum biomass production potentials at the fifth growing season (Kopp et al. 2001). In this study, willow yields were assessed at the first and forth growing seasons and poplar yields were assessed at the third and the sixth growing seasons. In this context, it will be interesting to see in the future if there would be any yield increases from these two woody species as they might have already reached their maximum yield capacities.

Fertilization effect

Herbaceous biomass species tested are C_4 plants and generally C_4 plants respond positively to fertilizer application, especially under marginal soil conditions (Engbers 2012). In this study, miscanthus and polyculture responded positively to fertilizer application (Table 3). Several other studies in Europe have also shown that miscanthus biomass yields are positively influenced by fertilizer application. For example, Ercoli et al. (1999) reported that under fertilized conditions miscanthus yields increased by nearly 50 % from approximately 17 odt ha^{-1} to nearly 25 odt ha^{-1}. Conversely, several other studies have reported no positive response to fertilizer application in relation to willow biomass yields (Kopp et al. 2001; Quaye and Volk 2013). Even on this site, a previous study conducted by Guillot (2014) also reported no response to fertilization. One explanation that can be given at this stage of growth is that as the willow stand matures, the plants may begin responding positively to fertilizer application. In this study (Table 3), willow resulted in significant increase in biomass yield as influenced by fertilizer application. The yields were not divided by three (rotation years) as the yields reported for both treatments are one year-growth yields. As further yield increase as influenced by fertilization cannot be predicted, this aspect needs more investigation and at this stage fertilizer influence on woody crops is inconclusive. To add, as the stand matures, the leaf and fine root turnover will also increase and this could lead to less demand for external nutrient addition via fertilizer and fertilizer influence may not be detected in the future.

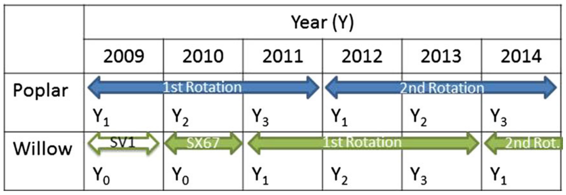


Fig. 3 The time (year) of management activities related to poplar and willow crop planting, coppicing, harvests and rotation sequence at the research site, University of Guelph, Guelph, Ontario, Canada. Note: Y_0– 2009-SV 1 willow (failed), Y_0-2010-SX 67 willow (base year growth and coppice year). Willow—Y_1 to Y_3—growth years associated with the 1st rotation (2011 to 2013). Poplar—Y_1 to Y_3– growth years associated with the 1st rotation (2009–2011), and similarly for the 2nd rotation (2012–2014)

From Table 3, even though switchgrass yield was not influenced by fertilization, it should be stated that the numerical increase in biomass yield was almost 2.5 times of the unfertilized yield ($p = 0.07$). The P value also suggests that it narrowly failed to result in statistical significance at $p = 0.05$. This warrants further investigation as well but, in general, it could be stated that all C_4 grass species tested in this study did respond to fertilization positively.

Conclusion

The overall goal of this study is to demonstrate to the growers in Ontario and in other parts of Canada that there are challenges associated with biomass crop establishment in southern Ontario, Canada. These challenges vary in nature and also specific to the type of biomass crop. For example, winter kill is common especially in miscanthus, and in this experiment they failed to establish in 2009 and they had to be replanted with another miscanthus variety. Weed control and associated soil disturbance and soil C losses and corresponding low biomass yields during the 'early growing stages', are few more added challenges. However, biomass yields are substantially higher in the 'mature growing stages', as reported in this study. This is what the study is trying to disseminate to the farming communities.

Given the results from this study, it seems appropriate to promote miscanthus and willow among the tested herbaceous and woody species, respectively, as most suitable biomass crops to be grown on southern Ontario marginal lands. Interestingly, without any fertilization, these two species significantly increased their biomass yield potentials over the tested period (2010–2014). However, with fertilizer application, miscanthus, polyculture and willow all responded positively and resulted in significantly higher biomass yields. Even though fertilization resulted in positive increases in biomass yields, the environmental negative impacts and more importantly the return on investment (cost-benefit analysis) all should be taken into consideration before any recommendations are made to the biomass growers. Poplar failed to record statistical significance associated with increase in biomass yields between early and mature growth stages in this study. However, at the early growth stage it resulted in numerically higher biomass yield, and also maintained its yield potential when compared with all tested biomass crops even at the mature growth stage. Therefore, including poplar along with miscanthus may be advantageous in order to derive economic yields at the early stage of biomass crop establishment.

Fertilization influenced biomass yields in three out of the five species tested in this study. Average yield increase across the three positively responding crops was 10.5 odt ha^{-1} y^{-1}. Given that around 50 % of the biomass contains carbon, the amount of CO_2 roughly removed from the atmosphere is close to 19 t CO_2 ha^{-1} y^{-1} [(10.5/2) × 3.67] (conversion factor from C to CO_2). We applied 75 kg N ha^{-1}, which implies that about 1.25 % of the applied N could have been emitted as N_2O (Cole et al. 1996), resulting in 0.30 t of CO_2 equivalent emission. It can also be stated that an equivalent amount or a higher fraction of the aboveground carbon can also be found belowground enhancing the C sequestration in these systems. Therefore, without considering CO_2 emissions associated with fertilizer production, transportation and application, in this study, as there is a good margin between CO_2 sequestered (19 t CO_2 ha^{-1} y^{-1}) by the biomass crops and CO_2 emission associated with fertilizer usage (0.30 t of CO_2 equivalent emission per hectare). It appears that fertilization might positively influence biomass yields and at the same time may not contribute to any additional GHG emissions. However, the reader is cautioned that the argument presented here is very rudimentary, but due to the large increase in biomass yield derived in this study as influenced by fertilization, it demands further research and verification. In addition, when it comes to extreme weather conditions due to climate change scenarios, past research studies conducted on this site have suggested that woody biomass crops may show more resilience to extreme climate conditions and thereby maintain economic yield levels when compared to herbaceous crops tested in this study (Cardinael et al. 2012; Clinch et al. 2009).

In addition to the above, crop management and harvest logistics too should be considered in terms of biomass crop selection for southern Ontario, Canada. Many parts of Canada receive high amount of snow loads during the winter months and this load often enhances lodging in switchgrass and polyculture and less in miscanthus, provided suitable miscanthus variety is selected for a given region. (Deen et al. 2011). However, although lodging is not an issue in woody crops (poplar and willow), it should be mentioned that woody biomass crops are harvested only at 3-year intervals and it takes 4 years before the first woody crop is harvested. In this context, from a landowner perspective, herbaceous crops such as miscanthus, should be integrated along with woody crops in order to diversify economic returns and also to reduce risks associated with pest and diseases influenced by climate change scenarios. This diversity of biomass crops is needed as most of the woody species are hybrids and therefore are genetically identical.

Acknowledgments We gratefully acknowledge funding received from several programs including the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), Canadian Wood Fibre Centre, Canadian Forest Service (CFS), NRCan, Agriculture and AgriFood Canada (AAFC) and three years of student placement by AgroParisTech., France. We would also like to especially thank the field staff Brent Coleman, Sean Simpson, Jordan Graham, Sarah Pratt and Idris Mohamad for laboratory assistance.

References

Cardinael R, Thevathasan NV, Gordon AM, Clinch RL, Mohammed I, Sidders D (2012) Growing woody biomass for bioenergy in a tree-based intercropping system in southern Ontario, Canada. Agrofor Syst 86(2):279–286. doi:10.1007/s10457-012-9572-y

Clinch RL, Thevathasan NV, Gordon AM, Volk TA, Sidders D (2009) Biophysical interactions in a short rotation willow intercropping system in southern Ontario, Canada. Agric Ecosyst Environ 131(1–2):61–69. doi:10.1016/j.agee.2009.01.018

Cole CV, Cerri C, Minami K, Mosier A, Rosengerg N, Sauerbeck D (1996) Agricultural options for mitigation of greenhouse gas emissions. In: Watson RT, Zinyowera MC, Moss RH (eds) Climate cange 1995. Impacts, adaptions and mitigation of climate change: scientific technical analysis. Published for the Intergovernmental Panel on climate change. Cambridge University Press, Cambridge, pp 745–771

Deen B, Young D, Rowsell J, Tubeileh A, Engbers H, Rosser B (2011) A comparative study assessing variety and management effects on C4 perennial grasses in a northern climate. Asp Appl Biol 112:205–211

Engbers HM (2012) Evaluation of nitrogen fertilization in C4 grasses grown for bioenergy. M. Sc, University of Guelph

Ercoli L, Mariotti M, Masoni A, Bonari E (1999) Effect of irrigation and nitrogen fertilization on biomass yield and efficiency of energy use in crop production of *Miscanthus*. Field Crops Res 63(1):3–11. doi:10.1016/S0378-4290(99)00022-2

Guillot S (2014) Assessment of factors influencing the sustainable production of biomass (feedstock) for bioenergy in Southern Ontario. Internship report, University of Guelph, Canada

Kauter D, Lewandowski I, Claupein W (2003) Quantity and quality of harvestable biomass from Populus short rotation coppice for solid fuel use—a review of the physiological basis and management influences. Biomass Bioenergy 24(6):411–427. doi:10.1016/S0961-9534(02)00177-0

Keoleian GA, Volk TA (2005) Renewable energy from willow biomass crops: life cycle energy, environmental and economic performance. Crit Rev Plant Sci 24(5–6):385–406. doi:10.1080/07352680500316334

Kopp R, Abrahamson L, White E, Volk T, Nowak C, Fillhart R (2001) Willow biomass production during ten successive annual harvests. Biomass Bioenergy 20(1):1–7. doi:10.1016/S0961-9534(00)00063-5

Labrecque M, Teodorescu T (2005) Field performance and biomass production of 12 willow and poplar clones in short-rotation coppice in southern Quebec (Canada). Biomass Bioenergy 29:1–9

Lemus R, Lal R (2005) Bioenergy crops and carbon sequestration. Crit Rev Plant Sci 24(1):1–21. doi:10.1080/07352680590910393

Lewandowski I, Scurlock JMO, Lindvall E, Christou M (2003) The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass Bioenergy 25(4):335–361. doi:10.1016/S0961-9534(03)00030-8

Mann J (2012) Comparison of yield, calorific value and ash content in woody and herbaceous biomass used for bioenergy production in southern Ontario, Canada. M. Sc, University of Guelph

McKendry P (2002) Energy production from biomass (part 1): overview of biomass. Bioresour Technol 83(1):37–46. doi:10.1016/S0960-8524(01)00118-3

Ontario Power Generation (2014) Atikokan station biomass conversion project. Ontario Power Generation Inc. http://www.opg.com/generating-power/thermal/stations/atikokan-station/pages/atikokan-station-biomass-conversion-project.aspx. Accessed 16 Dec 2015

Oo A, Kelley J, Lalonde C (2012) Assessment of biomass case for purpose-grown biomass in Ontario. http://www.ofa.on.ca/uploads/userfiles/files/assessment%20of%20business%

20case%20for%20purpose-grown%20biomass%20in%20ontario%20march%202012.pdf. Accessed on 16 Dec 2015

Quaye AK, Volk TA (2013) Biomass production and soil nutrients in organic and inorganic fertilized willow biomass production systems. Biomass Bioenergy 57:113–125. doi:10.1016/j.biombioe.2013.08.002

Sage RB (1998) Short rotation coppice for energy: towards ecological guidelines. Biomass Bioenergy 15(1):39–47. doi:10.1016/S0961-9534(97)10055-1

Thevathasan NV, Gordon AM, Simpson J, Peng X, Silim S, Soolanayakanahally R, de Gooijer H (2014) Sustainability indicators of biomass production in agroforestry systems. Open Agric J 8:1–11

Yue D, You F, Snyder SW (2014) Biomass-to-bioenergy and biofuel supply chain optimization: overview, key issues and challenges. Comput Chem Eng 66:36–56. doi:10.1016/j.compchemeng.2013.11.016