Comparison of Yield, Calorific Value and Ash Content in Woody and Herbaceous Biomass used for Bioenergy Production in Southern Ontario, Canada

by

John David Mann

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ABSTRACT

COMPARISON OF YIELD, CALORIFIC VALUE AND ASH CONTENT IN WOODY AND HERBACEOUS BIOMASS USED FOR BIOENERGY PRODUCTION IN SOUTHERN ONTARIO, CANADA

Advisors:
John David Mann
Professor A.M. Gordon
University of Guelph, 2012
Professor N.V. Thevathasan

Recently, the use of biomass to produce energy has resulted in evaluating each potential biomass species individually, and primarily in terms of yield potentials. However, discrepancies between species yield caused by varying site conditions and varying fertilization regimes between studies do exist. Therefore, this study attempts to address some of these discrepancies by growing multiple species simultaneously on marginal land with zero fertilization. The yield and fuel characteristics of the four most commonly used biomass feedstocks (*Miscanthus*, switchgrass, willow and poplar) in southern Ontario, along with one herbaceous polyculture, were investigated. Species’ influence on microclimatic modifications was quantified during the 2010 and 2011 growing seasons in order to understand its impact on biomass yields. Yield data was gathered for each species treatment for both growing seasons. Few significant differences were found between species during establishment. Fuel characteristics analyses including, gross calorific value, ash (%), and an elemental ash analysis were completed during 2010 and 2011. The differences between the combustion properties of the grass species and the woody species were obvious, but neither could be conclusively determined as universally better than the other. Yield and fuel characteristics change as plants mature, therefore research should be continued in future years once plots are fully established to determine which species are best suited for bioenergy production in Southern Ontario. This will help growers and energy producers focus on crops that have the most potential in achieving environmental sustainability and economic viability.
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ABBREVIATIONS LIST:

ASTM American Society for Testing and Materials
CAD/GJ Canadian dollars per gigajoule
CAD/odt Canadian dollars per oven dried ton
CRP Conservation Reserve Program
CREP Conservation Reserve Enhancement Program
GARS Guelph Agroforestry Research Station
GCV gross calorific value
GHG greenhouse gases
MAI mean annual increment
MWh Megawatt hours
odt oven dried tons
odt/ha/yr oven dried tons per hectare per year
OPG Ontario Power Generation
SRWC Short Rotation Woody Crops
INTRODUCTION AND LITERATURE REVIEW

1.1 Bioenergy Crops

Societal expansion brings about encroachment of new territory, and with it, a host of existing environmental problems worsen. While some concern for the environment has always existed, environmental issues are now a major topic of discussion in North America, even for the general public. The use of fossil fuels is of particular interest as greenhouse gases (GHG) from their use have caused changes to the global climate and their continued use may lead to even further global changes (Lewandowski and Kicherer 1997). Reducing reliance on fossil fuels is an important step in reducing GHG emissions to the atmosphere, but North America and the majority of the world continues its dependency on fossil fuels for almost all energy needs of everyday life, particularly transportation and electricity production. While transportation has primarily relied on fossil fuels in the past, completely electric mainstream cars like the Nissan Leaf and the Ford Focus Electric are already emerging and reducing the roadside fossil fuel consumption. The electricity that is fueling the electric cars still has to be generated, and while there are many different ways to produce electricity, coal fired power plants are still a major part of global electricity production (British Petroleum 2012). Coal fired power plants are widely used GHG emitters and their popularity comes from the cheap cost of coal. With global climate change, more and more pressure is being placed on the energy sector to develop alternative fuels that are "carbon neutral"; meaning that no net CO$_2$ is being released to the atmosphere. While carbon neutrality is not yet possible, alternative energy sources like wind, solar, and biomass are very close, especially when compared to fossil fuels. While all of these alternative energies have merit, the present study focuses on the feasibility of bioenergy derived from the production of biomass.
Bioenergy from biomass is simply energy obtained from biotic material, and can be derived from a variety of sources and processes in order to produce electricity. This study will focus on the use of dedicated energy crops (e.g. willow (*Salix* spp.)) grown exclusively for the purpose of producing high volumes of biomass, as opposed to a host of other biomass types such as: wood and agricultural residues and municipal solid waste (Easterly and Burnham 1996). While also feasible energy sources, organic wastes and urban residues are less homogeneous and are not as clean burning as dedicated crops. Growing dedicated crops for needs other than food is not a new concept and has been around at least since the Roman Empire where willow, a woody perennial, was grown for a variety of purposes including the framing of shields (Volk et al. 2006). Growing dedicated crops for the production of heat and electricity started emerging in North America in the 1970’s after the Arab oil embargo and again in the 1980’s due to environmental concern (Codner, 2001; Volk et al. 2006). Currently, growing bioenergy crops is not widely implemented in North America, but countries such as Sweden already derive a large portion of their power from biomass and intend to expand biomass production (British Petroleum, 2011). While it is evident that the technological viability exists and the potential for environmental benefits are great, North America has been slow to adopt this energy source (Tharakan et al. 2005). This is primarily due to two reasons: 1) the cost of biomass compared to coal, and 2) the absence of any monetary value placed on environmental benefits.

The main properties a bioenergy crop should have are: fast growth, high energy value, and low ash content. Additional properties are low moisture content at harvest, appropriate ash chemical composition, and the ability to grow with few inputs. Bioenergy crops should also be capable of growing on marginal or degraded lands, since this allows the grower to retire these types of lands from full agricultural productivity; in some cases, government programs offer financial incentives to do this (e.g. the U.S. Conservation Reserve Program (CRP) (Volk et al. 2006). While bioenergy crops would grow
better on higher quality sites, they would also compete with food crops for space and the opportunity for the reclamation of poorer quality lands would be missed. In southern Ontario, Canada, focus has been placed on willow, poplar (*Populus* spp.), *Miscanthus* grasses (*Miscanthus* spp.), and switchgrass (*Panicum virgatum* L.) for use as dedicated bioenergy crops in the region's climate.

The primary benefit to switching from coal to dedicated biomass crops is the environmental services and the reduction in GHG emissions that would result. Biomass crops do produce CO$_2$ when burned but the crops have obtained all of the carbon stored within their tissues from CO$_2$ from the atmosphere; while this is not a perfect carbon neutral fuel, it releases only the CO$_2$ it has collected from the atmosphere when combusted. Even when co-firing biomass with coal at rates of 10% biomass (by mass) the net global warming potential decreases by 7-10%, SO$_2$ emissions are reduced by 9.5% and NO$_x$ emissions are reduced by 10-30% from that of pure coal combustion (Battista et al. 2000; Heller et al. 2004). Every ton of biomass burned avoids 2.7-3.15 tons of fossil fuel CO$_2$ from being released into the atmosphere (Tillman, 2000). SO$_2$ and NO$_x$ reductions are also important, as SO$_2$ is responsible for acid precipitation and air quality reduction, while NO$_x$ is an indirect GHG which influences the production of direct GHG in the atmosphere (Easterly and Burnham 1996; Plattner et al. 2009). Besides the environmental benefits provided through reduced emissions, growing biomass crops can also provide additional environmental services. For example, dedicated biomass crops can provide habitat for wildlife by providing perennial cover conducive to many species of micro and macro fauna (Abrahamson et al. 1998). Biomass crops also improve soil structure over conventional food crops because they only experience tillage before planting and then at the end of their 22-year lifespan. The perennial nature of the crops and canopy closure also provides soil with constant protection from wind and water erosion and has been shown to increase soil organic carbon over time through annual litterfall inputs (Brandy and Weil, 2002; Henriksen et al. 2002).
Despite environmental concerns, there has not been a lot of incentives to reduce emissions or produce cleaner fuels in Ontario, but changes may be coming in the near future. Ontario Power Generation (OPG) is working on repowering the previously coal-fired Atikokan generating station to run on biomass fuel alone. This station is in northern Ontario and will likely be fed with forest residues from the timber industry, but OPG is also considering the potential to co-fire biomass with natural gas in its other plants in the future (Ontario Power 2012). The more southerly plants could derive their feedstock from dedicated biomass crops for co-firing, but steps to start producers growing bioenergy crops have yet to be taken. Ontario’s electricity supply in 2011 was 33% nuclear, 27% natural gas, 23% hydro, 13% coal, 4% wind and <1% was other (a section including biomass) (Ontario Power 2010). In contrast, Sweden met its energy demand in 2009 with 32% derived from biomass sources (British Petroleum, 2011). It is not realistic to expect all of Ontario's energy to come from biomass as it would require an unfeasible amount of land under biomass production. However it is possible to meet some of the electricity needs using biomass, but it is clear that biomass does not yet have a prominent place in Ontario’s energy sector (British Petroleum 2011).

There are other opportunities for biomass production in the greenhouse industry, which has a 3.9 billion dollar per year positive economic impact on Ontario’s economy. This industry currently spends over 160 million dollars a year on fuel, primarily in the form of coal and natural gas (Planscape 2009). As fossil fuel prices continue to rise, interest in heating greenhouses with biomass also rises. Currently there are no regulations on emissions for greenhouses, but if policy changes to help reduce the country’s emissions, using coal to heat greenhouses will no longer be attractive (Planscape 2009). Unfortunately, while biomass is far more carbon neutral than coal or natural gas, it is still more expensive.
It is very difficult for dedicated biomass crops to compete with the price of coal. This is primarily because coal is an abundant and dense fuel. Currently, the estimated delivered cost for producing biomass crops like willow and poplar are $3.04 CAD/GJ or approximately $57.70/odt and are based on assumed yields between 10-15 odt/ha/yr (Volk et al. 2006). The delivered price of coal is half the price, ranging from $1.11-1.92 CAD/GJ of energy (Tharakan et al. 2003; Khanna et al. 2008). The estimated breakeven delivered cost of Miscanthus is $2.48-4.47 CAD/GJ ($50-59 CAD/odt), and that of switchgrass is $65-98 CAD/odt (Khanna et al. 2008). The prices for Miscanthus and switchgrass are based on an estimated yield of 36 odt/ha/yr and 9.4 odt/ha/yr respectively, and an estimated 112kg of nitrogen fertilizer would be needed annually to obtain these yields (Khanna et al. 2008). Should yields be lower than expected the price per unit energy would increase. While the willow and switchgrass yields assumed by these cost estimates are close to yield averages, Miscanthus is near the top of its projected yield and if grown on marginal lands, may not be nearly as high. As it currently stands, all of these crops are not price-competitive with coal but this could change if policies or subsidies are put in place to help reduce the cost of biomass production.

The cost of the environmental benefits that all biomass crops provide, would enhance the appeal of biomass as an energy source. In the U.S., the Conservation Reserve Program (CRP) and Conservation Reserve Enhancement Program (CREP) allows certain land qualities to qualify for replanting under permanent cover in order to improve soil and water quality as well as habitat creation (Volk et al. 2006). Since growing biomass crops have been shown to perform these benefits, biomass crops have qualified for use in the CRP and CREP. The CRP and CREP provides the landowner with annual rent payments for 10-15 years (contract dependent) as well as 50-90% of the establishment costs of the new vegetation paid for (Volk et al. 2006). This dramatically reduces the costs of producing biomass if the marginal land qualifies for retirement under these programs. Since Short Rotation Woody
Crops (SRWC) and Miscanthus have high establishment costs. The reduction provided by the CRP and CREP combined with annual payments, would reduce the delivered cost of biomass crops to that of coal (Volk et al. 2006). The price of biomass crops can also be reduced by breeding programs which produce higher yielding clones and the development of more efficient harvesters. A better more efficient harvester, for example, is estimated to reduce the cost of willow biomass by $0.51 CAD/GJ (Volk et al. 2006). The alternative to subsidizing biomass fuels would be to impose a tax on "dirty" fuels like coal, once again making biomass cost-competitive (Tharakan et al. 2005). While programs like the CRP and CREP in the U.S. are important for the continued adoption of dedicated bioenergy crops, they could be more readily available to all growers who wish to switch to producing a cleaner fuel (Volk et al. 2006). If Canada is seriously considering developing bioenergy crops to contribute to meeting its energy needs, similar subsidy programs need to be developed here in order to foster the switch to cleaner fuels.

1.2 Short Rotation Woody Crops

As humans have been burning wood as fuel for generations, a great deal of focus has been recently placed on SRWC like willow and poplar, primarily because they often have low ash content. Poplar and willow make good bioenergy crops because they are fast growing, establish quickly, grow in poor conditions and can resprout new shoots after harvest (Kauter et al. 2003). Whether growing willow or poplar, the basic planting and maintenance procedures are similar. These species are planted from 20-25cm cuttings, typically in double or triple rows and harvested every 3 years. Weeds should be controlled during the first 1-2 years of growth to achieve best establishment (Kauter et al. 2003). Ideally, herbicides should be used in large-scale operations, but there are not yet any registered herbicides for willow or poplar. During the first year, the double row spacing allows small tractors or mowers between the double rows (but not within the rows) as a means of weed control. Once established, weeding does
not have to be done for the lifespan of the plantation, typically 21 years or 7 cycles. Economic yields are achieved during the first cycle, but peak yields are not until the second or third harvest.

Yields for SRWC can vary depending on the site location and soil quality in which they are planted. The better the site and more inputs into the system, the higher the yields willow and poplar will produce. Under high fertilization and irrigation on a good quality site, yields of willow have been reported to reach 30 odt/ha/yr (Volk et al. 2006; Kauter et al. 2003). While proven possible, normal values for willow yields under limited fertilization and rainfed management regimes during the first harvest cycle are usually around 7.5 odt/ha/yr (Volk et al. 2006). Poplar produces similar yields under limited fertilization and rainfed management regimes. Yields between 10-20 odt/ha/yr are possible once fully established under a 3 year harvest cycle, and can be increased if the harvest interval is lengthened to 6-7 years. *Populus* species reach maximum mean annual increment (MAI) later than willow: poplar attains maximum MAI at age 4-10 and willow at age 3-5 (Kauter et al. 2003; Keoleian and Volk 2005). Unfortunately, equipment to harvest and process larger diameter stems has not been adequately developed to consider this as an option at this time (Kauter et al. 2003). Harvesting equipment is also not equipment that farmers already posses and this is therefore a barrier to the successful implementation of SRWC. Future scenarios would likely involve journeyman contractors for planting, harvesting and transportation.

The moisture content of biomass at harvest is also problematic. SRWC have a moisture content of about 50% at harvest, but cannot be burned in conventional boilers without losing energy, reducing efficiency and causing problems to the boiler system (Kauter et al. 2003). One effective method to reduce moisture content to acceptable levels post harvest is to bale and store the biomass in the field over the winter and/or summer until acceptable (~12-15%) moisture levels are attained (Kauter et al.
Other potential methods include oven drying or ventilated warehouse storage, but while effective, these options cost more and make SRWC less carbon neutral.

1.3 Herbaceous Bioenergy Crops

Advocates for the use of herbaceous perennials for bioenergy focus on species of Miscanthus and switchgrass. Unlike their woody counterparts both grasses have the advantage of having annual harvests, allowing the grower income every year as opposed to every 3 years. Income is generated annually, but the cost of harvesting is also incurred annually, unlike SRWC which are only harvested once every 3 years. The Miscanthus proposed for use in bioenergy is a C₄ perennial grass originating from southeast Asia. While not a native species, the risk of escape and invasiveness is very low since this Miscanthus is a sterile triploid, unable to produce viable seed or cross-pollinate with native grasses (Heaton et al. 2004). Miscanthus giganteus is relatively cold tolerant and can tolerate spring frosts of -6C (Farrell et al. 2006). This allows Miscanthus to also grow late into the fall when heavy frosts kill leaves and the plant senesces (Dohleman and Long 2009; Wang et al. 2008). The cold tolerance Miscanthus displays helps increase the length of its growing season, and allows it more time to accumulate biomass. Miscanthus has been shown to be particularly high yielding, and depending on site conditions and fertilization, yields of 10 and 40 odt/ha/yr can be achieved by the third year, over a lifespan of 20 years (Clifton-Brown et al. 2004). In a study by Heaton et al. (2004) summarized 97 observations of Miscanthus yield and found that the average yield was 22 odt/ha/yr. Since most studies only report yields after 3 years of growth it is difficult to compare yields from establishing plots. It is possible to estimate mature stand yields from first and second year growth (Engbers 2012). First year growth is
estimated as 30% and second year growth is estimated at 70% of the potential yield of a mature stand (Engbers 2012).

Switchgrass is a native warm season C₄ grass, but has not yet produced yields as high as Miscanthus, and once established only has a lifespan of 10 years (Khanna et al. 2008). Switchgrass is also only reported after the third year, but the same estimation can be made for establishing plots as are made in Miscanthus (Engbers 2012). Typically, switchgrass yields range from 5-20 odt/ha/yr depending on site characteristics and management regime (Lemus et al. 2008; Virgilio et al. 2007). The potential yield of both switchgrass and Miscanthus are impressive, but how these species perform under poor soil quality and low input management regimes is still uncertain. Switchgrass does have an advantage over Miscanthus because it has a much lower planting cost. Switchgrass is seeded unlike Miscanthus which is vegetatively propagated via rhizomes or plugs and planted with a potato planter, which increases the time and cost of harvest significantly (Christian et al. 2002). Harvesting both grasses is relatively easy as harvesters are commonplace in the farm community for harvesting grasses like switchgrass, and Miscanthus can be harvested with a corn silage harvester or additionally, balers following mowers can be used (Heaton et al. 2004). This currently represents a large economic advantage over SRWC because the machinery to harvest SRWC is not commonplace on farms and could require significant capital investment.

Moisture content of grasses harvested in the fall are typically lower than that of SRWC. If harvested during the winter or spring, switchgrass and Miscanthus moisture content reduces to well below that of SRWC. Fall harvests of Miscanthus moisture content is similar to SRWC, around 50%, but when spring harvested, reduces to between 20-30% moisture content (Lewandowski and Heinz, 2003; Lewandowski and Kicherer 1997). Typical switchgrass moisture content at fall harvest is around 35%, but drops to 7% when harvested in the spring (Adler et al. 2006). The trade off is that, as the crops dry
down, yield is also lost to decomposition, wind removal and lodging (Heaton et al. 2004). Lodging, the flattening or bending of a herbaceous crop, can be very detrimental to the yield and fuel quality. Switchgrass is particularly prone to lodging if left standing over winter, and benefits from windrowing as a better means to dry over the winter (Christian et al. 2002). In most cases a yield loss of between 15-50% are observed between fall and spring harvests of grasses (Lewandowski and Heinz 2003; Heaton et al. 2004; Adler et al. 2006). While moisture content is important when determining storage issues and combustion efficiency both SRWC and herbaceous grasses can be dried effectively in the field to below the 15% limits suggested for transport and use as a bioenergy crop (Lewandowski and Heinz 2003).

1.4 Fuel Characteristics and Quality

Since the industrial revolution humankind has learned a considerable amount about the combustion of coal. Coal is a cheap and accessible fuel which accounts for almost 30% of global energy consumption, almost half of which is consumed by China (BP 2011; Demirbas 2003). Today, almost 2.5 billion tons of coal is burned annually to meet the ever-rising global demand for energy (Demirbas 2003). Despite the cheap cost of burning coal, and relative abundance of the resource, most developed countries are moving away from using coal as the primary energy source due to detrimental environmental issues associated with its combustion. The threat of global climate change, with a focus on CO₂ emissions, has forced countries to find alternative energy resources and enforce the reduction of coal usage in order to reduce CO₂ emissions. Since coal is a fossil fuel, burning it releases the long-trapped carbon back into the atmosphere where it increases the concentration of greenhouse gases (GHG). In order to reduce GHG emissions to the atmosphere, reducing or eliminating the use of coal and other fossil fuels is necessary. One way to meet this goal is by burning biomass fuels that have sequestered their own carbon from existing atmospheric sources. While this process is not carbon neutral, it is a significant reduction of GHG when compared to burning coal (Tillman 2000).
One of the problems with switching to renewable energy sources is the required modifications to industry and infrastructure, with subsequent high capital costs. One of the advantages dedicated biomass crops currently have over other renewable energy sources is that they can be used in existing boilers and with minimal alterations to the system (Battista et al. 2000). Current boilers used in the production of heat and electricity are designed for coal and the specific problems associated with burning it. Ideally, these same boilers could be used to burn biomass fuels with little to no modifications to the process; however, because biomass is not coal, it has different problems associated with its combustion. These problems include, but are not exclusive to: clinkering, slagging and fouling. Clinkering occurs when low viscosity ash becomes molten and causes molten masses, or the agglomeration, of bed particles on the stoker grate (Magasiner et al. 2001). Stoker fired boilers are more prone to clinkers due to their long burn time compared to pulverized fuel boilers (Magasiner et al. 2001). Slagging occurs when molten ash particles, transported by air currents, collide with furnace walls. These deposits are the build-up of molten ash particles as well as any dry ash particles that adhere to the sticky ash (Magasiner et al. 2001). Fouling is the condensation, adherence, and sintering of volatile ash components on the heating surfaces of the boiler (Magasiner et al. 2001). Essentially, the fine particles form a compact material, in a process similar to the way in which ceramics are made (Magasiner et al. 2001). While these are the main problems caused by using biomass fuels, they are not the only drawbacks to using biomass as a fuel for heat and electricity.

Biomass has a much lower gross calorific value (GCV) than coal, which reduces the amount of energy obtained per unit mass. Coal typically has a GCV of around 30 (bituminous) MJ/kg, but depends on the type of coal, while biomass ranges from 15-20 MJ/kg (Heller et al. 2004; Kauter et al. 2003). This is considered an important quality for a fuel, but may not be the best comparison for fuels since GCV does not account for oxygen bound in the fuel or the flame temperature which impacts fuel efficiency
(Jenkins et al. 1998; Demirbas 2003). In general, the higher the flame temperature, the higher the theoretical maximum efficiency of the fuel in the boiler (Jenkins et al. 1998). Despite having a GCV 33% higher than biomass, coal and biomass have the same adiabatic flame temperature (Demirbas 2003). In a more extreme example, Jenkins et al. (1998) show that methane had the same adiabatic flame temperature as biomass even though it had almost three times the GCV. In terms of heating efficiency, biomass may be understated as a fuel because too much emphasis is placed on GCV (Jenkins et al. 1998).

One of the main differences between the burning of biomass and the burning of coal, is the moisture content. Moisture is a problem because it impacts the heating value of the fuel (Jenkins et al. 1998; Kauter et al. 2003). Since evaporation is an endothermic reaction, moisture content has been shown to reduce the GCV quite significantly. In a study by Kauter et al. (2003), poplar with a 16% moisture content had its GCV reduce by 5 MJ/kg or 25% when compared to its dry GCV. This reduces the energy obtained from burning biomass in boilers, but moisture content can also increase the incidence of slagging or fouling. Magasiner et al. (2001) indicate that so long as moisture content is below 30%, slagging or fouling is unlikely to be enhanced by the moisture content of the biomass. While moisture content does impact the heating value and potentially slagging or fouling, it is possible to modify the moisture content through proper management. In most cases, leaving biomass to dry naturally in the field over winter reduces the moisture content of herbaceous grasses by approximately 75% (Adler et al. 2006). Storing harvested woody biomass in the field over the following summer was shown to be an effective way to reduce moisture (Kauter et al. 2003). While both of these techniques rely on weather and seasonal variation, they are economical ways of reducing moisture content. The alternative to field drying would be an investment of energy to oven dry the harvested material or to invest money in ventilated storage facilities that would slowly dry the biomass until use. Both of these alternatives would
increase the cost of using biomass, but also make the biomass system less carbon neutral by increasing inputs, so field drying is preferable. Allowing biomass to dry in the field reduces moisture but in grasses it also reduces some of the chemical components detrimental to the combustion process.

Grasses are often considered a less effective fuel than woody species for bioenergy because grasses are high in elements like chlorine, silicates, and alkali metals (Jenkins et al. 1998). Some of these undesirable elements found in herbaceous biomass can be reduced through the overwintering process; in particular, the water soluble compounds, which leach out of the plant during the fall, winter and early spring (Lewandowski and Heinz 2003). Adler et al. (2006), working on switchgrass overwintering, found a reduction in potassium and chlorine of between 38-83%, in magnesium and phosphorus of between 41-67%; and in calcium, sulphur and nitrogen of between 5-28%. While grasses do see improvements in fuel quality by spring harvesting, they also suffer substantial yield losses in the range of 20-40% (Adler et al. 2006). During the fall, winter and early spring, the grasses lose approximately 10% of their mass to decomposition and leaf loss (Adler et al. 2006). This yield loss is beneficial for the fuel characteristics because the leaves of the grasses typically have worse fuel characteristics than the stems because they have a higher concentration of nutrients (Lewandowski and Kicherer 1997). Much of the reduction in yield comes from residues left behind by the harvester or bailer, and the amount of snowfall during the winter has a large impact on this (Adler et al. 2006). This reduction in biomass is not desirable as a potential product is no longer available for sale. Yield losses may be mitigated by improved harvesting techniques during spring harvests, although the risk for soil contamination may increase with the collection of lodged grasses (Adler et al. 2006). The combination of elements leaching from the plant and the reduced concentration of leaves in the biomass makes the fuel characteristics of spring harvest grasses more suited for use in today's boilers (Lewandowski and Kicherer 1997).
There are a variety of indices used to estimate whether a particular coal is suitable for modern boilers. These indices are usually based on the amount of alkali elements in the coal, the acid to base ratio, or the sulphur content. Coal is a fouling fuel, and boiler systems are outfitted with sootblowers to remove volatiles from the air to reduce their incidence and build up on heating surfaces (Magasiner et al. 2001). Unfortunately, biomass has fuel characteristics that are quite different from coal so the indices designed for coal are not appropriate for predicting or evaluating biomass as a fuel (Magasiner et al. 2001; Jenkins et al. 1998). While the indices are not valuable tools to predict which biomass fuels will cause slagging or fouling, there are known elements which are problematic in the combustion of biomass fuels.

Sulphur is an element that is known to cause fouling in coal; however, compared to coal, biomass contains very little sulphur (Monti et al. 2008; Battista et al. 2000; Tillman 2000; Heller et al. 2004). Sulphur is important because fouling seen in coal due to SO₃ contacting the heating surfaces is not problematic in biomass (Magasiner et al. 2001). A high sulphur content in the fuel also leads to emissions of SO₂ which are known to cause acid precipitation and air quality problems (Monti et al. 2008). Since biomass has so much less sulphur than coal, even cofiring with small biomass additions significantly reduces emissions. In fact, studies have found that cofiring biomass (10% by mass) with coal leads to SO₂ emissions being reduced by 9.5% (Heller et al. 2004). Biomass may be an improvement from coal, in terms of sulphur, but the majority of elements make biomass more problematic than coal if used in current boiler designs.

Chlorine is another element to consider when discussing the advantages and disadvantages linked to the combustion of biomass fuels. Coal is very low in chlorine, but biomass sources may contain more, especially herbaceous grasses which often are over the 1 mg/kg recommended concentration limits for current coal-burning boilers (Magasiner et al. 2001; Demirbas 2004; Monti et al. 2008). It is
important to minimize chlorine in the feedstock because it leads to the production of HCl and dioxin which can cause corrosion in the super heater tubes, and are harmful when released into the environment (Lewandowski and Kicherer 1997). Chlorine can also combine with available potassium to form KCl, which can also corrode heating surfaces in the boiler (Lewandowski and Kicherer 1997; Monti et al. 2008). Chlorine causes corrosion and damages the boiler system, which consequently increases maintenance and repairs, and ultimately increases the costs of using a high chlorine biomass fuel.

Another less understood problem when dealing with chlorine, is that chlorine can increase ash formation by facilitating the movement of the inorganic compounds (Monti et al. 2008). This can cause unexpected deposits to form on the surfaces of the boiler (Jenkins et al. 1998). For this reason, if biomass is to be used as an alternative fuel to coal, it should contain only small amounts of chlorine.

Potassium and sodium are both alkali metals and perform similar roles during combustion. Both are among the most detrimental elements to combustion in boilers that are found in biomass. Since potassium is found in much higher concentrations in biomass than sodium is, focus in this review will be on potassium. Potassium is It is not found in coal, and potassium causes many problems when burned in today's coal-burning boilers (Magasiner et al 2001; Miles et al. 1996). Potassium’s high reactivity with other compounds during the combustion process is at the heart of the problem. Potassium can combine with chlorine to form KCl and corrode heating surfaces, but even more seriously, it can also react with silicon (Lewandowski and Kicherer 1997). Alkali metals can be leached out of biomass through washing using water or acetic acid, which can lead to reductions in K and Na of 32% and 70% respectively (Davidsson et al. 2002). Leaching in the study by Davidsson et al. (2002) was more effective for woody material than straw. Silicon is commonly found in coal and normally causes no problems during its combustion, but when potassium reacts with it, the resulting ash's melting point is drastically reduced (Monti et al. 2008). Silicon ash normally melts at 1700°C, but when combusted with 32% K, the melting
point is reduced to 769° C (Miles et al. 1996). This interaction between Si and K causes slagging to increase, and the deposits formed are very hard and glasslike. This is particularly a problem in some grasses as their elemental composition is very similar to commercial glass (Miles et al. 1996; Jenkins et al. 1998). Due to the high potassium content of most biomass it is important that Si is low.

Calcium is another element that causes slagging because it is also responsible for lowering the ash melting point (Monti et al. 2008). Even though calcium can perform a similar role and lower silicon's melting point, it is preferable to potassium because the deposits formed are not as hard and easier to remove (Jenkins et al. 1998; Lewandowski and Kicherer 1997; Monti et al. 2008). It is another element not readily found in coal, but is one of the most common elements found in deposits along with Si, K and S (Miles et al. 1996).

Physical properties of a fuel are also important when considering a fuels' efficacy in a boiler system. The bulk volume is of primary importance in the physical properties of the fuel for a couple of reasons. When the bulk volume (the volume taken up per unit mass) is low, it is easier to cost effectively transport the fuel. Coal has a bulk volume of 1.1-1.5 m³Mg⁻¹, while wood chips and bales of grass are around 4.4-5.9 m³Mg⁻¹ and 4.9-9 m³Mg⁻¹ respectively (Easterly and Burnham 1996). Since the higher the bulk volume, the more transportation costs incurred, pelletizing near growers becomes important. Pelletized biomass has a bulk volume similar to coal at 1.6-1.8 m³Mg⁻¹ (Easterly and Burnham 1996). Cofiring with chips or bales means, even low percentage by mass means that by volume biomass could make up a large fraction of the stoked fuel. Tillman (2000) illustrates that even cofiring at 5% switchgrass by mass, by volume that switchgrass makes up 37%. This can cause problems in efficiency and the stoking of the furnace in grasses, especially if mixed prior to the delivery system (Tillman 2000).
One of the benefits to cofiring or using biomass alone is the low incidence of nitrous oxides (NO\textsubscript{x}) produced during combustion compared to coal. While temperature plays a role in the production of NO\textsubscript{x} emissions it is accepted that biomass reduces emissions even when cofired (Demirbas 2003). When cofiring at a rate of 10% most researchers indicate a reduction in NO\textsubscript{x} emissions of between 10-30% (Battista et al. 2000). This reduction decreases as concentration of nitrogen in the biomass increases, and for this reason, fertilization may reduce fuel quality if it leads to buildup of nitrogen in the plant tissues (Lewandowski and Kicherer 1997). One benefit to reduced NO\textsubscript{x} emissions could be reduced costs. NO\textsubscript{x} is estimated to be worth $1200-3000 per metric ton (Battista et al. 2000). If these saving could be realized by energy producers through incentives or tax breaks, biomass would become more appealing as an alternative energy source.

The environmental benefits to using biomass as a fuel for the production of heat and electricity are well documented, but it must also be economical to burn in commercial boilers in order to be implemented. It is important to study the combustion of biomass fuels so that clinkering, slagging and fouling can be accurately predicted and prevented. The boiler systems designed for coal can be optimised for burning biomass but more research is needed.
CHAPTER 2

2.0 HYPOTHESES AND OBJECTIVES

The purpose of this study was to investigate the efficacy of 5 different biomass feedstocks (willow, poplar, switchgrass, Miscanthus, and a polyculture consisting of indiangrass, big bluestem grass, little bluestem grass and switchgrass in a 25:25:25:25 mixture) when produced on marginal land with no fertilization, in southern Ontario. Yield and fuel characteristics will be used to determine the effectiveness of a species as a biomass feedstock in this study because both are necessary in order to predict the economic success of a feedstock for electricity and heat production. The study had four main objectives in attempts to evaluate two main hypotheses:

H01: the four species and the polyculture produce equal biomass yields when grown on marginal soil at the same location.

H02: the four species and the polyculture all possess similar properties related to combustion.

The objectives used to test the above hypotheses were:

1. To determine if there are significant differences in the biomass yields between different biomass species grown on the same site.

2. To determine if yield differences between the four species and the polyculture are associated with differences in soil microclimates.

3. To determine if the amount of energy per unit of biomass (gross calorific value) is the higher in woody species than herbaceous species.

4. To determine if there are significant differences in the ash content of different biomass species.
Hypothesis 1 and objectives 1 and 2 are investigated in Chapter 3 using observational and field gathered data, and Hypotheses 2 and objectives 3 and 4 are investigated in Chapter 4 using lab analyzed data.
CHAPTER 3

YIELD PARAMETERS OF 5 SPECIES OF BIOMASS CROPS GROWN ON MARGINAL LAND

3.1 Materials and Methods

3.1.1 Field Location and Design

The field site was established at the University of Guelph's Agroforestry Research Station in Guelph, Ontario (latitude 43°32'28" N, longitude 80°12'32"W). The location receives an average of 923 mm of precipitation annually, 432 mm occur during the growing season (May-Sept.) and has an average daily temperature of 6.5°C (Environment Canada Climate Normals 1971-2000) (See Table 3.1 for monthly temperature and precipitation data). The soils are classified as gray brown luvisols with a fine sandy loam texture and fell under class 4 in the Canada Land Inventory (agriculture) designation. Soils designated class 3 or worse are considered marginal or have severe limitations that make them less suitable for food crops. The field design was a Randomized Complete block design with 5 treatments and 4 blocks. The location was established within a field previously planted under corn (Zea mays L.), soybeans (Glycine max L.), winter wheat (Triticum aestivum L.) and/or barley (Hordeum vulgare L.) rotation for 25 years. The site is on a gentle slope facing Northeast and for this reason blocks were aligned perpendicular to the direction of the slope (see Figure 3.1).
Table 3.1 Average monthly temperature (°C) and precipitation (mm) for the 2010 and 2011 growing season from Elora, ON (Environment Canada, 2012).

<table>
<thead>
<tr>
<th></th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>Sept</th>
<th>Oct</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average temperature</td>
<td>8.8</td>
<td>13.8</td>
<td>16.9</td>
<td>20.2</td>
<td>19.4*</td>
<td>14.4</td>
<td>8.5*</td>
</tr>
<tr>
<td>Total precipitation</td>
<td>47.5</td>
<td>99.9</td>
<td>184.1*</td>
<td>89.4</td>
<td>12.1*</td>
<td>117.8</td>
<td>52.6*</td>
</tr>
<tr>
<td>2011</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average temperature</td>
<td>5.5</td>
<td>12.6*</td>
<td>16.5</td>
<td>21.4</td>
<td>19.1</td>
<td>15</td>
<td>8.9*</td>
</tr>
<tr>
<td>Total precipitation</td>
<td>100.7</td>
<td>113.3*</td>
<td>87</td>
<td>31.9</td>
<td>158.6*</td>
<td>76.1</td>
<td>128.9*</td>
</tr>
</tbody>
</table>

*Averages based on incomplete data.

Figure 3.1 Aerial photograph of open field plots September, 2010.
A duplicate location was established 700m from the open field site in an intercropped agroforestry field. This site is at the same elevation as the open field, only on the opposite side of the drumlin. Originally setup for comparison with the open field site, planting dates and unforeseen problems made this location unsuitable for comparison or rigorous statistical analysis and it was removed from this thesis work, in consultation with my advisory committee. The same establishment and sampling methodology was applied at both locations, in accordance with the original intention. Information on the duplicate location can be found in Appendix A.

The site, planted in 2009, had 5 treatment types and 4 replications totalling 20 total plots. Each plot's dimensions are 10m x 10m and are separated from each other by 3m buffers (Figure 3.2). The five treatments randomly assigned to a plot within each replication consisted of willow (*Salix miyabeana* clone SX67), poplar (*Populus* hybrid clone 2293-19), switchgrass (*Panicum virgatum*), *Miscanthus giganteus* (Nagara), and a polyculture (containing *Panicum virgatum* [switchgrass], *Sorghastrum nutans* [indiangrass], *Andropogon gerardii* [big bluestem] and *Schizachyrium scoparium* [little bluestem] in a 25:25:25:25 mix). Due to establishment issues (see section 3.2) the Experiment was split into 2 Experiments to enable appropriate treatment comparison; Experiment 1 included the poplar, switchgrass and the polyculture; Experiment 2 included *Miscanthus* and the willow.

Willow and poplar plots were both planted in 4 double rows with 1.5m between double rows. Each individual row was 0.75m apart and within each row each cutting was 0.6m apart (Figure 3.3). This resulted in a planting density of 15000 stools/ha. The *Miscanthus* was planted in a grid pattern all spaced 0.75m apart, while the other herbaceous grasses were broadcast seeded at 45 kg/ha over the 100m² plot.
Figure 3.2 Open location plot layout for RCBD Experiment located at the GARS, Guelph, ON, Canada. Treatment 2, 3 and 5 used in Experiment 1 and treatment 1 and 4 used in Experiment 2.

Figure 3.3 Spacing design for plots; willow and poplar plant spacing (left), Miscanthus plant spacing (Right).
3.1.2 Establishment

The location was established in the second week of June, 2009 and was planted with 5 species treatments. All plots were prepared by rototilling the soil prior to planting. The herbaceous plots were then packed with a 5 ft brillion and then planted. Switchgrass was planted by seeding the 10x10m plot by hand using a broadcast method at a seeding rate of 45 kg/ha. The polyculture seed was a 25:25:25:25 ratio combined for a total seeding rate of 45 kg/ha seeded using the same method. Both seeded grasses were then packed again using the 5 ft brillion and walking the plots and packing with boots any spots that were missed. *Miscanthus giganteus* (variety M1 Select) was planted using rhizomes in a grid pattern (0.75m spacing) for its initial planting in June 2009. M1 Select failed to establish, so the variety Nagara was planted which is also a *Miscanthus giganteus*. Nagara was planted the following year, June 2010, using plugs instead of rhizomes, but still using the same grid spacing. The plugs were irrigated to ensure survival during the first month of establishment due to minimal precipitation during this time period. Willow and poplar plots were both planted with 20 cm cuttings using a modified tractor-drawn tomato planter in double rows. The cuttings were left a maximum of 1 cm above flush with the soil surface. Fill planting of poplar and willow was done by hand in late June also with 20 cm cuttings.

During the first growing season poplar survival of planted stock was 90%. Poplar plots were fill planted in June, 2010. The switchgrass and the polyculture both showed high colonization of their plots. Only 30% of the initial willow (SV1) cuttings emerged and after 6 weeks so they were pulled out and fresh cuttings of SX67 (taken from nursery stoolbeds on site) were planted by hand. The willow failed during its first planting in 2009, likely due to bad stock as cuttings had some mold and had thicker diameters than are usually used for planting. The switch to SX67 was chosen as a replacement for SV1 based on stock availability alone, since performance of both species was equal in previous studies at the GARS (Clinch 2008). The fresh cuttings taken in the middle of July were leafed out and far from ideal
stock and also had to be replanted in June, 2010 when only 40% of the willow leafed out or emerged. SX67 was used again but the cuttings planted were cut and prepared at the proper time of year. Survival for the final planting of willow was 85% and deemed acceptable. Initial establishment of the *Miscanthus giganteus* (M1 Select) rhizomes were successful (85% emergence), but showed minimal growth during the growing season (average of 30cm tall). After the winter of 2009/2010 only 10% of the M1 Select re-emerged and the decision was made to replace these with Nagara plugs. The low emergence was a function of poor first year growth combined with winter kill of rhizomes, indicating that M1 Select was not well suited to grow at the latitude and site conditions of the GARS. The Nagara established with 100% survival during the first growing season with the plugs, and the following spring emerged with 95% survival. This 5% winter kill, was replanted from a row of Nagara grown adjacent to the plots. The poor winter survival of willow and M1 Select forced these two species to be replanted during the spring of 2010 and separate the species comparison into the 2 Experiments.

When comparing species for yield and fuel characteristics the species comparisons will be separated into 2 Experiments. Experiment 1 will refer to poplar, switchgrass and the polyculture, since these species all began growth in 2009. Experiment 2 will refer to the willow and *Miscanthus* which began growth in 2010. Other than planting date and the species involved the two Experiments are no different in terms of methodology.

3.1.3 Management Regime

The year prior to establishment the biomass plots were under corn in the rotation, but in commercial practice the site would remain fallow during the season prior to planting and undergo weed control.
The plots were not fertilized before or anytime after planting. The site has not been fertilized since 2008 when corn was being grown. This is an attempt to evaluate the potential each biomass species has at establishing and growing on marginal land without inputs to the system. The plots are also rain fed and not irrigated for the same reason (with the exception of the Miscanthus and willow during the first month after replanting in 2010 to ensure survival during dry conditions). Miscanthus and willow plants were irrigated twice a week during the first month with a watering can to make sure plugs and cuttings did not desiccate and die.

In 2009 the weeds were initially controlled using a tractor-drawn rototiller around the plots and between the double rows of the willow and poplar. The remaining weeds between the willow and poplar were weeded using hand tools. The switchgrass and polyculture grasses in 2009 were weeded by hand to ensure no damage was done to the new growth. Miscanthus was weeded using hand tools. In commercial practice the grasses and woody species would be weeded using herbicides (not yet registered for biomass species) but due to the close proximity to each other this was deemed an unnecessary risk. In 2010, weed control was done in the same manner, specific care taken using weed whackers instead of the tractor-drawn rototiller in willow and poplar plots. By the end of the season it was not necessary to use the weed whackers between the poplar rows as the canopy provided a dense shade. A tractor-drawn mower was used to clear around the plots to avoid potential root damage to plants within plots. In 2011 weed control continued with a tractor-drawn mower clearing around the plots and hand tools within the plots as necessary. Poplar plots did not need any weeding during this season due to the dense shade caused by the canopy. By July Miscanthus did not need weeding as it colonized much of the plot and provided a dense shade below its leaves. Switchgrass and the polyculture required hand weeding twice a month to remove the relatively few broadleaves that managed to grow within the well colonized plots. Willow having been coppiced during the winter.
required weed whackers and hand tools throughout the season as its canopy had not yet completely closed.

Due to replanting willows were not coppiced until April, 2011. Willows were coppiced 5cm above the ground with hand pruners. In practice coppicing willows with a harvester may leave stumps anywhere from 5-10cm above the soil surface. Willow and poplar will both follow 3 year harvesting cycles. Unlike willow, poplar was not coppiced and instead left for the first 3 years as a single stem. Switchgrass and the polyculture were harvested using a jerry mower in the first week of December and windrowed over the winter. Miscanthus was left standing over the winter and harvested from the plots using a jerry mower in the last week of March 2011, and a tractor drawn mower in the first week of April 2012, once the site conditions were dry enough.

3.1.4 Measurements

3.1.4.1 Baseline Soil Characteristics

Baseline measurements of soil texture, soil carbon, pH and electrical conductivity were all taken in October 2009. Two soil samples were collected from two depths (0-10 cm and 10-20 cm) for every plot using a 5 cm diameter soil auger and frozen until analysis. Soil texture was done at Lab services at the University of Guelph using the pipette method. Soil carbon was measured using a Leco Carbon Determinator CR-12 following the dry combustion technique (Canadian Society, 2008). Soil pH was measured using the standard method in water (Canadian Society, 2008). Electrical conductivity was done following the fixed ratio extraction method using a 1:4 soil to water ratio (Canadian Society, 2008).
3.1.4.2 Emergence and Senescence

Emergence was monitored starting from April 20th, 2011. In poplar, willow and Miscanthus this was done by taking counts of 10 plants per plot. The plants were randomly selected and took place every 2-3 days. The counts were used as an estimate for the percentage of plants that had broken bud (woody plants) or the emergence of new growth from the soil (herbaceous plants). The switchgrass and polyculture plots were monitored for new shoot emergence but specific counts were not done. Emergence for switchgrass and the polyculture were measured by first emergence. Emergence for Miscanthus was determined based on new shoots alone and not greening within old shoots which was present on some but not all plants.

Senescence was estimated based on % leaf drop for the poplar and willow. Miscanthus, switchgrass and the polyculture were considered senesced when leaves browned. This was particularly difficult to estimate for Miscanthus as Miscanthus began browning and losing leaves at the base of the plant and worked up over the course of a month.

3.1.4.3 Biomass Yield and Moisture Content

Estimating yield in willow, poplar, and Miscanthus was done by taking 2 plants from 2 randomized sampling locations in every plot. Samples were collected for all species on the same day. Fall sampling took place in late November in 2010 and early December in 2011. Spring harvest was collected during the first week of April 2011 (See Table 3.2 for dates of operations). The Miscanthus samples were harvested with pruning shears 5cm from the ground to simulate harvesting. The willow and poplar samples were harvested using hand pruners (pruning saws were required to harvest the poplar in 2011) also 5 cm above the ground. Switchgrass and the polyculture were harvested by taking two 0.25m$^2$ quadrats from each plot. Each quadrat was harvested 5cm above the ground using pruning shears. The
fresh samples were weighed and placed in a walk-in dryer at (65°C) for one week. The samples were then weighed to obtain the dry weight and an estimate for yield in odt/ha/year was calculated. Moisture content of the biomass samples were then calculated at harvest using the following formula:

\[
\text{% Moisture} = \frac{(\text{fresh weight}) - (\text{oven-dried weight})}{\text{oven-dried weight}} \times 100\% 
\]

Table 3.2 Dates of sampling and harvesting operations completed in the 2010 and 2011 growing seasons.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Date performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Sampling</td>
<td>last week of every month (1 day)</td>
</tr>
<tr>
<td>Fall Harvest 2010</td>
<td>Nov 29th 2010</td>
</tr>
<tr>
<td>Spring Harvest 2011</td>
<td>April 7th 2011</td>
</tr>
<tr>
<td>Clearing of previous season growth 2011*</td>
<td>April 7th 2011</td>
</tr>
<tr>
<td>Fall Harvest 2011</td>
<td>Dec 13th 2011</td>
</tr>
<tr>
<td>Clearing of previous season growth 2012*</td>
<td>April 6th 2012</td>
</tr>
</tbody>
</table>

*This was done for grasses only.

3.1.4.4 Soil Moisture

In 2010, two randomized soil moisture samples were taken with an 5 cm diameter auger from every plot, every month, throughout the growing season (May-September). Samples remained frozen anywhere from 2 weeks to 6 months until they could be analyzed. This created 160 samples to be analyzed every month. In 2011, a single sample was taken from every plot, every month, throughout the growing season. A single sample at 0-40cm depth was collected using a soil auger and frozen until
analysis. After thawing, samples were homogenized using a mortar and pestle and sieved through a 2mm mesh sieve, then a 10g subsample was analyzed for gravimetric soil moisture content using the oven-dry (105 °C) method for 48 hours (Reynolds 1970).

3.1.4.5 Soil Nitrogen

Soil samples taken for moisture content were also used for soil nitrogen analyses. After soil samples were thawed and homogenized, samples were allowed to completely air dry over 1 week then total nitrogen was analyzed. After homogenizing, precisely 0.2000g of soil was measured into tin cups. The cups were folded and rolled into balls for use in the Leco FP-428 nitrogen analyzer. Total nitrogen was determined by the Technicon nitrogen analyzer in % mass for each subsample.

3.1.4.6 Soil Temperature

Soil temperature was measured using HOBO® H8 Outdoor 4-Channel External Logger sensors (Onset Computer Corporation) every 30 minutes throughout the growing season of 2010 and 2011 (May-September). A sensor was placed (15cm depth) in every plot for 3 blocks at both the open and agroforestry location. All 4 blocks were not sampled for temperature because there were only 8 available HOBO data loggers. Data was collected using a HOBO shuttle every week and uploaded to a lab computer. Data was collected every week to monitor for HOBO device errors and broken or loose cables. HOBO data loggers and hobo cables were replaced after two attempts of fixing them.

3.1.5 Statistical Analysis

Statistical analysis was done using IBM® SPSS® Statistics 19 (SPSS Inc., Chicago IL). Soil moisture, soil temperature, and soil nitrogen comparison between all species and blocks was done via ANOVAs with Tukeys HSD test. A bivariate correlation analysis of temperature and moisture were done to
determine if the 2 variables were correlated. Yield comparison analyses for Experiment 1 were done using an ANOVA and Tukeys HSD test to identify significant differences between species. An ANOVA was done for Experiment 2 to determine if willow and Miscanthus means were significantly different. Levene's test for homogeneity of variance was done to determine that all analyses met the assumption of equal variance.

3.2 Results

3.2.1 Baseline Soil Characteristics

The baseline soil characteristics for the site were obtained from samples taken in 2009. The soil texture of the gray brown luvisol was a sandy loam, composed of 56% sand, 34% silt and 10% clay. Total soil carbon for the plots averaged 2.06% (1.7% organic; 0.36% inorganic) at 0-10cm deep and averaged 2.05% at 10-20cm deep (1.68% organic; 0.37% inorganic). Soil pH of the site averaged 7.2 and soil electrical conductivity averaged 96.7 umho/cm at 0-10cm deep and 100.8 umho/cm at 10-20cm deep. Total soil nitrogen averaged 0.14% at 0-10 cm deep and 0.13% at 10-20 cm deep. There were no significant differences in soil nitrogen between species or blocks at baseline (October 2009). Table 3.3 shows the average soil characteristics of the site.

Table 3.3 Summary of baseline soil characteristics taken in October 2009.

<table>
<thead>
<tr>
<th>Soil Parameter</th>
<th>0-10 cm</th>
<th>10-20 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC (umho/cm)</td>
<td>96.7</td>
<td>100.8</td>
</tr>
<tr>
<td>pH</td>
<td>7.18</td>
<td>7.18</td>
</tr>
<tr>
<td>N%</td>
<td>0.145</td>
<td>0.129</td>
</tr>
<tr>
<td>Total C%</td>
<td>2.06</td>
<td>1.70</td>
</tr>
<tr>
<td>Organic C%</td>
<td>2.05</td>
<td>1.68</td>
</tr>
</tbody>
</table>
3.2.2 Spring Emergence and Fall Senescence (2011).

Emergence was monitored starting from April 20th, 2011 and by April 27th willow and poplar had broken bud. New *Miscanthus* shoots at this time had just started to emerge from the soil (10% had new shoots). By May 11th all *Miscanthus* plants had new shoots emerging from the soil and many opening into their first leaf. By May 16th willow shoots were beginning to elongate and were on average 15 cm tall. The switchgrass and polyculture at this time had emerged and were 5 cm tall throughout the plots. There was no noticeable difference between the emergence date of switchgrass and the polyculture. *Miscanthus* emerged 1 week before the other herbaceous grasses, but poplar and willow both broke dormancy 2 weeks ahead of the majority of the *Miscanthus* plants.

Senescence in poplar began August 19th as the lower leaves began to drop, but did not complete until October 3rd. By September 29 most of the poplar leaves had dropped leaving only the top 20% (see Figure 3.5). Switchgrass and the polyculture remained green until October 3rd when the majority of plants browned. Willow and *Miscanthus* did not stop growth as early as the species in Experiment 1. Willow retained all of its leaves until October 24th, when it began to lose them. Despite the willow leaves being completely senesced by November, a few leaves remained attached to the stems. *Miscanthus* also grew into the fall, and remained green until October 28th when frosts below -3C killed the aboveground biomass. See Figure 3.4 for growing season visualization for each species.
Figure 3.4: Approximate date of 100% emergence to senescence for each treatment during the 2011 growing season. Total growing season given in days for each species.

3.2.3 Biomass Yield and Moisture (2010)

An ANOVA of biomass yields for the fall, 2010 harvest found no significant differences in Experiment 1 between the 2 species and the polyculture (Table 3.4).

An ANOVA of moisture content at harvest for the fall, 2010 (Table 3.4) harvest found significant differences in Experiment 1. Poplar had significantly more moisture at harvest (49.9%) than either switchgrass (15.3%) or the polyculture (21.8%) which were not significantly different from each other.

An ANOVA of biomass yields for the fall 2010 harvest found significant differences in Experiment 2 between the two species. Miscanthus had a significantly higher yield (0.6 odt/ha/yr) during its first season of growth than willow (0.31 odt/ha/yr) (Table 3.5).
An ANOVA of the moisture content for Experiment 2 in the fall of 2010 (Table 3.5) harvest revealed a significant difference. Willow had significantly higher moisture content at harvest (51.6%) than Miscanthus (29.9%).

3.2.3.1 Yield of Fall vs Spring harvested grasses

An ANOVA of the biomass yields for the fall 2010 and spring 2011 harvest dates found no significant differences between species in either Experiment. See Table 3.6 for yields and moisture content of fall vs. spring harvested grasses.

3.2.3.2 Moisture content of Fall vs Spring harvested grasses

An ANOVA of moisture content for the fall 2010 and spring 2011 harvest dates found significant differences in Experiment 1. In Experiment 1 both the polyculture (15.3% moisture in the fall compared to 1.33% moisture in the spring) and the switchgrass (21.82% moisture in the fall compared to 1.13% moisture in the spring) treatments had higher moisture contents in their tissues during the fall harvest than the spring harvest (Table 3.6).

Miscanthus in Experiment 2 showed no significant differences in moisture content between the fall and spring harvest dates (Table 3.6).
Table 3.4 Results of yields and moisture content of poplar, switchgrass and a polyculture grown in Southern Ontario, Canada in 2010.

<table>
<thead>
<tr>
<th>Species Treatment</th>
<th>Yield (odt/ha/yr)</th>
<th>se</th>
<th>Moisture at Harvest (%)</th>
<th>se</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poplar</td>
<td>2.77 a</td>
<td>0.17</td>
<td>49.9 b</td>
<td>3.6</td>
</tr>
<tr>
<td>Polyculture</td>
<td>2.96 a</td>
<td>0.43</td>
<td>21.8 a</td>
<td>2.5</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>3.43 a</td>
<td>0.23</td>
<td>15.3 a</td>
<td>2</td>
</tr>
</tbody>
</table>

Means in the same column with the same letter are not significantly different according to Tukey's HSD test at p<0.05.

Table 3.5 Results of yields and moisture content of *Miscanthus* and willow grown in Southern Ontario, Canada in 2010.

<table>
<thead>
<tr>
<th>Species Treatment</th>
<th>Yield (odt/ha/yr)</th>
<th>se</th>
<th>Moisture at Harvest (%)</th>
<th>se</th>
</tr>
</thead>
<tbody>
<tr>
<td>* Miscanthus</td>
<td>0.6*</td>
<td>0.25</td>
<td>29.9*</td>
<td>2.1</td>
</tr>
<tr>
<td>Willow</td>
<td>0.31*</td>
<td>0.76</td>
<td>51.6*</td>
<td>4.5</td>
</tr>
</tbody>
</table>

* Averages are significantly different at p<0.05.

Table 3.6 Results of yields and moisture content of fall vs spring harvest of 3 species of grasses grown in Southern Ontario, Canada in 2010.

<table>
<thead>
<tr>
<th>Species Treatment</th>
<th>Yield (odt/ha/yr)</th>
<th>se</th>
<th>Moisture Content (%)</th>
<th>se</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyculture</td>
<td>2.96 a</td>
<td>0.43</td>
<td>21.82 b</td>
<td>2.52</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>3.43 a</td>
<td>0.23</td>
<td>15.30 c</td>
<td>5.62</td>
</tr>
<tr>
<td>Spring Polyculture</td>
<td>3.6 a</td>
<td>0.37</td>
<td>1.13 a</td>
<td>0.34</td>
</tr>
<tr>
<td>Spring Switchgrass</td>
<td>3.37 a</td>
<td>0.18</td>
<td>1.33 a</td>
<td>0.34</td>
</tr>
<tr>
<td>Experiment 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Miscanthus</td>
<td>0.6</td>
<td>0.09</td>
<td>29.91</td>
<td>2.12</td>
</tr>
<tr>
<td>Spring * Miscanthus</td>
<td>0.59</td>
<td>0.06</td>
<td>33.84</td>
<td>0.84</td>
</tr>
</tbody>
</table>

Means in the same column with the same letter are not significantly different according to Tukey's HSD test at p<0.05.

* Averages are significantly different at p<0.05.
3.2.4 Biomass Yield and Moisture (2011)

An ANOVA of the biomass yields in the fall 2011 harvest found significant differences in Experiment 1 between species. The poplar treatment (7.71 odt/ha/yr) had significantly higher yield than the polyculture treatment (5.14 odt/ha/yr), but the switchgrass treatment (5.42 odt/ha/yr) was not significantly different to either species (Table 3.7).

An ANOVA of the moisture at harvest for the fall, 2011 harvest also found significant differences between species in Experiment 1. In contrast to the data from the previous year, poplar had a significantly lower moisture content (32.9%) at harvest than the polyculture (50.3%) or the switchgrass (47.7%)(Table 3.7).

Experiment 2’s ANOVA for fall 2011 yield showed no significant differences between willow and Miscanthus (Table 3.8). The ANOVA for Experiment 2 showed there were no significant differences between moisture content at harvest between Miscanthus and willow (Table 3.8).
Table 3.7 Results of yields and moisture content of poplar, switchgrass and a polyculture grown in Southern Ontario, Canada in 2011.

<table>
<thead>
<tr>
<th>Species Treatment</th>
<th>Yield (odt/ha/yr)</th>
<th>se</th>
<th>Moisture at Harvest (%)</th>
<th>se</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poplar</td>
<td>7.71 b</td>
<td>0.85</td>
<td>32.9 a</td>
<td>4.3</td>
</tr>
<tr>
<td>Polyculture</td>
<td>5.14 a</td>
<td>0.73</td>
<td>50.3 b</td>
<td>8.6</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>5.42 ab</td>
<td>0.48</td>
<td>47.7 b</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Means in the same column with the same letter are not significantly different according to Tukey's HSD test at p<0.05.

Table 3.8 Results of yields and moisture content of *Miscanthus* and willow grown in Southern Ontario, Canada in 2011.

<table>
<thead>
<tr>
<th>Species Treatment</th>
<th>Yield (odt/ha/yr)</th>
<th>se</th>
<th>Moisture at Harvest (%)</th>
<th>se</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Miscanthus</em></td>
<td>5.96</td>
<td>1.06</td>
<td>45.1</td>
<td>2.7</td>
</tr>
<tr>
<td>Willow</td>
<td>3.21</td>
<td>1.04</td>
<td>48.9</td>
<td>2.5</td>
</tr>
</tbody>
</table>

* Averages are significantly different at p<0.05.

Figure 3.5 Poplar plot in Block 2 nearing complete senescence on September 29, 2011.
3.2.5 Soil Moisture, Temperature and Nitrogen

3.2.5.1 Soil temperature 2010 and 2011

There were no significant block effects during the 2010 growing season. All treatments follow the same general pattern and converge as the growing season ends.

During the 2010 growing season there were no significant differences in soil temperature between species in Experiment 1.

There were no significant differences in soil temperature between treatments in Experiment 2 except in the month of August during the 2010 growing season (Table 3.9). In August soil temperature of willow plots were significantly lower than Miscanthus plots, but there were no other months in 2010 where there were significant differences between these two species.

<table>
<thead>
<tr>
<th>Species</th>
<th>June</th>
<th>se</th>
<th>July</th>
<th>se</th>
<th>August</th>
<th>se</th>
<th>September</th>
<th>se</th>
<th>October</th>
<th>se</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poplar</td>
<td>18.5</td>
<td>0.15</td>
<td>20.8</td>
<td>0.55</td>
<td>20.4</td>
<td>0.54</td>
<td>16.1</td>
<td>0.16</td>
<td>9.7</td>
<td>0.11</td>
</tr>
<tr>
<td>Polyculture</td>
<td>20.0</td>
<td>0.98</td>
<td>21.9</td>
<td>0.49</td>
<td>20.7</td>
<td>0.49</td>
<td>16.2</td>
<td>0.33</td>
<td>10.0</td>
<td>0.17</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>19.3</td>
<td>0.32</td>
<td>22.0</td>
<td>0.05</td>
<td>20.9</td>
<td>0.19</td>
<td>16.3</td>
<td>0.17</td>
<td>10.2</td>
<td>0.14</td>
</tr>
<tr>
<td><strong>Experiment 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miscanthus</td>
<td>19.2</td>
<td>0.25</td>
<td>22.1</td>
<td>0.23</td>
<td>22.1*</td>
<td>0.28</td>
<td>16.7</td>
<td>0.21</td>
<td>9.9</td>
<td>0.19</td>
</tr>
<tr>
<td>Willow</td>
<td>18.8</td>
<td>0.23</td>
<td>22.0</td>
<td>0.11</td>
<td>21.2*</td>
<td>0.12</td>
<td>16.7</td>
<td>0.23</td>
<td>10.4</td>
<td>0.14</td>
</tr>
</tbody>
</table>

* Averages are significantly different at p<0.05.

There were significant differences in species effect on soil temperature between May and August, 2011 in Experiment 1. Poplar had significantly lower soil temperature than switchgrass during all months of the 2011 season, but had significantly lower soil temperature than the polyculture only during May and June 2011 (Table 3.10).
In the 2011 growing season the soil temperature of Miscanthus and willow plots were not significantly different to each other during any month of the 2011 growing season. All species followed the same soil temperature pattern through the 2011 growing season. There were no significant block effects on soil temperature in the 2011 growing season.

Table 3.10 Soil temperature (°C) of plots grown with 5 different bioenergy crops during the 2011 growing season.

<table>
<thead>
<tr>
<th>Species</th>
<th>May</th>
<th>se</th>
<th>June</th>
<th>se</th>
<th>July</th>
<th>se</th>
<th>August</th>
<th>se</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poplar</td>
<td>13.2 a</td>
<td>0.19</td>
<td>16.4 a</td>
<td>0.15</td>
<td>19.9 a</td>
<td>0.29</td>
<td>18.9 a</td>
<td>0.16</td>
</tr>
<tr>
<td>Polyculture</td>
<td>14.2 b</td>
<td>0.22</td>
<td>18.2 b</td>
<td>0.27</td>
<td>21.3 ab</td>
<td>0.73</td>
<td>19.8 ab</td>
<td>0.59</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>14.1 b</td>
<td>0.03</td>
<td>18.5 b</td>
<td>0.09</td>
<td>23.2 b</td>
<td>0.55</td>
<td>21.7 b</td>
<td>0.77</td>
</tr>
<tr>
<td><strong>Experiment 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miscanthus</td>
<td>14.3</td>
<td>0.41</td>
<td>18.4</td>
<td>0.42</td>
<td>22.4</td>
<td>0.61</td>
<td>20.2</td>
<td>0.35</td>
</tr>
<tr>
<td>Willow</td>
<td>14.1</td>
<td>0.18</td>
<td>18.9</td>
<td>0.28</td>
<td>23.5</td>
<td>0.8</td>
<td>21.5</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Means in the same column with the same letter are not significantly different according to Tukey's HSD test at p<0.05.

3.2.5.2 Soil moisture (2011)

In the 2011 growing season there were no significant differences in soil moisture in Experiment 1 between species from May to October except for the months of July and September. During these two months, soil moisture in poplar plots was significantly lower than soil moisture in switchgrass plots, but not significantly lower than the soil moisture of the polyculture.

In Experiment 2 Miscanthus plots had significantly lower soil moisture (13%) than willow plots (15%) during the month of September, but there were no significant differences in soil moisture in any of the other months. (Table 3.11). All species plots followed the same general soil moisture pattern
through the 2011 growing season. There were no significant block effects on soil moisture in the 2011 growing season.

Table 3.11 Soil moisture (%) of plots grown with 5 different bioenergy crops during the 2011 growing season.

<table>
<thead>
<tr>
<th>Species</th>
<th>May</th>
<th>se</th>
<th>June</th>
<th>se</th>
<th>July</th>
<th>se</th>
<th>August</th>
<th>se</th>
<th>September</th>
<th>se</th>
<th>October</th>
<th>se</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poplar</td>
<td>17.8</td>
<td>0.77</td>
<td>17.4</td>
<td>0.51</td>
<td>7.1</td>
<td>a</td>
<td>0.35</td>
<td>7.9</td>
<td>1.37</td>
<td>a</td>
<td>0.58</td>
<td>16.6</td>
</tr>
<tr>
<td>Polyculture</td>
<td>13.2</td>
<td>3.83</td>
<td>14.1</td>
<td>1.52</td>
<td>7.4</td>
<td>ab</td>
<td>0.30</td>
<td>8.4</td>
<td>0.77</td>
<td>ab</td>
<td>0.34</td>
<td>17.8</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>17.0</td>
<td>1.11</td>
<td>15.5</td>
<td>3.55</td>
<td>8.4</td>
<td>b</td>
<td>0.33</td>
<td>8.8</td>
<td>0.77</td>
<td>b</td>
<td>0.46</td>
<td>19.1</td>
</tr>
<tr>
<td><strong>Experiment 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miscanthus</td>
<td>16.8</td>
<td>0.93</td>
<td>14.7</td>
<td>2.36</td>
<td>7.4</td>
<td>0.50</td>
<td>7.8</td>
<td>0.63</td>
<td>13.0</td>
<td>*</td>
<td>0.48</td>
<td>18.3</td>
</tr>
<tr>
<td>Willow</td>
<td>18.8</td>
<td>1.42</td>
<td>14.4</td>
<td>1.72</td>
<td>6.9</td>
<td>0.47</td>
<td>7.9</td>
<td>0.17</td>
<td>15.0</td>
<td>*</td>
<td>0.40</td>
<td>18.7</td>
</tr>
</tbody>
</table>

Means in the same column with the same letter are not significantly different according to Tukey's HSD test at p<0.05.
* Averages are significantly different at p<0.05.

3.2.5.3 Soil Nitrogen (2011)

There was no significant differences between treatments in total soil nitrogen between May and October, 2011 in either Experiment 1 or Experiment 2 (Table 3.12). There were significant block effects during the months of July and August, 2011. Block 2 had significantly less total soil nitrogen than all other blocks during July, and significantly less than block 1 and 4 during August. In the other months there were no significant differences between blocks but numerically block 2 always had the lowest total soil nitrogen among all the blocks (Table 3.13). The general pattern of total soil nitrogen was obscured due to high variability, but the trend is to dip in July and then increase until September then drop in October.
Table 3.12 Total soil nitrogen (%) of plots grown with 5 different bioenergy crops grown during the 2011 growing season.

<table>
<thead>
<tr>
<th>Species</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poplar</td>
<td>17.8</td>
<td>17.4</td>
<td>7.1</td>
<td>7.9</td>
<td>13.7</td>
<td>16.6</td>
</tr>
<tr>
<td>Polyculture</td>
<td>13.2</td>
<td>14.1</td>
<td>7.4</td>
<td>8.4</td>
<td>15.3</td>
<td>17.8</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>17.0</td>
<td>15.5</td>
<td>8.4</td>
<td>8.8</td>
<td>15.9</td>
<td>19.1</td>
</tr>
<tr>
<td>Experiment 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miscanthus</td>
<td>16.8</td>
<td>14.7</td>
<td>7.4</td>
<td>7.8</td>
<td>13.0</td>
<td>18.3</td>
</tr>
<tr>
<td>Willow</td>
<td>18.8</td>
<td>14.4</td>
<td>6.9</td>
<td>7.9</td>
<td>15.0</td>
<td>18.7</td>
</tr>
</tbody>
</table>

There were no significant differences between species.

Table 3.13 Block effect on total soil nitrogen (%) during the 2011 growing season.

<table>
<thead>
<tr>
<th>Block</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block 1</td>
<td>0.073</td>
<td>0.081</td>
<td>0.079 b</td>
<td>0.098 b</td>
<td>0.119</td>
<td>0.070</td>
</tr>
<tr>
<td>Block 2</td>
<td>0.055</td>
<td>0.078</td>
<td>0.037 a</td>
<td>0.053 a</td>
<td>0.090</td>
<td>0.062</td>
</tr>
<tr>
<td>Block 3</td>
<td>0.077</td>
<td>0.087</td>
<td>0.073 b</td>
<td>0.074ab</td>
<td>0.092</td>
<td>0.062</td>
</tr>
<tr>
<td>Block 4</td>
<td>0.084</td>
<td>0.092</td>
<td>0.095 b</td>
<td>0.102 b</td>
<td>0.094</td>
<td>0.089</td>
</tr>
</tbody>
</table>

Means in the same column with the same letter are not significantly different according to Tukey's HSD test at p<0.05.
3.3 Discussion

3.3.1 Emergence and Senescence

The emergence and senescence of a bioenergy species is an important factor in its biomass production. The longer the species is actively growing, the more time it has to accumulate biomass. This study supports that the growing season for these bioenergy species is not the same length. Poplar and willow both began growing earlier in the season than the grass species, and Miscanthus emerged before the switchgrass or the polyculture, which emerged at the same time. An early emergence allows for an earlier start to the growing season but can also make the plant susceptible to late spring frosts which could set back growth if the species is unable to tolerate cold temperatures. All species in this study are perennial bioenergy species which emerge relatively early compared to other proposed annual crops like corn (Dohleman and Long, 2009).

Senescence is also important, because it indicates the end of all possible photosynthetic activity for that season. The longer the species has to accumulate energy the more potential biomass can be obtained each season. Poplar, switchgrass and the polyculture all completed senescence at the start of October, but willow and Miscanthus remained green the longest and continued photosynthesizing until the last week of October. Poplar, switchgrass and the polyculture had a shorter growing season (156 days, 139 days and 139 days respectively) than willow and Miscanthus, which had the longest growing periods in the 2011 season at 181 and 169 days respectively. Miscanthus had begun to lose its lower leaves in mid October, but the top leaves remained green until heavy frosts (-3 °C) stopped its growth. The ability to grow until a heavy frost stops growth provides more opportunity for growth by increasing the length of the growing season for that species, an ability Miscanthus has consistently shown throughout the literature (Dohleman and Long, 2009; Wang et al., 2008). In other studies on the cold tolerance of Miscanthus giganteus, plants have been shown to continue growing until -6 °C, this allows...
plants to survive late spring frosts but also stay green well into the fall as observed in this study (Farrell et al. 2006). Both willow and Miscanthus continued to grow into the fall providing more time to accumulate biomass, which may help them produce more biomass than other species once fully established. More research should be done to pinpoint the length of the growing season of each bioenergy species in southern Ontario, but also what triggers the beginning and end of growth for each species. This would help determine what species were most suited to sites within the region and might help identify what species will survive cooler regions.

3.3.2 Yield and Moisture

In the 2010 growing season variability was high within switchgrass and the polyculture in Experiment 1. Switchgrass and the polyculture had not yet fully colonized the plots, causing less dense locations and even gaps. The poplar grew uniformly during the 2010 growing season. During the 2011 growing season switchgrass and the polyculture continued to colonize the plots and became uniform leaving few gaps. Poplar growth remained uniform within plots during the 2011 growing season.

In Experiment 2 the first year willow growth was variable, some plants greater than 1.5m tall while others were merely 30cm. Given the variability within the willow plots it is likely the number of randomized samples was not enough to capture an accurate representation of the plots. This was unavoidable due to the small plot size and the multiple seasons of growth required in woody species. Taking more plants would have changed the growth conditions and reduced the number of plants left to sample the following year. Miscanthus grew uniformly during the 2010 growing season and variability within plots was not a problem. The coppiced year willow (2011) growth was more uniform than the previous year but there was still variation between the smallest and the largest plants. There were fewer small plants in the willow plots than in the previous year but randomized sampling may have
underestimated willow yield due to continued disparity between largest and smallest plants. *Miscanthus* had uniform growth during the 2011 growing season.

The samples taken in 2010 for Experiment 1 indicated there was no significant differences in yield between poplar, switchgrass or the polyculture (Table 3.4). This supported the null hypothesis and showed that during second season of establishment, yield between these three bioenergy species did not differ. When samples were taken in 2011, poplar was significantly higher than the polyculture but not switchgrass, which were not significantly different from each other (Table 3.7). The increase in annual yield in poplar from the second growing season to the third growing season is due to the mean annual increment (MAI) increases that poplar experiences (Kauter et al. 2003). If harvesting large diameter stems was easier, longer harvest cycles would increase poplar yields significantly, since its MAI reaches a maximum between 4 and 10 years (Kauter et al. 2003). Experiment 1 indicated that poplar yields more than switchgrass or the polyculture, but further research should be done when the site is fully established in order to track the difference between the yield of poplar, switchgrass and the polyculture.

Experiment 2 showed that during the first season of growth *Miscanthus* yielded significantly more than willow (Table 3.5). Willow yields in 2011 are only based on the first season growth due to coppicing after 2010, and would be higher at the end of the cycle than the beginning. Although there was no significant difference between *Miscanthus* and willow, *Miscanthus* was numerically higher and more uniform in its growth than willow (Table 3.8). During the first two establishment years, *Miscanthus* yielded more than willow, although not significantly more in the second year. This would indicate at least for the first two establishment years, *Miscanthus* yields more than willow. This location should be revisited once the site is fully established so that accurate yields based on mature stands be gathered.
In Experiment 1 poplar plots reached 7.71 odt/ha/yr by the end of its third season of growth. This was higher than the average (6.9 odt/ha/yr) first harvest of 16 poplar studies reported across the UK (Aylott et al. 2008). In Southern Quebec poplar yields averaging 17.4 odt/ha/yr have been obtained without fertilizer (Labrecque and Teodorescu, 2005). The poplar in this study do not approach the average yield in Quebec but, this is likely due to poor soil conditions at the GARS combined with the low precipitation during June and July of the 2011 growing season. The precipitation during the 2011 growing season may account for some yield loss, but yields of 17.4 odt/ha/yr at first harvest would not have been obtained at the GARS (Table 3.1). Herbaceous yields in Experiment 1 for the 2010 season should be approaching 70% of the mature stand yield for switchgrass and the polyculture, and nearing 100% for the 2011 yields as described by Engbers (2012). That would suggest the switchgrass and polyculture plots would yield only 4.9 odt/ha and 4.23 respectively once they have become a mature stand based on 2010 yields. This estimate is even less than the 2011 yields collected in this study (5.42 odt/ha and 5.14 odt/ha), however these values are lower than that of the average yields for switchgrass (10 odt/ha) given in Heaton et al. (2004) for mature stands (3 or more years growth). Despite being half of the average yield found in the literature the switchgrass and the polyculture are within the yield range (5-12 odt/ha) of the studies cited in Heaton et al. (2004). It is probable that even after 3 seasons of growth the switchgrass and the polyculture have not attained full yield potential for the site. Yield in these plots should increase as plant density within switchgrass and polyculture plots increases, but also the 2011 season was dry during the months of June and July which may have contributed to its below literature average yield during its third year (Table 3.1). It is also possible that the climate differences between Southern Ontario and Illinois are too dissimilar for comparison. It is also possible that on marginal land with no fertilizer input switchgrass and the polyculture will not reach the average mature yield of 10 odt/ha. Despite a difficult 2011 growing season poplar produced yields comparable to that found in the literature, while switchgrass and the polyculture produced yields that were below the
average yield found in the literature. This indicates the potential for growing all 3 species treatments on marginal land under no fertilization.

In Experiment 2 *Miscanthus* yield should be 30% of mature yields in 2010 and 70% in 2011, but at 0.6 odt/ha and 5.96 odt/ha respectively it does not approach the average seen in the literature (22 odt/ha) (Engbers 2010; Heaton et al. 2004). This 22 odt/ha average includes fertilized and non fertilized management regimes on a variety of sites (97). While helpful this average is possibly higher than the potential yields that could be achieved at the GARS due to some studies with high fertilization and excellent soil conditions. It is likely that the second year *Miscanthus* is not at 70% of its maximum due to slow establishment and poor soil conditions at the GARS. This is not uncommon to poor quality sites or cooler regions where establishment can take 4-5 years (Pyter et al. 2009; Clifton-Brown and Lewandowski 2002). The precipitation during 2011 growing season may have limited the potential yield of *Miscanthus* because there was only 87mm in June and 31.9mm in July and *Miscanthus* yields are sensitive to moisture availability (Table 3.1) (Heaton et al. 2004). Willow first year yields of 0.31 odt/ha/yr were lower, but after coppice yields of 3.21 odt/ha/yr were higher than yields found in Clinch (2008). Clinch (2008) was also conducted at the GARS with first year yields of 0.46 odt/ha/yr and yields after coppice of 1.03 odt/ha/yr. If the willow maintains the biomass accumulation per season (3.21 odt/ha/yr) that it did during the 2011 season, it may have first harvest yields similar to that found in the literature where the average yield of unfertilized SX67 in Quebec was 9.44 odt/ha/yr at the end of the first harvest (Labrecque and Teodorescu 2005). Despite the low precipitation in the 2011 growing season willow produced yields similar to that found in the literature, *Miscanthus* did not reach the average yields seen in the literature, but showed promise as yield increased almost 1000% from its first year to its second year. Had precipitation in June and July been closer to the average, *Miscanthus* may
have been closer to second year growth in the literature. Both species in Experiment 2 should be considered for continued research on biomass production on marginal land.

The difference in yield between the fall and the spring harvests for the herbaceous species did not show any significant differences between harvest dates. It is typical that up to 30-50% of biomass is lost over winter in mature stands of the herbaceous species (Adler et al. 2006). The yield reduction was not observed in this study due to small scale harvesting combined with low leaf loss over the 2010/2011 winter. The lack of leaf drop can indicate improper translocation of nutrients to belowground structures during the fall, which is not uncommon to Miscanthus during its first year of growth (Clifton-Brown and Lewandowski, 2000). This was not observed in the second year of growth, as after the 2011/2012 winter, Miscanthus had dropped almost all of its leaves. In large-scale harvests, with proper equipment, the leaves and lodged plants would be left behind after harvest reducing spring yields by 30-50% as seen in other studies, but due to hand harvesting, all material from each plant was collected.

Moisture content in Experiment 1 during 2010 harvests revealed that poplar had higher moisture than switchgrass and the polyculture (Table 3.4). These grasses further reduced their moisture over the winter, and a spring harvest reduced moisture to extremely low percentages (Table 3.6). This would be ideal for use in boilers as moisture content in biomass reduces its fuel quality and GCV.

In Experiment 2 Miscanthus did not have a significantly different moisture content between fall and spring dates but did have a lower moisture content than willow at fall harvest in 2010. Grasses typically have a lower moisture content at fall harvest than woody species, which may potentially make them cheaper if oven drying is required. However, field drying for both herbaceous and woody species is effective and can reduce moisture content by 50-70% of initial harvest (Adler et al. 2006; Kauter et al. 2003). Fall harvest during 2011 was forced to be close to precipitation events due to time restrictions...
and the high incidence of precipitation events and overcast days. It had rained two days prior to harvest but it was clear when harvesting the material had not completely dried. Moisture content for this season was much higher in the grasses which seemed to absorb or hold moisture in their dead tissue. For this reason it is more useful to use data from 2010 when making comparisons.

3.3.3 Soil Moisture, Temperature and Nitrogen

Soil temperature data revealed that in both 2010 and 2011 poplar plots had the lowest soil temperatures in Experiment 1. This is likely a combination of a shading effect and a transpiration effect the poplar has on the plot. While the switchgrass and the polyculture would also be influencing the plots in the same way, the poplar plots may have provided a denser shade. No species shaded out itself in a way that negatively impacted its yield, but canopy closure and plot colonization was sufficient to prevent weed growth after mid July in all species except willow. This was expected as bioenergy species only require 1-2 years of weed control (Heaton et al. 2004; Kauter et al. 2003). The shade under the 3 year old poplar was dense and prevented all weed growth from the start of the growing season, until senescence. This dense shade likely caused the majority of the cooling effect. Lower soil temperatures slow root growth but also reduces water loss, but despite being cooler the poplar plots did not retain more moisture. This may be due to a higher transpiration rate during the growing season followed by a higher evaporation rate once the poplar lost its leaves in the fall.

In Experiment 1 the soil moisture data did not show significant differences between the species except in the month of September where poplar had lower soil moisture than switchgrass and the polyculture. This may be due to the lower soil temperature in poplar plots or higher soil evaporation rates as poplar had almost to senesced all its leaves by the sampling date (see Figure 3.5) or it may be simply the result of randomized sampling.
In Experiment 2 the soil moisture data did not show significant differences between *Miscanthus* and willow except in the month of September where *Miscanthus* had significantly less soil moisture than willow. The individual month differences between *Miscanthus* and willow could simply be due to randomized sampling or this could be due to higher water use of *Miscanthus* during the month of September. Species in Experiment 2 did not differ during the majority of the growing season and seemed adept at growing without irrigation despite the low precipitation during the months of June and July.

Data on total soil nitrogen revealed that there were no significant differences between species in either Experiment over the 2011 growing season. This suggests species were not benefitting from higher nitrogen levels, giving no one species an advantage in biomass production. While there was not a species effect there was a significant block effect on soil nitrogen. Block 2 consistently had the least amount of total nitrogen among the blocks even though this difference was only significant during July and August. This did not have an effect on the yield as there were no significant differences in yield between blocks. While not statistically significant *Miscanthus* did have the lowest yields in block 2, but no other species showed this effect. This may indicate that *Miscanthus* yields are more sensitive to N than other species despite many studies indicating N fertilization had no effect on *Miscanthus* yields (Christian et al. 2008; Clifton-Brown et al. 2007). The effect of N on *Miscanthus* should more thoroughly be examine on poorer quality sites as it is possible that this is where the most significant effects will be observed. A bioenergy species be able to produce large amounts of biomass in low input systems in order to keep the systems as carbon neutral as possible, but also economical. The more carbon neutral the larger the environmental benefit when replacing coal with biomass.
3.4 Conclusions

During the establishment years poplar seemed to modify its environment by reducing the soil temperatures especially in its third season of growth, but this did not have a significant effect on soil moisture. In general the species had similar effects on the site and no significant differences between species in soil moisture, temperature or nitrogen were observed in 2010 or 2011.

By the end of establishment poplar produced the highest yields in Experiment 1, although not significantly more than switchgrass. In Experiment 2 Miscanthus produced higher yields than willow, although not significantly higher. (Note that spring harvests would reduce Miscanthus yields.) This means that during early establishment poplar and Miscanthus are the best bioenergy species based on fall yields alone. Future research on the site once fully established may show dramatically different results as willow MAI increases, poplar becomes multi stemmed, grasses fully colonize the entire plot and Miscanthus plants continue to expand in size and height.

Fall harvest versus spring harvest in this study did not have a yield effect because harvests were done by hand rather than with machinery and the lack of leaf drop during the 2010/2011 winter. This may have been different if sampled after the 2011 or 2012 winter as leaf drop did occur in Miscanthus, which would have reduced yields.

Moisture content of the plants at harvest would normally be reduced as growers would wait until the material had a chance to dry, but due to time constraints and high precipitation during 2011 this was not possible. Moisture content was reduced in all grasses except Miscanthus when allowed to overwinter during 2010. If moisture contents of 1-2% as seen in the first year of this study could be achieved in mature stands of switchgrass and the polyculture just by overwintering, this would be very appealing for use in boilers because moisture content reduces fuel quality and energy output.
Based on growing season length *Miscanthus* and willow may have an advantage over other bioenergy species in southern Ontario. *Miscanthus* was clearly superior to the other herbaceous species in terms of emergence and senescence, and while willow and poplar emerged at the same time, willow continued to grow for a month past poplar. *Miscanthus* may have had the longest growing season because it was green until heavy frosts below -3°C killed the leaves. More research needs to be done to identify what the growing season is for each bioenergy species and what triggers their emergence and senescence in order to accurately predict their use in other regions of Ontario.
CHAPTER 4

FUEL CHARACTERISTICS OF BIOMASS FEEDSTOCKS

4.1 Materials And Methods

Fuel characteristic subsamples were taken from the top 3 yielding plots of each species treatment from the fall 2010 harvest and fall 2011 harvest. The samples were taken from the already obtained yield samples. The samples were ground using a mill and homogenized to 2cm mesh. A 50g subsample was then packaged and sent to CENNATEK in Sarnia, Ontario for analysis. CENNATEK provided 5 different analyses for fuel characteristics: Gross calorific values (GCV), ash (%), sulphur (%), chlorine (%), and elemental ash analysis. All analyses were done using standard procedures. Ash % was done using the American Society for Testing and Materials (ASTM) standard E1755, a dry combustion method expressed as mass percent of the residue. Sulphur % was done following standard ASTM D4239, a method using high-temperature tube furnace combustion. Chlorine was done using ASTM D4208, a method to determine total chlorine by oxygen bomb combustion and an ion selective electrode. Elemental ash analysis was done using ASTM D6349, a method for determining major and minor elements by X-ray fluorescence. The GCV analysis was done using ASTM E711, a method for determining GCV using a bomb calorimeter.

Statistical analysis was done using IBM® SPSS® Statistics 19 (SPSS Inc., Chicago IL). Fuel characteristics for Experiment 1 were statistically analyzed with ANOVAs and Tukeys HSD test to determine if there were significant differences between species for each element. Differences between willow and Miscanthus fuel characteristics were identified using ANOVAs of each element. A Type 1 error rate of p<0.05 was used for all analyses. Levene's test for homogeneity of variance was done to determine that all analyses met the assumption of equal variance.
4.2 Results

4.2.1 Energy Output

The results (Table 4.1) on second year growth for Experiment 1 indicate that there was a difference between GCV of woody and herbaceous species as poplar (20.24 MJ/kg) was significantly higher than switchgrass (19.39 MJ/kg) and the polyculture (19.26 MJ/kg) which were not significantly different from each other.

Experiment 2 indicated that willow (20.56 MJ/kg) had a significantly higher GCV than Miscanthus (19.81 MJ/kg). The results support the literature and in both Experiments show that in terms of GCV woody biomass is preferable to herbaceous material.

Table 4.1 Lab results for the 2010 establishment phase gross calorific values for four species and a polyculture. Potential energy (MJ) per hectare and MWh calculated based on 2011 yields.

<table>
<thead>
<tr>
<th>Species</th>
<th>Mean (MJ/kg)</th>
<th>se</th>
<th>Mean (MJ/ha)</th>
<th>Mean MWh/ha**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poplar</td>
<td>20.24 a</td>
<td>0.02</td>
<td>156050.4</td>
<td>43.35</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>19.39 b</td>
<td>0.07</td>
<td>105093.8</td>
<td>29.19</td>
</tr>
<tr>
<td>Polyculture</td>
<td>19.26 b</td>
<td>0.09</td>
<td>98996.4</td>
<td>27.50</td>
</tr>
<tr>
<td>Experiment 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Willow</td>
<td>20.56 *</td>
<td>0.1</td>
<td>65997.6</td>
<td>18.33</td>
</tr>
<tr>
<td>Miscanthus</td>
<td>19.81 *</td>
<td>0.19</td>
<td>118067.6</td>
<td>32.80</td>
</tr>
</tbody>
</table>

Means in the same column with the same letter are not significantly different according to Tukey's HSD test at p<0.05.
* Averages are significantly different at p<0.05.
**1 MWh = 3600 MJ
4.2.2 Ash and Elemental Analysis Fall 2010

The fuel components for the second year growth of the 2 species and the polyculture in Experiment 1, as well as the fuel components of the first year growth in Experiment 2, are given in Table 4.2 and Table 4.3.

In Experiment 1 poplar had significantly lower ash (1.86%) than the switchgrass (7.01%) and the polyculture (6.00%) which were not significantly different from each other. Switchgrass (0.097%) had a significantly higher chlorine content than poplar (0.028%) and the polyculture (.028%) which were not significantly different to each other.

In Experiment 2 willow (3.92%) had a significantly lower ash content than Miscanthus (5%). In Experiment 2 chlorine concentration in Miscanthus (0.09%) was significantly higher than willow (0.02%).

As expected sulphur in all biomass species was low compared to that of coal and is therefore not an issue in its combustion, but rather a benefit. While switchgrass and Miscanthus did have high chlorine concentrations, in the 2010 growing season, both species were still below the recommended limits (0.1%) for chlorine and therefore would probably not represent a problem during combustion (Monti et al. 2008).
Table 4.2 Lab results for clinkering, slagging, or fouling components in 5 species treatments of biomass 2010.

<table>
<thead>
<tr>
<th>Species</th>
<th>Ash (%DW)</th>
<th>S (%DW)</th>
<th>Cl (%DW)</th>
<th>SiO$_2$ (%Ash)</th>
<th>K$_2$O (%Ash)</th>
<th>Na$_2$O (%Ash)</th>
<th>CaO (%Ash)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poplar</td>
<td>1.86 a</td>
<td>0.027 a</td>
<td>0.028 a</td>
<td>0.47 a</td>
<td>18.45 b</td>
<td>0.023 a</td>
<td>53.8 b</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>7.01 b</td>
<td>0.030 a</td>
<td>0.097 b</td>
<td>80.20 c</td>
<td>2.80 a</td>
<td>0.010 a</td>
<td>10.1 a</td>
</tr>
<tr>
<td>Polyculture</td>
<td>6.00 b</td>
<td>0.016 a</td>
<td>0.028 a</td>
<td>78.24 b</td>
<td>3.46 a</td>
<td>0.010 a</td>
<td>11.1 a</td>
</tr>
<tr>
<td><strong>Experiment 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Willow</td>
<td>3.92 *</td>
<td>0.036 *</td>
<td>0.034</td>
<td>0.34 *</td>
<td>14.20 *</td>
<td>0.160</td>
<td>65.2 *</td>
</tr>
<tr>
<td>Miscanthus</td>
<td>5.00 *</td>
<td>0.045 *</td>
<td>0.085</td>
<td>64.81 *</td>
<td>6.29 *</td>
<td>0.163</td>
<td>14.0 *</td>
</tr>
</tbody>
</table>

Means in the same column with the same letter are not significantly different according to Tukey’s HSD test at p<0.05.

* Averages are significantly different at p<0.05.

Table 4.3 Lab results for ash components of other potential causes for clinkering, slagging, or fouling of 5 species treatments of biomass (% ash) 2010.

<table>
<thead>
<tr>
<th>Species</th>
<th>MgO</th>
<th>P$_2$O$_5$</th>
<th>Al$_2$O$_3$</th>
<th>MnO</th>
<th>Cr$_2$O$_3$</th>
<th>TiO$_2$</th>
<th>Fe$_2$O$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poplar</td>
<td>11.85 b</td>
<td>15.00 b</td>
<td>0.230 a</td>
<td>0.073 a</td>
<td>0.013 a</td>
<td>0.010 a</td>
<td>0.14 a</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>4.40 a</td>
<td>2.03 a</td>
<td>0.287 a</td>
<td>0.053 a</td>
<td>0.010 a</td>
<td>0.013 ab</td>
<td>0.19 a</td>
</tr>
<tr>
<td>Polyculture</td>
<td>4.14 a</td>
<td>2.24 a</td>
<td>0.440 b</td>
<td>0.147 b</td>
<td>0.017 a</td>
<td>0.020 b</td>
<td>0.29 b</td>
</tr>
<tr>
<td><strong>Experiment 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Willow</td>
<td>7.64 *</td>
<td>11.73 *</td>
<td>0.317 *</td>
<td>0.117 *</td>
<td>0.020 *</td>
<td>0.01 *</td>
<td>0.24 *</td>
</tr>
<tr>
<td>Miscanthus</td>
<td>6.62 *</td>
<td>6.05 *</td>
<td>0.967 *</td>
<td>0.287 *</td>
<td>0.033 *</td>
<td>0.06 *</td>
<td>0.71 *</td>
</tr>
</tbody>
</table>

Means in the same column with the same letter are not significantly different according to Tukey’s HSD test at p<0.05.

* Averages are significantly different at p<0.05.
There were very large differences in the main components of the remaining ash. Silicon was the primary constituent of the ash in the switchgrass (80.2%) and the polyculture (78.24%) while SiO$_2$ made up a very small portion of the poplar ash (.47%). This also held true in Experiment 2 between willow and Miscanthus where 64% of the ash in Miscanthus was SiO$_2$ but SiO$_2$ was only 0.34% of the ash in willow. The primary component in woody ash seems to be CaO as both Experiment 1 and 2 showed the woody species as having significantly higher CaO percentages. Almost 54% of poplars ash was composed of CaO while switchgrass and the polyculture had much lower percentages, 10.1% and 11.1% respectively. The same was seen in Experiment 2 where 65% of the willow ash was CaO, significantly higher than that of Miscanthus, only 14%. Potassium was another prime component in the ash of the woody species. Poplar (18.45%) had significantly higher K$_2$O than switchgrass (2.8%) or the polyculture (3.46%) which were not significantly different to each other. The difference was less dramatic between the woody and herbaceous species in Experiment 2. Willow ash composed of 14.2% K$_2$O, significantly higher than Miscanthus (6.29%). The other alkali earth metal sodium, was not significantly different between the two species and the polyculture in Experiment 1 or between Miscanthus and willow in Experiment 2. Phosphorus was also represented more in woody species for both Experiments. Poplar had 15% P$_2$O$_5$ which was significantly more than switchgrass (2.03%) and the polyculture (2.24%) which were not significantly different to each other. In Experiment 2, willow (11.73%) had significantly more P$_2$O$_5$ than Miscanthus (6.05%). Magnesium also was a large portion of the remaining ash. In Experiment 1 poplar(11.85%) has significantly more MgO than switchgrass (4.4%) or the polyculture (4.14%) which were not significantly different from each other. In Experiment 2, willow (7.64%) had significantly more MgO than Miscanthus (6.62%), but the difference between the woody species and the herbaceous was less pronounced.
4.2.3 Ash and Elemental Analysis Fall 2011

Fuel characteristics for third year growth (Experiment 1) and second year growth (Experiment 2) in the four species in the polyculture were collected in fall 2011 (see Table 4.4 and Table 4.5). The amount of ash found in poplar (2.44%) was significantly lower than switchgrass (4.95%) or the polyculture (4.36%) which were not significantly different from each other. In Experiment 2 willow and Miscanthus did not have significantly different ash percentages in 2011. In 2011 there were no significant differences between the concentration of chlorine in poplar, switchgrass and the polyculture, but in Experiment 2 Miscanthus still had significantly higher Cl than willow, but all the treatments were below the recommended limits.
Table 4.4 Lab results for clinkering, slagging, or fouling components in 5 species treatments of biomass 2011.

<table>
<thead>
<tr>
<th>Species</th>
<th>Ash (%DW)</th>
<th>S (%DW)</th>
<th>Cl (%DW)</th>
<th>SiO$_2$ (%Ash)</th>
<th>K$_2$O (%Ash)</th>
<th>Na$_2$O (%Ash)</th>
<th>CaO (%Ash)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poplar</td>
<td>2.44 a</td>
<td>0.085 a</td>
<td>0.044 a</td>
<td>3.17 a</td>
<td>16.06 b</td>
<td>0.71 a</td>
<td>57.15 b</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>4.95 b</td>
<td>0.049 a</td>
<td>0.036 a</td>
<td>69.51 b</td>
<td>5.69 a</td>
<td>0.59 a</td>
<td>14.21 a</td>
</tr>
<tr>
<td>Polyculture</td>
<td>4.36 b</td>
<td>0.037 a</td>
<td>0.022 a</td>
<td>70.58 b</td>
<td>5.09 a</td>
<td>0.39 a</td>
<td>14.59 a</td>
</tr>
<tr>
<td><strong>Experiment 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Willow</td>
<td>2.58</td>
<td>0.067</td>
<td>0.002</td>
<td>0.87</td>
<td>15.49</td>
<td>0.5</td>
<td>63.48</td>
</tr>
<tr>
<td>Miscanthus</td>
<td>2.11</td>
<td>0.056</td>
<td>0.055</td>
<td>52.99</td>
<td>11.13</td>
<td>0.97</td>
<td>18.03</td>
</tr>
</tbody>
</table>

Means in the same column with the same letter are not significantly different according to Tukey's HSD test at p<0.05.
* Averages are significantly different at p<0.05.

Table 4.5 Lab Results for ash components of other potential causes for clinkering, slagging, or fouling of 5 species treatments of biomass 2011.

<table>
<thead>
<tr>
<th>Species</th>
<th>MgO</th>
<th>P$_2$O$_5$</th>
<th>Al$_2$O$_3$</th>
<th>MnO</th>
<th>Cr$_2$O$_3$</th>
<th>TiO$_2$</th>
<th>Fe$_2$O$_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poplar</td>
<td>10.35 b</td>
<td>11.67 b</td>
<td>0.07 a</td>
<td>0.09 a</td>
<td>0.01 a</td>
<td>0.01 a</td>
<td>0.25 a</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>6.35 a</td>
<td>2.62 a</td>
<td>0.03 a</td>
<td>0.13 ab</td>
<td>0.01 a</td>
<td>0.02 ab</td>
<td>0.31 ab</td>
</tr>
<tr>
<td>Polyculture</td>
<td>5.36 a</td>
<td>2.72 a</td>
<td>0.15 a</td>
<td>0.2 b</td>
<td>0.02 a</td>
<td>0.03 b</td>
<td>0.39 b</td>
</tr>
<tr>
<td><strong>Experiment 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Willow</td>
<td>7.87 *</td>
<td>11.24 *</td>
<td>0.01 *</td>
<td>0.12 *</td>
<td>0.05</td>
<td>0.01 *</td>
<td>0.23 *</td>
</tr>
<tr>
<td>Miscanthus</td>
<td>6.88 *</td>
<td>7.39 *</td>
<td>0.56 *</td>
<td>0.56 *</td>
<td>0.1</td>
<td>0.06 *</td>
<td>0.76 *</td>
</tr>
</tbody>
</table>

Means in the same column with the same letter are not significantly different according to Tukey's HSD test at p<0.05.
* Averages are significantly different at p<0.05.
There were differences in the main components of the ash in the 2011 harvest. Silicon remains the dominant component in the grasses of Experiment 1 and 2. Both switchgrass (69.51%) and the polyculture (70.58%) had significantly higher SiO$_2$ in the remaining ash than poplar (3.17%). In Experiment 2 Miscanthus ash composed of 53% SiO$_2$ which was significantly higher than willow ash (0.87%). Calcium remained the primary constituent of woody ash in both Experiments. Poplar ash was composed of 57.15% CaO, significantly higher than that of switchgrass (14.21%) and the polyculture (14.59%) which were not significantly different to each other. Willow ash also had high CaO at 63.48%, while Miscanthus had significantly less at 18%. Potassium was significantly higher in poplar (16.06%) than in switchgrass (5.69%) or the polyculture (5.09%) which were not significantly different from each other. Experiment 2 showed similar results though the difference between the wood species and herbaceous species was much less. Willow ash composed of 15.49% K$_2$O significantly higher than Miscanthus ash (11.13%). Sodium in 2011 also did not show any significant differences between species treatments in Experiment 1 or Experiment 2. Poplar ash (11.69%) also had significantly more P$_2$O$_5$ than switchgrass (2.62%) or the polyculture (2.72%) which were not significantly different from each other. Experiment 2 also showed the woody species, willow (11.24%), as having significantly more P$_2$O$_5$ than the herbaceous species, Miscanthus (7.39%). Magnesium was also a large component in the ash of the biomass species. Poplar (10.35%) had significantly more MgO than switchgrass (6.35%) or the polyculture (5.36%) in Experiment 1 and willow (7.87%) had significantly more MgO than Miscanthus (6.88%) in Experiment 2. Other ash components that were not as abundant can be found in Table 4.5.

4.2.5 Changes in Ash Characteristics of Grasses Between Harvest Times

For the 2010 growing season grass samples were harvested in the fall and spring to determine if fuel characteristics would improve (Table 4.6). Ash content was significantly lower when harvested in the spring with Miscanthus (3.37% compared to 5.00%), but was not significantly different in either
switchgrass or the polyculture. This indicates *Miscanthus* fuel characteristics changed over winter, and despite no significant differences in the other grasses, they changed as well. There were no significant differences in sulphur content for any of the grass species treatments, but since levels of sulphur were already low a further reduction is not important. The reduction in chlorine was not significantly different between harvest dates for any of the grasses. While the concentration of these two elements within the tissues of the grasses did not change, the elemental composition of the ash did have significant differences between harvest dates.
Table 4.6 Comparison of lab results from the fall 2010 harvest and the spring 2011 harvest of Miscanthus, switchgrass and the polyculture.

<table>
<thead>
<tr>
<th></th>
<th>Fall Miscanthus</th>
<th>Spring Miscanthus</th>
<th>Fall Polyculture</th>
<th>Spring Polyculture</th>
<th>Fall Switchgrass</th>
<th>Spring Switchgrass</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Dry Weight</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash</td>
<td>5</td>
<td>3.37</td>
<td>6</td>
<td>6.91</td>
<td>7.01</td>
<td>6.31</td>
</tr>
<tr>
<td>Sulphur</td>
<td>0.045</td>
<td>0.039</td>
<td>0.016</td>
<td>0.021</td>
<td>0.030</td>
<td>0.027</td>
</tr>
<tr>
<td>Chlorine</td>
<td>0.075</td>
<td>0.074</td>
<td>0.028</td>
<td>0.035</td>
<td>0.097</td>
<td>0.107</td>
</tr>
<tr>
<td>% Ash Basis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td>64.81</td>
<td>70.91</td>
<td>78.24</td>
<td>82.68</td>
<td>80.2</td>
<td>83.91</td>
</tr>
<tr>
<td>CaO</td>
<td>14.02</td>
<td>11.66</td>
<td>11.05</td>
<td>9.80</td>
<td>10.08</td>
<td>10.11</td>
</tr>
<tr>
<td>K₂O</td>
<td>6.29</td>
<td>4.39</td>
<td>3.46</td>
<td>1.33</td>
<td>2.80</td>
<td>1.02</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>6.05</td>
<td>4.35</td>
<td>2.24</td>
<td>1.49</td>
<td>2.03</td>
<td>1.41</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.16</td>
<td>0.37</td>
<td>&lt;0.01</td>
<td>0.04</td>
<td>&lt; 0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>0.97</td>
<td>2.00</td>
<td>0.44</td>
<td>1.58</td>
<td>0.29</td>
<td>1.02</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.71</td>
<td>1.27</td>
<td>0.29</td>
<td>0.92</td>
<td>0.19</td>
<td>0.58</td>
</tr>
<tr>
<td>MgO</td>
<td>6.62</td>
<td>4.66</td>
<td>4.14</td>
<td>1.90</td>
<td>4.40</td>
<td>1.83</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.06</td>
<td>0.13</td>
<td>0.02</td>
<td>0.11</td>
<td>0.01</td>
<td>0.06</td>
</tr>
<tr>
<td>Cr₂O₅</td>
<td>0.03</td>
<td>0.05</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Mn</td>
<td>0.29</td>
<td>0.21</td>
<td>0.15</td>
<td>0.13</td>
<td>0.05</td>
<td>0.06</td>
</tr>
</tbody>
</table>
The composition of the ash from fall 2010 to spring 2011 changed in several important ways. The percentage of SiO$_2$ in the ash increased for all grass species from fall to spring harvest. *Miscanthus* showed the largest increase, from 64.8% to 70.9% over the winter. This indicates silicon is not leached out or lost over the winter. Calcium was significantly lower in *Miscanthus* and the polyculture during the spring harvest but was not significantly different in switchgrass. This indicates that calcium was lost over winter and this improves the fuel quality. Potassium showed the largest reductions in all grasses between 31%-64%, and unlike chlorine. The decrease in potassium is also beneficial when considering grasses as potential fuels. There was also a significant reduction of P$_2$O$_5$ found in the ash of *Miscanthus* and the polyculture but not in switchgrass. Spring harvested *Miscanthus* was significantly higher in Na$_2$O than in the fall but there was no significant difference in Na$_2$O in the ash of switchgrass or the polyculture. Magnesium showed a significant decrease in the spring harvest of all grasses, while other metals like aluminum and iron showed significant increases in the spring harvest of all grasses.

4.3 Discussion

4.3.1 Energy Output.

These results obtained in this study are supported by the literature, but usually the reported GCVs are slightly lower for all species (18.22 MJ/kg for switchgrass and 19-20 MJ/kg for willow and poplar) (Lemus et al. 2008; Jenkins et al. 1998). The GCV obtained in this study seem to be elevated by about 1 MJ/kg. This elevation could be the result of sampling from establishing stands that have not yet reached maturity. The literature shows that the characteristics of a fuel will change over time as a plant establishes (Lewandowski and Kicherer 1997). While the results were slightly above reported results both Experiments show that in terms of GCV woody biomass is preferable to herbaceous material. The
GCV of a biomass species is important when considering it for commercial use. In biomass production, high yields are all important, but a high GCV can increase the value of each metric ton produced. In Experiment 1 poplar had a GCV of 20.24 MJ/kg while the polyculture had a GCV of 19.26 MJ/kg. In order to provide the same amount of energy when burned, the polyculture would need to supply 4.8% more biomass to the boiler than poplar. The larger the difference between the GCVs, the more the species with the lower GCV must yield in order to compete. This study found that biomass from woody species like willow and poplar had higher GCV and would make a better fuel based on this category, than herbaceous grasses like switchgrass, Miscanthus and the polyculture. If GCV is factored into the quality and price of biomass pellets, then having a higher GCV would be an asset.

4.3.2 Ash and Elemental Analyses 2010/2011

These compounds when combusted interact in a complex array of ways. Attempts to estimate boiler slagging, clinkering and fouling of a biomass fuel using indices using only a couple of these elements is unreliable in terms of how the fuel will actually perform (Magasiner et al. 2001; Jenkins et al. 1998). For this reason this study has presented the ash composition data by compound and element as in other studies (Adler et al. 2006; Demirbas 2004; Lewandowski and Kicherer 1997; Lemus et al. 2008) so that the data can be used in future studies. See Appendix B for analysis of data using indices.

Having significant ash content is a negative attribute for a bioenergy crop to have because it reduces the GCV and can create hard deposits inside the boilers (Jenkins et al. 1998). In 2010 woody species produced significantly lower ash than herbaceous species in Experiment 1 and 2. Based on 2010 results alone, the woody species, poplar and willow, would be the best candidates for bioenergy based on the relatively low amounts of ash they produced when compared to the grasses in each Experiment. This did not continue to hold true for all herbaceous species in 2011. Poplar still had significantly less ash than switchgrass or the polyculture, but in Experiment 2, willow and Miscanthus did not have
significantly different ash concentrations. As the site continues to establish the ash values may continue to change, but in 2011, poplar would make the best candidate for a bioenergy crop based on ash percentages in Experiment 1 and both willow and Miscanthus would be equally good candidates for a bioenergy crop in Experiment 2. The reduction in ash percentages observed in the grasses, especially Miscanthus, is due to the increased proportion of canes to leaves compared to the previous year. It should also be noted that willow was harvested as 1 year old shoots in both 2010 and 2011 due to coppicing, and therefore the bark to wood ratio was much higher than it would be during a 3 year harvest cycle. Since the bark fraction produces more ash (and has higher elemental concentrations) than the wood fraction, the ash percentage of the willow in this study would be higher than in an actual harvest (Tharakan et al. 2003). The relatively low ash content of poplar (2.4%), willow (2.6%) and Miscanthus (2.11%) are low enough to be suitable for use in boilers, but the elemental composition of the ash plays an even more important role in determining a good bioenergy feedstock (Magasiner et al. 2001).

Sulphur is low in bioenergy crops and no significant differences were found between species treatments in either Experiment. The low sulphur in all the biomass species means that switching or cofiring with biomass would reduce the SO$_2$ emissions into the atmosphere; a pollutant known to cause acid precipitation and reductions in air quality (Monti et al. 2008). In addition biomass would not produce as much SO$_2$ as coal which can cause fouling when it contacts heating surfaces (Magasiner et al. 2001). When comparing sulphur to coal all biomass species in both Experiments would be good candidates for firing or cofiring for heat and electricity.

Chlorine poses more of a problem for biomass species, because unlike coal which has small amounts of chlorine, herbaceous grasses can have relatively large amounts (Magasiner et al. 2001). In 2010 switchgrass had a significantly higher chlorine concentration in its tissues than either poplar or the
polyculture. The average level of chlorine in switchgrass (0.097%) for that year was barely below the recommended limit (0.1%) for current boilers (Monti et al. 2008). In Experiment 2, the chlorine concentration of *Miscanthus* (0.09%) was also significantly higher than that of willow, and was nearing the recommended limit, its tissues containing an average of 0.087% Cl. This may make the woody species and the polyculture more suitable for combustion (based on the 2010 harvest) because chlorine can be so harmful. Chlorine represents a problem because it is leads to the production of hydrochloric acid and dioxin which cause corrosion in the boiler and environmental harm (Lewandowski and Kicherer 1997). It can cause further corrosion when in the presence of potassium (an element common in biomass) because it forms KCl which corrodes heating surfaces within the boiler (Lewandowski and Kicherer 1997). Finally chlorine can also increase ash formation and deposits by facilitating the movement of other elements to the surfaces of the boiler (Monti et al. 2008). In 2011, the chlorine concentration in both switchgrass and *Miscanthus* decreased well below the recommended limit (0.1%), but *Miscanthus* chlorine concentration (0.055%) remained significantly higher than willow chlorine concentration (0.002%) (Monti et al. 2008). It is important that biomass maintain a low chlorine concentration within its tissues because of the negative impacts the element can have on a boiler's function. It has been shown that reducing chlorine concentration for grasses can be achieved by performing a spring harvest instead of a fall harvest (Lewandowski and Heinz 2003). Despite what other authors have found, all species in this study were all below the recommended limits for chlorine even when fall harvested. This would suggest all species could be used within current boilers, though willow had the lowest chlorine concentration.

Silicon is normally found in coal ash around 50%, but the silicon in coal ash maintains a high melting point because coal does not have much potassium, calcium or phosphorus (Magasiner et al. 2001; Monti et al. 2008). Potassium, calcium and phosphorus are all responsible for lowering the
melting point of silicon and therefore SiO$_2$ in the ash of biomass species (which are relatively high in potassium and calcium) causes problems. When silicon has its melting point reduced, it increases the amount of slagging that occurs, and the deposits that form are extremely hard and glasslike (Miles et al. 1996; Jenkins et al. 1998). Woody species like poplar and willow had very low SiO$_2$ in the remaining ash, in both 2010 and 2011, while the herbaceous species all had SiO$_2$ percentages above that of coal in 2010 and 2011. The SiO$_2$ percentage in the ash of all the herbaceous species did drop from 2010 to 2011 by approximately 10% in all cases. This indicates that increased establishment time may have had a positive effect on the silicon concentration in the tissues of the grasses. Despite the reduction the concentration of silicon in the grasses remained above coal. Due to the way that silicon acts in the presence of elements common to biomass, poplar and willow may make better candidates for bioenergy crops based on silicon content.

Potassium and calcium are both a main component in biomass ash, and along with silicon, are the primary elements in the deposits found in boilers after burning biomass (Miles et al. 2006). Poplar and willow were both higher in potassium and calcium than the grasses during 2010 and 2011. Switchgrass and the polyculture had the lowest values for both K$_2$O and CaO and if not for the interaction with Si would be clearly more preferable as a bioenergy crop to poplar. Miscanthus had K$_2$O and CaO values higher than the other grasses, especially K$_2$O, which was close to that of poplar and willow. Poplar and willow ash had calcium values of approximately 60% and potassium values between 15-16%. These values are much higher than coal ash which only has 5% CaO and less than 1% K$_2$O (Magasiner et al. 2001). Potassium is very problematic because it is very reactive with other elements and causes deposits to be much harder than those composed of Ca (Jenkins et al. 1998). Based on amount of K$_2$O and CaO, switchgrass and the polyculture would be better candidates than poplar as a bioenergy crop and Miscanthus would be a better candidate than willow for the same reason.
Phosphorus is another element during combustion that also has the potential to reduce the melting point of silicon (Monti et al. 2008). It also represents nutrients that are removed from the growing site as P is a primary plant nutrient. The more P that is removed from the site the more P fertilizer will need to be added to the site to make sure the soil is not depleted of this crucial nutrient. This increases costs to the grower while reducing the fuel quality. Since the herbaceous grasses ash in this study contained less $P_2O_5$ than willow or poplar, switchgrass, the polyculture and Miscanthus would be better bioenergy crops when considering phosphorus.

4.3.3 Changes in Ash Characteristics of Grasses Between Harvest Times

Harvest date for grasses is very important because it can alter the fuel characteristics significantly, in most cases spring harvest being most desirable (Lewandowski and Heinz 2003; Adler et al. 2006). Decreases in elements in the ash composition represent the loss of those elements over winter, and increases show that the elements are not lost or leached out over winter, and proportions therefore increase as the result of losing elements that are leached out. One of the significant elements for the combustion of grasses, chlorine, is often cited as reducing quite significantly over winter (Adler et al. 2006). This was not observed in this study as none of the grass species showed reductions in chlorine between harvest dates. Without chlorine reductions switchgrass and Miscanthus were close to the recommended limit of 0.1% for current boilers, and some switchgrass samples actually exceeded the chlorine limit (Monti et al. 2008). If chlorine is not reduced through spring harvesting this could be a barrier to the use of grasses as a bioenergy feedstock.

While the proportions of different elements in the ash changed, the most important ones to mention are the K$_2$O, CaO, and P$_2$O$_5$. The reductions in K$_2$O, CaO and P$_2$O$_5$ all represent a reduction in the amount of elements, which reduce the melting point of SiO$_2$ (Monti et al. 2008). This reduces the
probability of the ash melting or sticking to the boiler surfaces and also reduces the amount of deposits formed. The reduction of $P_2O_5$ also means that more plant nutrients are staying on the site and less fertilization is needed. It is important that fall and spring harvests be compared once the site is fully established to more accurately describe the changes to fuel characteristics.

4.4 Conclusions

It is difficult to predict the complex interactions that occur during combustion so instead this study has chosen to evaluate fuel characteristic separately and rate each species treatment in terms of each individual characteristic. While useful in determining which species has higher values of potentially undesirable components it does not effectively capture how a species treatment will perform when combusted in a boiler. The following are the conclusions based on individual fuel characteristics of each biomass species used in this study and how they each may impact combustion in conventional boilers.

Poplar and willow had higher GCVs indicating they have a higher energy value per unit mass, which would make them preferable to switchgrass, Miscanthus and the polyculture. The low ash content of poplar, willow and Miscanthus make these species more suited to being used in combustion of current boilers. The relatively high chlorine concentration in the tissues of switchgrass, and Miscanthus make these species also less suited than poplar and willow for use as a biomass fuel source. The sulphur in biomass species is low and makes them all cleaner fuels than coal and suitable for combustion. The ash composition between woody and herbaceous species varied significantly, each having advantages and disadvantages when compared to the other. Herbaceous species have very high $SiO_2$ in the remaining ash, which may increase the incidence of very hard glasslike deposits, while woody species have higher $K_2O$ and $CaO$ which may contribute to forming deposits and react with other elements within the ash. The woody species also remove a larger amount of phosphorus from the site, meaning P
will become depleted from the site more quickly than in the grasses, and will have to be added to the site more frequently. The results do not clearly indicate that any particular species in the early establishment years is a poor candidate for bioenergy production. The fuel characteristics of the species should be evaluated again once the species have all matured and the results are more indicative of a commercial harvest.
CHAPTER 5

5.0 DISCUSSION

Switching to a more carbon neutral energy source like biomass requires careful thought and planning, including which species will produce the highest yields on the desired land class and which species have suitable thermo-chemical properties to undergo combustion in current boilers. Currently, species or hybrids of poplar, willow, Miscanthus, and switchgrass have been nominated as potential bioenergy feedstocks for southern Ontario. In an effort to keep the energy source as carbon neutral as possible, minimizing inputs like nitrogen fertilizers to the bioenergy crops is very important. Marginal or abandoned farmland would be most appropriate for bioenergy crops since it could create additional income for farmers and potentially rehabilitate the land, all the while not competing with increasing food production demands. For a bioenergy crop to be truly successful economically and environmentally, it should require minimal inputs, be able to grow on existing marginal land, be high yielding, and have suitable fuel characteristics.

This study investigated the yield of poplar, willow, Miscanthus, switchgrass and a native polyculture on marginal land in southern Ontario, without the use of fertilizer or irrigation. In order to help further understand which potential bioenergy crops would be suited for heat and electricity production, analysis of GCV, ash (%), sulphur (%), chlorine (%), and elemental ash analysis was done on each potential crop to determine its fuel characteristics. Data from 2 establishment years was collected on each species, but once all species are fully established, future studies will more accurately evaluate the potential feedstock’s efficacy as a bioenergy fuel.

In chapter 3, Hypothesis 1 and objectives 1 and 2 were investigated using observational and field gathered data on yield and soil measurements. The field setup was designed to identify yield
The first objective was to determine if there were significant differences in the biomass yields between different biomass species grown on the same site. Using the 2010 yield data there were no significant differences in yield in Experiment 1 between poplar, switchgrass or the polyculture, thus supporting the null hypothesis. A further season of growth and establishment (2011 data) revealed that poplar was significantly higher yielding than the polyculture, but not significantly higher than switchgrass, and the two grasses were not significantly different from one another. The increase in biomass per year for poplar was much higher than the increase in biomass per year for the switchgrass or the polyculture. This refutes the null hypothesis and indicates that during establishment poplar produces higher yields on marginal land than the polyculture and if this trend continues poplar will yield more than both grasses once fully established. Using the Experiment 2 yield data for 2010, Miscanthus has a higher yield than willow, refuting the null hypothesis. Using the 2011 yield data, willow ‘catches up’ to Miscanthus and produces yields that are not significantly different, which supports the null hypothesis. Ultimately, the closer to maturity and full establishment the plots, the more indicative of the actual yields a species would produce; Therefore, the 2011 data supports the null hypothesis except in the case of the polyculture, which produced significantly less biomass than poplar. Future work on this site will more accurately support or refute hypothesis 1 once species treatments are all fully established.

The second objective was to determine if microclimate impacted the biomass yields of the four species and the polyculture. There were few differences in temperature and moisture between species treatments. The most notable in 2011, where soil temperatures in poplar were cooler than other species treatments. The minute microclimate differences were unlikely to have had an impact on the final yields and are also a product of the species modifying its own environment. There were no microclimate block
effects and baseline data shows that no species treatment had a pre-existing advantage over another. Thus hypothesis 1 was not influenced by microclimate because no treatment had an advantage over another. In the future as the site matures this may change as each species will continue to modify the plots in different ways.

Chapter 4 investigated hypothesis 2 through objective 3 and 4 using the data derived from lab analyses on fuel characteristics. The GCV was measured as a way to describe how effective a fuel is without getting into how detrimental the fuel was to a boiler. The percent ash, sulphur and chlorine were used in combination with the elemental ash analysis to determine if all bioenergy species were likely to cause increased maintenance and damage to boilers when compared with coal.

The third objective was to determine if the amount of energy per unit biomass (GCV) for all species was the same. Using the GCV data from 2010, poplar had a significantly higher GCV than switchgrass or the polyculture in Experiment 1. In Experiment 2 willow had a significantly higher GCV than Miscanthus. Both poplar and willow had significantly higher GCV than the herbaceous species in the Experiments. This refutes the null hypothesis and shows that woody species produce more energy per unit mass than herbaceous species, which did not come as a surprise as this is well documented in the literature.

The fourth objective was to determine if the percent ash of each species was different. In Experiment 1 poplar had significantly lower ash content than switchgrass and the polyculture which were not significantly different from each other in 2010 and 2011. Based on percent ash alone poplar has the potential to cause much less damage to a boiler than switchgrass and the polyculture. Experiment 2 revealed a similar result in 2010, where the woody species, willow, had a significantly lower percent ash than the herbaceous species, Miscanthus. Using 2011 data, however, willow and
Miscanthus did not have significantly different percent ash. Based on the percent ash data from Experiment 2 both species are equally likely to cause damage to boilers. It is important that the species be sampled again once plots are fully established and during the 3rd year of growth for the woody species. Willow fuel characteristics will likely change the most since both sampling years were based on first year growth when the bark to wood ratio is highest, 2010 after planting and 2011 after coppicing.

Chlorine was also used to determine which species may cause damage to current boilers. In 2010, poplar and the polyculture had significantly lower percent chlorine than switchgrass, which was near or exceeded the recommended limit of 0.1% for current boiler systems. However, in 2011 switchgrass percent chlorine was dramatically less and there were no significant differences between any of the species in Experiment 1. In Experiment 2 Miscanthus had significantly higher percent chlorine in both 2010 and 2011 than willow, but was under the recommended limit during both years. During 2010 both switchgrass and Miscanthus had chlorine values very close to the recommended limit and therefore could potentially cause more damage to boilers than their counterparts in each Experiment. Once again, a future study should examine the fully established plots to gain a more accurate understanding of how these species compare at maturity. Comparisons were made from fall data, but there were no differences between fall and spring chlorine concentrations in the herbaceous species in this study.

The elemental ash analysis of the four species and the polyculture revealed that there was no clear preferred species in either Experiment. This is because all species had pros and cons when considering how their ash composition may influence combustion in boilers for the production of heat and electricity. Silicon was the primary component of the ash in herbaceous species for both experiments and was significantly higher than the woody species, which had minute amounts of silicon in the remaining ash. Silicon has the potential to be very detrimental to a boiler system when combined
with potassium, sodium and calcium, all of which are found in all biomass species. Coal also has high silicon but does not contain much potassium, sodium or calcium and therefore hard glassy deposits are not formed during its combustion. Since the herbaceous fuels have both the silicon and have potassium, sodium and calcium they may produce glasslike deposits when burned alone. When burned with coal the formation of glassy deposits may decrease because the concentration of the potassium, sodium and calcium in the ash compared to the concentration of the silicon in the ash is relatively low. When burned alone the woody fuels may cause increased maintenance compared to coal, but the deposits would be less difficult to remove because they would be primarily composed of calcium, not like the glasslike silicon formations. When burned with coal, the woody fuels may form the same glasslike deposits herbaceous species do because of the high silicon in coal. Although, if cofiring biomass fuels at rates of 5-10% by mass it is unlikely the melting point of much of the silicon would be reduced and very few glasslike deposits would form. However, all biomass species in this study are liable to cause increased maintenance to the boilers based on the elemental ash analysis data from both 2010 and 2011, which supports the null hypothesis. Future examination of how these species would perform in boilers should be done once the site has fully established, and small scale test runs in actual boilers would help better understand the way in which these species actually perform during combustion.

To summarize, in Experiment 1 poplar produces higher yields and more energy per unit mass, with less ash than the switchgrass and the polyculture, but whether it causes more maintenance and damage to a boiler system than its herbaceous counterparts is not conclusive. In Experiment 2 willow also had a higher GCV than its herbaceous counterpart but did not produce significantly different yields. Predicting whether willow or Miscanthus would cause more maintenance and damage to a boiler system was inconclusive and requires research performed in actual boilers and once the site reaches maturity.
6.0 CONCLUSIONS

6.1 Conclusions

In this study, both herbaceous and woody species showed promise as potential carbon neutral bioenergy feedstocks for the production of heat and electricity. While this study just examined these potential feedstocks during the establishment stage, it does highlight a few key differences between the species: 1) all species are able to produce similar yields on marginal land with no fertilizer or irrigation inputs; 2) poplar and willow had the highest energy per unit mass, however, from an end-user point of view, a difference of 1 to 2 GJ per odt may not be of importance; and 3) the chemical makeup of woody and herbaceous biomass is very different, but both would likely cause increased maintenance to a boiler system. It remains inconclusive which species would cause more detrimental problems in a boiler due to the complexity of the combustion process, but further research on a fully mature site in conjunction with test runs in boilers rather than with lab equipment may help to conclusively determine which species would be the best fuel. Based on this study all species should be considered as potential bioenergy crops (See Table 6.1 for a summary of pros and cons), although with yield being close to equal during establishment, focus should be applied to poplar, willow and Miscanthus, as percent ash was low, while GCVs were high compared to switchgrass and the polyculture.
Table 6.1 Summary of observed pros and cons of four biomass species and a polyculture grown in Southern Ontario, Canada for the production of heat and electricity.

<table>
<thead>
<tr>
<th>Biomass Characteristics</th>
<th>Species</th>
<th>Poplar</th>
<th>Switchgrass</th>
<th>Polyculture</th>
<th>Miscanthus</th>
<th>Willow</th>
</tr>
</thead>
<tbody>
<tr>
<td>yield potential</td>
<td></td>
<td>high</td>
<td>med</td>
<td>med</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>moisture content</td>
<td></td>
<td>high</td>
<td>med</td>
<td>med</td>
<td>med</td>
<td>high</td>
</tr>
<tr>
<td>overwinter drying</td>
<td></td>
<td>effective</td>
<td>effective</td>
<td>effective</td>
<td>effective</td>
<td>effective</td>
</tr>
<tr>
<td>ash %</td>
<td></td>
<td>low</td>
<td>high</td>
<td>high</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>silica %</td>
<td></td>
<td>low</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>potassium %</td>
<td></td>
<td>high</td>
<td>low</td>
<td>low</td>
<td>med</td>
<td>high</td>
</tr>
<tr>
<td>growing season</td>
<td></td>
<td>long</td>
<td>short</td>
<td>short</td>
<td>long</td>
<td>long</td>
</tr>
<tr>
<td>survival</td>
<td></td>
<td>high</td>
<td>high</td>
<td>high*</td>
<td>high*</td>
<td>high*</td>
</tr>
<tr>
<td>caloric value</td>
<td></td>
<td>high</td>
<td>low</td>
<td>low</td>
<td>med</td>
<td>high</td>
</tr>
<tr>
<td>planting cost</td>
<td></td>
<td>high</td>
<td>low</td>
<td>low</td>
<td>high</td>
<td>high</td>
</tr>
<tr>
<td>harvesting cost</td>
<td></td>
<td>high</td>
<td>low</td>
<td>low</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>overwinter yield loss</td>
<td></td>
<td>low</td>
<td>high</td>
<td>high</td>
<td>high</td>
<td>low</td>
</tr>
</tbody>
</table>

*With appropriate species selection for the region and good planting stock.
6.2 Future Research and Recommendations

If this experiment was to be repeated, selecting a *Miscanthus giganteus* variety that could overwinter in the region and planting good willow stock from the start, would be the most essential improvement. This would improve the chances of survival and the likelihood that all species would establish during the same year. Potential growers should note that obtaining high quality stock from a reputable source and of a species capable of growing in the desired region is necessary for the success of the operation. Additionally, this experiment would have benefitted from the land being prepared in the previous fall season in order to have obtained full weed control during establishment. This would have reduced the weed pressure significantly and improved the colonization and first year growth of all species. Future studies should focus on established crops in their second and third cycles to determine the yield and fuel characteristics of the species proposed for bioenergy. It would also be beneficial to examine the possibility of limited or no fertilizer use on a site after many harvests to examine the effects on soil nutrient pools and the sustainability of bioenergy crops under low input regimes. However, information was most uncertain regarding the combustion of biomass. It would also be helpful to have a full-scale experiment in which a commercial boiler was optimized for each biomass crop. This would determine which species required a modified boiler system or which species could be burned with limited maintenance in unmodified systems. This would require a large amount of biomass from each feedstock and would increase the experimental costs. Future long term studies on soil carbon buildup for soil carbon sequestration should also be established to quantify any extra environmental benefits attained through biomass production. There are many unknowns in the biomass field, and much more research remains to be done in order to fully understand which species would be best suited for bioenergy production in Southern Ontario. However, the technology is available, and with subsidies or tax incentives, farmers could already be growing Ontario’s energy.
Chapter 7

Literature Cited


APPENDIX A

1.1 Agroforestry Location Methodology

Originally set up as a duplicate location, the agroforestry site follows the same methodology as the open location. For several reasons this location was not included in the main body of the thesis. The first was because it could not be compared to the open location as it was planted 2 weeks after the open location. The other reason it was not included was because block 1 was mistakenly harvested after the first year by an external party and block 3 was mowed down in the second year by another external party. These problems coupled with poor survival of poplar made weak comparisons. Therefore this appendix should be read with this in mind.

The entire north agroforestry field, containing 25 year old trees, consists of 260 m long rows with 5 m tree spacing and 15 m between tree rows. The tree rows are oriented northwest to southeast which maximizes sunlight to the alleys (between the tree rows) in this latitude. The plots are located in northwest corner of the north agroforestry field, in the center 10 m of the alleys. The mature trees that surround the plots are primarily black walnut and red oak but also poplar and black locust. The plots are the same size and shape as the open field, but all four blocks were arrayed differently (Figure 1.1). The plots were established in this location to correspond with the elevation of the open field and what alleys were available at the time.

During the first growing season poplar survival of planted stock was 90% in the open location but only 50% in the agroforestry location. This could have been due to the different planting times and/or due to the shading provided by the mature trees in the agroforestry location. Poplar plots in the agroforestry location were fill planted in June, 2010. The willow failed during its first planting in 2009 just as it did in the open location, likely due to bad stock as cuttings had some mold and had thicker
diameters than are usually used for planting. M1 Select survived the initial planting in 2009 but failed to overwinter and was replanted with the Nagara variety in 2010. This forced the original Experiment comparing all species treatments into two Experiments. Experiment 1 containing poplar, switchgrass and the polyculture and Experiment 2 containing *Miscanthus* and willow.

Figure 1.1 Agroforestry location plot layout for initial RCBD Experiment located at the GARS, Guelph, ON, Canada. Treatment 2, 3 and 5 used in Experiment 1 and treatment 1 and 4 used in Experiment 2.
1.2 Agroforestry Location Results

An ANOVA of biomass yields for the fall, 2010 harvest found no significant differences in Experiment 1 between the 2 species and the polyculture (Table 1.1). An ANOVA of biomass yields for the fall 2010 harvest also found no significant differences in Experiment 2 between the two species. *Miscanthus*.

An ANOVA of moisture content at harvest for the fall, 2010 harvest found no significant differences in Experiment 1. An ANOVA of the moisture content for Experiment 2's fall 2010 harvest also revealed no significant differences.

Table 1.1 Results of yields and moisture content of 4 biomass species and a polyculture grown in an agroforestry setting in Southern Ontario, Canada in 2010.

<table>
<thead>
<tr>
<th>Species</th>
<th>Yield (odt/ha/yr)</th>
<th>se</th>
<th>Moisture (%)</th>
<th>se</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td>Poplar</td>
<td>1.14</td>
<td>0.373</td>
<td>45.3</td>
</tr>
<tr>
<td></td>
<td>Polyculture</td>
<td>1.44</td>
<td>0.211</td>
<td>49.4</td>
</tr>
<tr>
<td></td>
<td>Switchgrass</td>
<td>1.3</td>
<td>0.236</td>
<td>40.2</td>
</tr>
<tr>
<td>Experiment 2</td>
<td><em>Miscanthus</em></td>
<td>0.91</td>
<td>0.216</td>
<td>49.9</td>
</tr>
<tr>
<td></td>
<td>Willow</td>
<td>0.54</td>
<td>0.191</td>
<td>44.8</td>
</tr>
</tbody>
</table>

An ANOVA of the biomass yields in the fall 2011 harvest found significant differences in Experiment 1 between species. The poplar treatment (2.12 odt/ha/yr) had significantly lower yield than the switchgrass treatment (4.36 odt/ha/yr), but the polyculture treatment (3.4 odt/ha/yr) was not significantly different to either species (Table 1.2). Experiment 2's ANOVA for fall 2011 yield showed *Miscanthus* (5.8 odt/ha/yr) has a significantly higher yield than the willow (2.2 odt/ha/yr).

An ANOVA of the moisture at harvest for the fall, 2011 harvest found significant differences between species in Experiment 1 and in Experiment 2. In contrast to the data from the previous year where there were no significant differences, poplar had a significantly higher moisture content (44.3%)
at harvest than the switchgrass (30.7%), but the polyculture’s (40.7%) moisture content was not significantly different to either species (Table 1.2). There were also significant differences in moisture content in Experiment 2, *Miscanthus* (34.2%) had significantly lower moisture than willow (49%) at harvest.

Table 1.2 Results of yields and moisture content of 4 biomass species and a polyculture grown in an agroforestry setting in Southern Ontario, Canada in 2011.

<table>
<thead>
<tr>
<th>Species</th>
<th>Yield (odt/ha/yr)</th>
<th>se</th>
<th>Moisture (%)</th>
<th>se</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poplar</td>
<td>2.12 a</td>
<td>0.447</td>
<td>44.3 b</td>
<td>3.00</td>
</tr>
<tr>
<td>Polyculture</td>
<td>3.40 ab</td>
<td>0.439</td>
<td>40.7 ab</td>
<td>3.41</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>4.36 b</td>
<td>0.819</td>
<td>30.7 a</td>
<td>3.00</td>
</tr>
<tr>
<td>Experiment 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Miscanthus</em></td>
<td>5.80 *</td>
<td>0.658</td>
<td>34.2 *</td>
<td>0.81</td>
</tr>
<tr>
<td>Willow</td>
<td>2.20 *</td>
<td>0.508</td>
<td>49.0 *</td>
<td>2.26</td>
</tr>
</tbody>
</table>

Means in the same column with the same letter are not significantly different according to Tukey's HSD test at p<0.05.
* Means are significantly different at p<0.05.

1.3 Agroforestry Location Discussion

Yield was randomly sampled twice from every plot, just as it was in the open location, in an attempt to collect a representative sample. In the 2010 growing season variability was quite high within switchgrass and the polyculture in Experiment 1 and within willow plots in Experiment 2. Complete colonization of the switchgrass and the polyculture plots had not yet occurred, causing less dense locations and even gaps within these grass plots. Poplar variability was also quite high due to unscheduled harvesting as well as natural variation within plots. It is likely that being a primary succession species poplar does not tolerate the shade within the mature trees. The first year willow growth was also variable, some sampling locations being less than 30cm while others were well over a meter. Given the variability within these species it is likely the number of randomized samples was not enough to capture an accurate representation of the plots. *Miscanthus* grew uniformly during the 2010
growing season, except for block 4 where a gradient formed from southeast to northwest likely due to light availability. During the 2011 growing season switchgrass and the polyculture continued to colonize the plots and became very uniform leaving fewer gaps, with the exception being block 1 and block 4 switchgrass which continued to have low colonization. Poplar plots were more uniform in the 2011 season but unscheduled harvesting and shading still made poplar growth variable. The 2011 year willow growth after coppice was more uniform but there was still a large variation between plants. *Miscanthus* was uniform during the 2011 growing season, except for block 4 where the gradient remained from southeast to northwest.

The samples taken in 2010 for Experiment 1 indicated there was no significant differences in yield between poplar, switchgrass or the polyculture. This supported the null hypothesis and showed that during second season of establishment, yield between these three bioenergy species did not differ. Experiment 2 showed that during the first season of growth *Miscanthus* and willow had no significant differences once again supporting the null hypothesis. When samples were taken in 2011, poplar yields were significantly lower than switchgrass yields but not the polyculture yields, which were not significantly different from each other. Unlike on the open location poplar plots had lower yields during the 2011 season, this could be due to the unscheduled harvests of blocks 1 and 3 compounded with poplars shade intolerance, but it is clear that in shaded conditions switchgrass and likely the polyculture will outperform poplar. Willow yields in 2011 are only based on the first season growth due to coppicing after 2010, and would likely be higher at the end of the cycle. Therefore despite the yield difference between *Miscanthus* and willow it is likely that as willow reaches its max mean annual increment (MAI) in later years of its cycle it will perform similarly to *Miscanthus*. During the first two establishment years, *Miscanthus* yielded more than willow, although not significantly more in the first year. This would indicate at least for the first two years of establishment *Miscanthus* yields more than willow. Even
between 2 years the increase in yield during establishment is substantial. This can be visualized in Figure 1.3 as the 2010 harvest is at least doubled by the 2011 harvest of all species. It is important that this location be revisited once fully established so that accurate yields based on mature stands be gathered.

![Graph showing yield comparison between 2010 and 2011 for various species.]

**Figure 1.3** Fall yields for 4 biomass species and a polyculture for the 2010 and 2011 growing seasons grown in an agroforestry setting in Southern Ontario, Canada.

### 1.4 Agroforestry Location Conclusions

The agroforestry location had two unscheduled "harvests" of blocks one in 2010 and 2011 that made the data gathered less valuable. The agroforestry location did reveal that poplar is not suitable for shaded location if the intended purpose is bioenergy, this species needs full sunlight to thrive. Switchgrass and the polyculture perform well even when shaded, though not quite as well as in full sunlight. Willow seemed to be able to tolerate shaded areas and growth will improve as MAI increases.
One surprise was how well *Miscanthus* performed under the mature tree canopy. Observationally it grew taller canes than the open location but biomass produced was very similar, despite the reduction in incoming radiation. This was likely offset by the increased moisture availability provided in the sheltered agroforestry location. More research should be done on *Miscanthus* and the effects of shading on stem to leaf ratio. If shade effectively increases the stem to leaf ratio without reducing yield it would create a more desirable fuel as the stems contain fewer nutrients and burn cleaner. Based on yields and growth observations in the agroforestry location *Miscanthus*, willow, switchgrass and the polyculture, should be the focus of future biomass research in a shaded or agroforestry environment.
Appendix B

COMBUSTION INDICES

1.1 Methods

To approximate the potential of a biomass species to cause problems in a boiler system 3 different indices were applied to the fuel data obtained from CENNATEK described in Chapter 4. The alkali index (AI) and the base-to-acid ratio ($R_{b/a}$) were used to estimate the slagging and fouling potential of the fuel. The bed agglomeration index (BAI) was used to estimate the potential bed agglomeration. The AI equation used is a function of the alkali oxides per unit energy and was calculated using the following equation:

$$AI = \frac{kg(K_2O + Na_2O)}{GJ}$$

This index predicts that AI values below 0.17 kg/GJ are unlikely to cause fouling or slagging, AI values between 0.17 to 0.34 kg/GJ may or may not cause slagging or fouling, but values above 0.34 kg/GJ are highly likely to cause fouling or slagging (Magasiner et al. 2001; Vamvuka and Bandelis 2010). The $R_{b/a}$ index used is a sum of the bases found in the ash divided by the sum of the acids found in the ash and was calculated using the equation:

$$R_{b/a} = \frac{\%(Fe_2O_3 + CaO + MgO + K_2O + Na_2O)}{\%(SiO_2 + TiO_2 + Al_2O_3)}$$

In the $R_{b/a}$ index the fouling potential of the ash increases as the $R_{b/a}$ value increases, with an approximate minimum acceptable $R_{b/a}$ value of 0.75 for biomass (Vamvuka and Zografos 2004). The BAI evaluates the tendency for agglomeration in fluidized-bed reactors based on the percent of $Fe_2O_3$ to the percent $K_2O$ and $Na_2O$ within the ash using the following equation:
In this index, BAI values lower than 0.15 indicate that bed agglomeration is likely to occur (Vamvuka and Bandelis 2010).

Statistical analyses were performed using IBM® SPSS® Statistics 19 (SPSS Inc., Chicago IL) on the calculated data to determine significance between treatments. Statistical significance testing (p-value) was determined at \( p = 0.05 \). Experiment 1 employed ANOVAs with Tukeys HSD test to identify significant differences between the species treatments. An ANOVA for Experiment 2 was done to determine if there were significant differences between the two species treatments.

1.2 Results and Discussion

1.2.1 Analysis of indices using fall 2010 harvest data

An ANOVA with Tukeys HSD test for the fall 2010 harvest found no significant differences in the AI between poplar switchgrass and the polyculture in Experiment 1 (Table 1.1). Using the AI all species are unlikely to cause fouling or slagging (Table 1.2). All species treatments were significantly different for the BAI values in fall 2010. Poplar had the lowest BAI value (0.008) and the polyculture had the highest value (0.085). Bed agglomeration is likely to occur in all species treatments as none were above the 0.15 minimum value. The \( R_{b/a} \) values for Experiment 1 showed that poplar (232.17) was significantly higher than switchgrass (0.22) or the polyculture (0.24) which were not significantly different to each other. Using the \( R_{b/a} \) index poplar is likely to cause fouling as it is well above the max value of 0.75, but switchgrass and the polyculture are unlikely to cause fouling.

An ANOVA of the species in Experiment 2 for the fall 2010 harvest found significant differences between species treatments in all indices (Table 1.1). Miscanthus has a significantly lower AI value than...
willow. Using the Al *Miscanthus* would be unlikely to cause slagging or fouling, and willow may or may not cause slagging or fouling based on this index (Table 1.2). *Miscanthus* had a significantly higher BAI value than willow, but both were still below the minimum value of 0.15, therefore bed agglomeration is likely to occur in the combustion of both species treatments. In Experiment 2 the willow had a significantly higher \( R_{b/a} \) value than the *Miscanthus*. Willows high \( R_{b/a} \) value (139.16) indicates that it is likely to cause fouling while *Miscanthus*’ value (0.42), was below the maximum and is therefore unlikely to cause fouling.

Table 1.1 The values for 5 bioenergy species treatments from indices for slagging, fouling and bed agglomeration calculated from Fall 2010 harvest data.

<table>
<thead>
<tr>
<th>Experiment 1</th>
<th>Al</th>
<th>se</th>
<th>BAI</th>
<th>se</th>
<th>( R_{b/a} )</th>
<th>se</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poplar</td>
<td>0.170</td>
<td>0.043</td>
<td>0.008</td>
<td>0.001 a</td>
<td>232.17</td>
<td>93.03 a</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>0.101</td>
<td>0.004</td>
<td>0.067</td>
<td>0.006 b</td>
<td>0.22</td>
<td>0.005 b</td>
</tr>
<tr>
<td>Polyculture</td>
<td>0.109</td>
<td>0.007</td>
<td>0.085</td>
<td>0.002 c</td>
<td>0.24</td>
<td>0.003 b</td>
</tr>
<tr>
<td>Experiment 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miscanthus</td>
<td>0.162</td>
<td>0.009 *</td>
<td>0.111</td>
<td>0.008 *</td>
<td>0.42</td>
<td>0.0178 *</td>
</tr>
<tr>
<td>Willow</td>
<td>0.274</td>
<td>0.014 *</td>
<td>0.017</td>
<td>0.001 *</td>
<td>139.16</td>
<td>21.764 *</td>
</tr>
</tbody>
</table>

Means in the same column with the same letter are not significantly different according to Tukey's HSD test at \( p<0.05 \).

* Averages are significantly different at \( p<0.05 \).
Table 1.2 Summary of 3 indices (AI, R_{b/a} and BAI) and the overall prediction for each species treatment calculated from Fall 2010 harvest data.

<table>
<thead>
<tr>
<th>Experiment 1</th>
<th>Alkali Index</th>
<th>Fouling/Slagging</th>
<th>Bed Agglomeration</th>
<th>R_{b/a}</th>
<th>Fouling</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poplar</td>
<td>0.170</td>
<td>may occur</td>
<td>0.008</td>
<td>occurs</td>
<td>232.17</td>
<td>likely</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>0.101</td>
<td>unlikely</td>
<td>0.067</td>
<td>occurs</td>
<td>0.22</td>
<td>unlikely</td>
</tr>
<tr>
<td>Polyculture</td>
<td>0.109</td>
<td>unlikely</td>
<td>0.085</td>
<td>occurs</td>
<td>0.24</td>
<td>unlikely</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment 2</th>
<th>Alkali Index</th>
<th>Fouling/Slagging</th>
<th>Bed Agglomeration</th>
<th>R_{b/a}</th>
<th>Fouling</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miscanthus</td>
<td>0.162</td>
<td>unlikely</td>
<td>0.111</td>
<td>occurs</td>
<td>0.42</td>
<td>unlikely</td>
</tr>
<tr>
<td>Willow</td>
<td>0.274</td>
<td>may occur</td>
<td>0.017</td>
<td>occurs</td>
<td>139.16</td>
<td>likely</td>
</tr>
</tbody>
</table>

1.2.2 Analysis of indices using fall 2011 harvest data

An ANOVA with Tukey's HSD test for the fall 2011 harvest found significant differences in the AI between poplar switchgrass and the polyculture in Experiment 1 (Table 1.3). The poplar had a significantly higher AI value than the polyculture, but was not significantly different to the switchgrass. Using the AI switchgrass and the polyculture are unlikely to cause fouling or slagging, but poplar fell under the category of may or may not cause fouling or slagging despite being not significantly different to switchgrass (Table 1.4). An ANOVA with Tukey's on the BAI showed the poplar treatment (0.015) was significantly higher than the switchgrass (.05) and polyculture (.063) treatment which were not significantly different to each other. Bed agglomeration would likely occur in all species treatments as none were above the 0.15 minimum value. The R_{b/a} values for Experiment 1 showed that poplar (33.06) was significantly higher than switchgrass (0.39) or the polyculture (0.37) which were not significantly different to each other. Using the R_{b/a} index poplar is likely to cause fouling as it is well above the max value of 0.75, but switchgrass and the polyculture are unlikely to cause fouling.
An ANOVA of the species in Experiment 2 for the fall 2011 harvest found significant differences between species treatments in all indices (Table 1.3). *Miscanthus* (0.128) has a significantly lower AI value than willow (0.201). Using the AI willow may or may not cause slagging or fouling, but *Miscanthus* is unlikely to cause slagging or fouling based on this index (Table 1.4). *Miscanthus* (0.064) had a significantly higher BAI value than willow (0.015), but both were still below the minimum value of 0.15, therefore bed agglomeration is likely to occur in the combustion of both species treatments. The $R_{b/a}$ value for willow was significantly higher than the $R_{b/a}$ value of *Miscanthus*. Willows high $R_{b/a}$ value (99.57) indicates that it is likely to cause fouling while *Miscanthus*’ value (0.71) was below the maximum of 0.75 and is therefore unlikely to cause fouling.

Table 1.3 The values for 5 bioenergy species treatments from indices for slagging, fouling and bed agglomeration calculated from Fall 2011 harvest data.

<table>
<thead>
<tr>
<th></th>
<th>AI</th>
<th>se</th>
<th>BAI</th>
<th>se</th>
<th>$R_{b/a}$</th>
<th>se</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poplar</td>
<td>0.201</td>
<td>0.011b</td>
<td>0.015</td>
<td>0.002a</td>
<td>33.06</td>
<td>11.2a</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>0.160</td>
<td>0.012ab</td>
<td>0.050</td>
<td>0.003b</td>
<td>0.39</td>
<td>0.032b</td>
</tr>
<tr>
<td>Polyculture</td>
<td>0.124</td>
<td>0.008a</td>
<td>0.063</td>
<td>0.008b</td>
<td>0.37</td>
<td>0.006b</td>
</tr>
<tr>
<td><strong>Experiment 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miscanthus</td>
<td>0.128</td>
<td>0.022*</td>
<td>0.064</td>
<td>0.0075*</td>
<td>0.71</td>
<td>0.033*</td>
</tr>
<tr>
<td>Willow</td>
<td>0.201</td>
<td>0.004*</td>
<td>0.015</td>
<td>0.0003*</td>
<td>99.57</td>
<td>6.403*</td>
</tr>
</tbody>
</table>

Means in the same column with the same letter are not significantly different according to Tukey’s HSD test at p<0.05.

* Averages are significantly different at p<0.05.
Table 1.4 Summary of 3 indices (AI, R_{b/a} and BAI) and the overall prediction for each species treatment calculated from Fall 2011 harvest data.

<table>
<thead>
<tr>
<th></th>
<th>Alkali Index</th>
<th>Fouling/Slagging</th>
<th>BAI</th>
<th>Bed Agglomeration</th>
<th>R_{b/a}</th>
<th>Fouling</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poplar</td>
<td>0.201</td>
<td>may occur</td>
<td>0.015</td>
<td>occurs</td>
<td>33.06</td>
<td>likely</td>
<td>may not be suitable</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>0.160</td>
<td>unlikely</td>
<td>0.050</td>
<td>occurs</td>
<td>0.39</td>
<td>unlikely</td>
<td>may be suitable</td>
</tr>
<tr>
<td>Polyculture</td>
<td>0.124</td>
<td>unlikely</td>
<td>0.063</td>
<td>occurs</td>
<td>0.37</td>
<td>unlikely</td>
<td>may be suitable</td>
</tr>
<tr>
<td><strong>Experiment 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miscanthus</td>
<td>0.128</td>
<td>unlikely</td>
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<td>0.71</td>
<td>unlikely</td>
<td>may be suitable</td>
</tr>
<tr>
<td>Willow</td>
<td>0.201</td>
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<td>occurs</td>
<td>99.57</td>
<td>likely</td>
<td>may not be suitable</td>
</tr>
</tbody>
</table>

The use of indices can be useful tools in predicting and identifying fuels that may or may not be suitable for combustion. However this study took place in the establishment phase and it is likely that fuel characteristics will change as the stands reach their potential yields. This may change the values obtained from the indices substantially and evidence of this can be seen in the differences between 2010 and 2011 data. It is also important to note that data was derived from fall harvested material and herbaceous species are known to benefit from overwintering in the field (Lewandowski and Heinz 2003). Index values from herbaceous species allowed to overwinter could be much better than a fall harvest scenario.

In this study The R_{b/a} index identified poplar and willow as potentially unsuitable fuels due to potential fouling caused by their high base:acid ratio. The high potassium and calcium found in these species and low Si cause the value of these species to be quite high, which indicates fouling is likely to occur. This high base:acid ratio in woody biomass is not always observed and may change over time as the crop matures (Tillman 2000). Similarly the AI index indicated the woody biomass was on the lower
end of the may or may not cause slagging or fouling range. The AI values for woody biomass in this study are higher, but similar to, that of woody biomass found in the literature (Jenkins et al. 1998; Miles et al. 1996). Herbaceous species treatments in both Experiments under both these indices were unlikely to cause slagging or fouling. The AI values in this study for herbaceous species are similar to that found in the literature, though switchgrass is typically found to have AI values above 0.34 (Jenkins et al. 1998; Miles et al. 1996). An increase in AI values of switchgrass in this study was observed from the 2010 season to the 2011 season and may indicate that as the site matures the AI value for switchgrass may continue to increase to levels found in the literature. Miscanthus showed the opposite seasonal change as the 2011 AI value was lower than the 2010 value. This is likely due to the decrease in remaining ash observed in Miscanthus in the 2011 season, attributed to the higher ratio of canes to leaves. The BAI indicates that all species treatments would have bed agglomeration occur. Bed agglomeration is common for biomass species as they are problematic fuels with relatively high K and Ca compared to coal (Nuutinen et al. 2004). Bed agglomeration is controllable by burning biomass fuels on different bed substrates (Nuutinen et al. 2004).

1.4 Conclusion

When considering all three indices used in this study switchgrass, the polyculture and Miscanthus are likely to be suitable with some bed agglomeration. Poplar and willow may not be suitable based on all three indices. If the R_{ba/a} index which indicated fouling is highly probably for poplar and willow was removed from consideration then all 5 species treatments may be suitable for combustion. While these indices can be useful tools, in order to accurately determine which fuels are suitable each fuel must be tested in actual boiler system, as combustion is an extremely complex process. It may be that these same indices may provide different predictions of each species treatment as the plots mature into their third and fourth year. For this reason the indices section of this paper was
included as an appendix as the fuel characteristics are not indicative of a stable and mature stand and may not accurately represent each species treatment.

1.5 References


