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PLANTING AND PRODUCTION OF SWITCHGRASS (*PANICUM VIRGATUM* L.)
AS A BIOENERGY CROP IN MICHIGAN'S UPPER PENINSULA

By

Kassidy Nikole Yatso

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Applied Ecology

MICHIGAN TECHNOLOGICAL UNIVERSITY

2011

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This thesis, "Planting and Production of Switchgrass (*Panicum virgatum* L.) as a Bioenergy Crop in Michigan's Upper Peninsula," is hereby approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE IN APPLIED ECOLOGY.

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Jacob 'Boots' Oswald

(1989-2010)

"You expected to be sad in the fall.

Part of you dies each year when the leaves fell from the trees
and their branches were bare against the wind and the cold, wintry light.

But you knew there would always be the spring,
as you knew the river would flow again after it was frozen.

When the cold rains kept on and killed the spring,
it was as though a young person had died for no reason."

~ Ernest Hemingway (*A Moveable Feast*, 1964)

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PREFACE

Kassidy Nikole Yatso has participated in the Transatlantic Master's Degree Program in Forest Resources (Atlantis), which is a two-year double degree Master's program organized by the University of Helsinki (UH), Swedish University of Agricultural Sciences (SLU), North Carolina State University (NCSU) and Michigan Technological University (MTU). Her thesis is jointly supervised by the University of Helsinki and Michigan Technological University.

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This thesis was written in partial fulfillment of the requirements for the Degree of Master of Science in Forest Ecology and Management, at Michigan Technological University's School of Forest Resources and Environmental Science. This thesis will also be submitted to the University of Helsinki, Finland, Faculty of Agriculture and Forestry for a Master of Science, in fulfillment of the dual degree requirements for the Transatlantic Master's Degree Program in Forest Resources (Atlantis).

This document details the Master's research work of Kassidy Nikole Yatso. The contents of this document include three chapters. The first chapter follows the requirements of the Michigan Tech Graduate School as a 'thesis introduction' or 'Unifying Chapter'. The second chapter will potentially be published in the near future, but follows the formatting required by the Michigan Tech Graduate School. The third chapter is written as a journal article, in a traditional peer-reviewed format, and includes Abstract, Journal Introduction, Materials and Methods, Results and Discussion, and Conclusion, that adhere to the format requested by the journal. The third chapter will be submitted for publication following the successful defense of this thesis. All other portions of this document include, and follow, the requirements of the Michigan Tech Graduate School.

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THESIS ABSTRACT

Switchgrass (*Panicum virgatum* L.) is a perennial grass holding great promise as a biofuel resource. While Michigan's Upper Peninsula has an appropriate land base and climatic conditions, there is little research exploring the possibilities of switchgrass production. The overall objectives of this research were to investigate switchgrass establishment in the northern edge of its distribution through: investigating the effects of competition on the germination and establishment of switchgrass through the developmental and competitive characteristics of Cave-in-Rock switchgrass and large crabgrass (*Digitaria sanguinalis* L.) in Michigan's Upper Peninsula; and, determining the optimum planting depths and timing for switchgrass in Michigan's Upper Peninsula.

For the competition study, a randomized complete block design was installed June 2009 at two locations in Michigan's Upper Peninsula. Four treatments (0, 1, 4, and 8 plants/m²) of crabgrass were planted with one switchgrass plant. There was a significant difference between switchgrass biomass produced in year one, as a function of crabgrass weed pressure. There was no significant difference between the switchgrass biomass produced in year two versus previous crabgrass weed pressure. There is a significant difference between switchgrass biomass produced in year one and two.

For the depth and timing study, a completely randomized design was installed at two locations in Michigan's Upper Peninsula on seven planting dates (three fall 2009, and four spring 2010); 25 seeds were planted 2 cm apart along 0.5 m rows at depths of: 0.6 cm, 1.3 cm, and 1.9 cm. Emergence and biomass yields were compared by planting date, and depths. A greenhouse seeding experiment was established using the same planting depths and parameters as the field study. The number of seedlings was tallied daily for 30 days. There was a significant difference in survivorship between the fall and spring planting dates, with the spring being more successful. Of the four spring planting dates, there was a significant difference between May and June in emergence and biomass yield. June planting dates had the most percent emergence and total survivorship. There is no significant difference between planting switchgrass at depths of 0.6 cm, 1.3 cm, and 1.9 cm.

In conclusion, switchgrass showed no signs of a legacy effect of competition from year one, on biomass production. Overall, an antagonistic effect on switchgrass biomass yield during the establishment period has been observed as a result of increasing competing weed pressure. When planting switchgrass in Michigan's Upper Peninsula, it should be done in the spring, within the first two weeks of June, at any depth ranging from 0.6 cm to 1.9 cm.

CHAPTER 1: UNIFYING CHAPTER

GENERAL OVERVIEW

BIOFUELS

Energy security and climate change are currently driving the energy sector and society to find alternatives to fossil fuels. In the race to replace fossil fuels, biofuels are in the lead, showing the greatest potential (Whitaker et al. 2010). Currently, perennial, warm-season (C4) grasses are considered to be both the most efficient and most sustainable biofuel energy crops in temperate regions, due to their potential for high yields on marginal lands (Adler et al. 2007; Karp and Shield 2008; Russi 2008; Williams et al. 2009; Lee et al. 2009; UNEP 2009; Dauber et al. 2010). In general, C4 grasses can grow for longer periods of time in warm, humid, or arid environments (Sage and Monson 1999; Wolf and Fiske 2009), giving them a competitive advantage over other species (Lee et al. 2009). Of the C4 grasses, the perennial species, *Panicum virgatum* L. (switchgrass), is one of the most popular and promising biomass feedstock in the southeastern and central United States (Cundiff and Marsh 1996; Vogel et al. 2002; Teel and Barnhart 2003; Parrish and Fike 2005; Comis 2006), second only to *Miscanthus x giganteus* (miscanthus) for energy-yielding cellulosic-ethanol feedstock (Heaton et al. 2008; Sanderson and Alder 2008; University of Illinois at Urbana-Champaign 2008; Mekete et al. 2009).

Switchgrass has received widespread attention due to its high productivity, low site impact, low energy input requirements, and limited vulnerability to pests and diseases (Froese 2007; Wolf and Fiske 2009; Min and Kapp 2010). Being a native species, switchgrass has been exposed to North American pathogens for decades, and possesses a broad genetic background (Parish and Fike 2005; Mitchell et al. 2008; Wolf and Fiske 2009). Switchgrass is an upright, C4 perennial bunchgrass native to North America (Parish and Fike 2005; Gibson and Barnhart 2007). It is typically found in southern tall grass prairies in the United States, Central America and Canada. Switchgrass seed is very small and dormant at harvest (Gibson and Barnhart 2007; Wolf and Fiske 2009); it can

require up to two years of after-ripening, and stratification to break dormancy (Shen et al. 2001; McLaughlin and Adams Kszos 2005; Wolf and Fiske 2009). As a crop, approximately three years are required to reach maximum productivity (Parish and Fike 2005; Gibson and Barnhart 2007). During the first year, the plant will grow to only one third of its potential (McLaughlin et al. 1999; Parish and Fike 2005), but once fully established the plant is quite vigorous (Gibson and Barnhart 2007; Wolf and Fiske 2009). Because switchgrass has widely adapted and favorable traits, it is of particular interest in the Great Lakes Region of the United States for biofuel production.

GROWING SWITCHGRASS IN THE GREAT LAKES REGION OF THE UNITED STATES - MICHIGAN'S UPPER PENINSULA

The Great Lakes Region of North America is made up of Ontario, Canada, and eight U.S. states: Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin (EPA 2010). Geographically, the region borders the Great Lakes - Superior, Michigan, Huron, Erie, and Ontario. According to the United States Environmental Protection Agency (2010), about 7% of American farm production and 25% of Canadian agricultural production are located in the Great Lakes region. The Great Lakes region is extremely dependent on coal for electric power generation, with Wisconsin, Minnesota, and Michigan having anywhere from two-thirds to four-fifths of their total generation from this resource (EIA 2008; Froese et al. 2010).

In particular, Michigan's Upper Peninsula has depleted or reclaimed agricultural and mining land that does not compete with food crops (Jain et al. 2010; Froese et al. 2010; Min pers. comm. 2009). *Panicum virgatum* L. var. *virgatum* ('Cave-in-Rock' switchgrass variety) showed excellent potential in the northern states of the United States, with an average yield of 5.7 dry metric tons per hectare in Michigan's Upper Peninsula (Min and Kapp 2010). Though Cave-in-Rock is an upland variety that originated in Southern Illinois, it is more cold-tolerant and thus better suited for the Upper Midwest, than the higher yielding lowland varieties of switchgrass (Wolf and Fiske 2009; Jain et al. 2010). Due to the biological attributes of switchgrass mentioned above, switchgrass production was investigated further in Michigan's Upper Peninsula (Min and Kapp

2010). Min and Kapp (2010) discovered that switchgrass is able to survive the winters of Michigan's Upper Peninsula, and that the switchgrass varieties Cave-in-Rock and Blackwell, consistently had the highest yields; thus, the rest of the Upper Peninsula became a candidate for switchgrass production. Managing switchgrass for bioenergy is not only energetically positive, but it is an environmentally sustainable production system for the Midwest (McLaughlin and Kszos 2005; McLaughlin et al. 1999; Mitchell et al. 2008). Thus, Michigan's Upper Peninsula could potentially be used to help meet U.S. bioenergy requirements in the near future because of its land base and suitable climatic conditions for growing switchgrass (Walsh et al. 1998; Mitchell et al. 2008).

Previous research in support of growing switchgrass in the Midwest and Great Lakes Region provides some framework for growing switchgrass in Michigan's Upper Peninsula. It is suggested that switchgrass seeds should be planted anywhere from 0.25 in (0.6 cm) to 0.50 in (1.3 cm) deep, but no deeper (Wolf and Fiske 2009); the exposure of the seed to soil moisture is predicted to increase with depth. Switchgrass germination should take place within a week after planting (Wolfe and Fiske 2009), though switchgrass germination is typically slow if soil temperatures are below 16°C. Switchgrass should be planted in the spring, within two to three weeks of before or after the recommended date for planting corn (*Zea mays*) in a region where switchgrass has not been planted (Wolf and Fiske 2009; Min and Kapp 2010; Mitchell et al. 2010). For the state of Michigan, corn is typically planted from late April to early June (Mitchell et al. 2010). Wolf and Fiske (2009) also suggest that while early June is ideal for planting switchgrass, planting even earlier is appropriate if weeds are an issue. Switchgrass will grow until the first *killing frosts* (defined as temperatures cold enough to kill all but the hardiest vegetation) in the fall, and should not be harvested sooner than six weeks from this date or to less than four inches (10 cm in height) to retain adequate carbohydrate storage and vigor for the following growing season (Mitchell et al. 2010). Single harvests should take place during the fall of a growing season, and are recommended to increase switchgrass productivity and survival (Mitchell et al. 2010). Spring and summer harvests should be avoided due to drought difficulties (Mitchell et al. 2010). Switchgrass can be

harvested and baled with current, commercial haying equipment (Min and Kapp 2010; Mitchel et al. 2010). Further research on every aspect of planting switchgrass in Michigan's Upper Peninsula is needed.

Future Research Needs

Research and literature on establishing switchgrass cropping systems in the Great Lakes Region is also lacking (Law and Watkinson 1987; Shainsky and Radosevich 1992; Sher et al. 2000; U.S. Department of Energy 2005; Mitchell et al. 2008; Froese 2009). Credible data on switchgrass establishment in Michigan's Upper Peninsula will be fundamental in determining switchgrass prices, locations, and quality and quantity of biomass for investors and developers associated with this emerging bioenergy market (U.S. Department of Energy 2005; Froese 2007). Of basic importance, is research on seasonal planting times of switchgrass and an optimal planting depth of this small seed in northern climates. Additionally, if switchgrass is to be established in Michigan's Upper Peninsula as a biofuel feedstock, there will be a competing community of weeds associated with this geographic region. Understanding the effects of competition from these weeds on switchgrass establishment and production will play a vital role in developing management strategies for Michigan's Upper Peninsula.

COMPETITION

In the study of weed-crop interactions, researchers quickly understood that early weed removal translated into reduced effects on crop yields and profit margins. As researchers further studied the interactions between crop and weed, one thing became apparent – there exists a balance between the abilities of the two species to compete, the stronger competitor claiming the bulk of the resources. Weedy species compete with desirable species by capturing nutrients, water, and solar radiation (Radosevich and Holt 1984; Aldrich and Kramer 1997). Initial densities and timing of establishment of competing species are also thought to have substantial effects on the dynamics of plant competition (Wedin and Tilman 1993). However, very little research has been conducted to determine the legacy effect of competition, (the long-term outcome of competition), on

growth rates of desirable plant species. In fact, most competition studies are conducted under the assumption that, at 6-8 weeks, the dominant species will remain dominant throughout the growing season. This assumption may not hold true for perennial species and/or species with different growth strategies. It is very important to understand the long-term effects of each species associated with perennial systems, as concentrations of limiting resources and differing plant traits can be responsible for differences in the resource reduction by each species (Wedin and Tilman 1993). The southern, perennial grass, switchgrass (*Panicum virgatum* L.), holds great promise as a biofuel source in the United States and Canada. However, large crabgrass (*Digitaria sanguinalis* L.) is a persistent annual weed in the natural range of switchgrass. While these two species co-occur in switchgrass cropping systems, they exhibit different growth strategies. Production growth strategies such as relative growth rate, relative leaf production rate, and unit leaf rates, as well as specific leaf areas and leaf area ratios are typically higher in annual grasses than in perennials (Garnier 1992). Studying the long-term competitive interaction of these two species will provide insight into competition in the early years of establishment, biomass allocation, as well as differences between these two competing species in resource allocation.

Weed Competition Studies

Though debate surrounds the definition of competition between plants (Zimdahl 2004); competition, at its most basic, is a negative interaction that occurs among organisms whenever two or more organisms require the same limited resource (Keddy 1989; Wedin and Tilman 1993). All organisms require resources to grow, reproduce, and survive; however, they cannot acquire a resource when other organisms consume that resource. Thus, competitors reduce each other's growth, reproduction, or survival (Gause 1934). Competition can be categorized as intraspecific or interspecific. Intraspecific competition refers to competition between members of the same species for the same resource in an ecosystem, such as solar radiation, nutrients, or space. Interspecific competition, on the other hand, deals with competition between members of different

species. In an agricultural cropping system, a weedy species competing with a desired species is an example of interspecific competition (Connolly et al. 2001).

Biologists typically recognize two main types of competition: interference and exploitative competition (Wedin and Tilman 1993). During interference competition, plants interact directly by physically interfering with each other to obtain resources in their environment (Encyclopædia Britannica 2010). This form of competition relies on an organism actively interfering with one another, with the more aggressive competitor preventing the other from obtaining resources, reproducing, and/or preventing physical establishment. In contrast, during exploitative competition, (also commonly referred to as resource competition), plants interact indirectly by consuming scarce resources; in turn, limiting the availability to others. For example, with exploitative competition, plants absorb nitrogen into their roots, making nitrogen unavailable to nearby plants; thus, plants that produce many roots typically reduce soil nitrogen to very low levels, eventually killing neighboring plants (Wedin and Tilman 1993).

Competition tends to be heavily affected by a plant's population density (nearness and number of neighbors), and resource availability (Murphy and Briske 1992). In addition, individual plants within low plant population densities may exploit larger pools of resources from above and below ground (Sanderson and Reed 2000). For example, in grasses, several morphogenetic changes, such as reduced tillering and increased height, are mechanisms to adapt to resource availability (Ballare et al. 1995). Weed species and density effects in various crops such as rice, corn, and other grasses, have been compared in numerous studies (Fleming et al. 1988; Hager et al., 1998; Hashem et al. 1998; Moechnig et al. 2003; Park et al. 2003; Ni et al. 2004). General guidelines have evolved from these studies as to relative competitiveness of weeds with various crops (Fleming et al. 1988; Hashem et al. 1998; Moechnig et al. 2003), the weed-free time needed following crop emergence (Hager et al. 1998), and the appropriate time of weed removal together with postemergence treatments to preclude loss of crop quantity and quality (Park et al. 2003; Ni et al. 2004). Because tillage, planting, and weed management practices have changed over the years, the former guidelines regarding crop/weed

competition should be revisited, in some instances modified, as new findings are reported.

There are other common limitations associated with competition studies, such as the short time frame under which it is studied. Most competition studies, whether the species are annuals or perennials, analyze plant parameters over one growing season or less (Law and Watkinson 1987; Sher, 2000; Shainsky and Radosevich 1992). A one-year time frame is suitable for annuals, but competition dynamics within a perennial community may vary greatly over a two-year, or more, period (Tarasoff 2006; Bennett et al. 2011). Short-term competition studies may also be inappropriate for perennial plants as perennial plants' extensive root systems are not yet fully developed, thus preventing them from maintaining limiting nutrients at critically low levels (Wedin and Tilman 1993; Bennett et al. 2011). Studies that evaluate perennial species over a two-year period are lacking (Bennett et al. 2011). Although final biomass is a common indicator of 'competitive success,' multiple measurements (such as height, belowground biomass accrual, and reproductive features) should be investigated over the course of a study to allow for an assessment of each species total growth rates.

Crop and weed competition investigations have focused on a variety of aspects such as the effects of weed density (Fleming et al. 1988), herbicide use (Hager et al. 1998), proximity factors (Hashem et al. 1998), productivity (Park et al. 2002), growth interactions (Moechnig et al. 2003), and competition modeling (Park et al. 2003; Ni et al. 2004). The results of these studies can be helpful in generating guidelines as to the relative competitive ability of various weeds at various densities within a desired crop. These studies also provide guidelines for the duration of weed-free conditions needed after crop emergence (Moechnig et al. 2003), and for the time of weed removal with post-emergence herbicides (Hager et al. 1998). The amount of time that a weed can remain with the crop and eventually be removed with no resultant deleterious effects on quantity and quality of crop yield is important in determining the legacy effect of competition. If the effect of competition does not go away once the competing plant is removed, there may be a lingering effect of competition. Multiple studies have determined how long

specific weeds can remain in annual crops with no deleterious effects on quantity and quality of crop yield (Shainsky et al. 1992; Hager et al. 1998; Sher et al. 2000), but perennial studies are lacking. In general, these studies tended to show that a moderate population of weeds could remain growing with the crop for up three to six weeks after planting and, once removed, would cause little or no crop yield loss (Shainsky et al. 1992; Hager et al. 1998; Sher et al. 2000).

Competition Studies involving *Panicum virgatum* L. - switchgrass

Switchgrass requires a long establishment period; therefore, it is likely that for this species to be economically viable the control of weeds will play a vital role (McLaughlin et al. 1999; Parrish and Fike 2005; Schmer et al. 2006; Perrin et al. 2008). Weed control in switchgrass establishment can approach a quarter of the total establishment cost (Duffy and Nanhou 2002; De La Torre Ugarte et al. 2003), but these costs are likely offset by a shortened establishment period (Tarasoff pers. comm. 2010). Thus, the long-term investment required to reach maximum growth rates translates into a greater need to control weeds early in the cropping cycle (Parrish and Fike 2005; Schmer et al. 2006; Wolf and Fiske 2009). Sanderson and Reed (2000) found resource inputs, such as nitrogen (N) fertility, and water availability affect interspecific plant competition in switchgrass, and that during early establishment, switchgrass biomass production was not affected by N inputs; variables such as tiller number, leaf area per plant, individual plant dry weight, and developmental stage were compared. Sanderson and Reed (2000) also discovered that an increase in plant spacing correlated with increases in tiller number, leaf area, plant dry weight, and morphological development stage. The competitive responses of switchgrass plants were controlled by competition for aboveground resources (Sanderson and Reed 2000). Thus, future switchgrass competition research should focus on aboveground aspects, while exploring above- and belowground relationships.

Delayed switchgrass establishment has been attributed to competition from grassy and broadleaf weeds (Mitchell et al. 2008), seed dormancy and poor seedling vigor (Gibson and Barnhart 2007). *Digitaria sanguinalis* L. (large crabgrass), a fast growing,

prostrate annual is of particular concern within the switchgrass cropping systems in Michigan's Upper Peninsula (Tarasoff pers. comm. 2009; Min pers. comm. 2009). The long-term effect of early weed competition on establishment rates of switchgrass is unknown. In addition, no literature has been found that contains studies relating the competitive interaction of large crabgrass and switchgrass, in Michigan's Upper Peninsula.

***Digitaria sanguinalis* L. - large crabgrass**

First documented in the United States in 1864, large crabgrass is native to southern Europe, and is now known as a serious and principal weed in cropping systems throughout temperate regions of North America (Peters and Dunn 1971). Large crabgrass is an annual, prostrate member of the Poaceae family that roots at the nodes, and forms smothering mats (Molinar and Elmore 2009). This species has very hairy leaves and sheaths that range from 6-8 cm wide and 5-15 cm long (Peters and Dunn 1971; Chism and Bingham 1991). Large crabgrass reproduces via tillers and seeds (Chism and Bingham 1991), and spreads primarily by seed (Molinar and Elmore 2009). The seeds germinate most vigorously from mid-spring to late summer, and seeds can remain viable for at least three years in soil (Molinar and Elmore 2009). Large crabgrass is a good competitor due to its early emergence and rapid vegetative growth through prolific branching (Chism and Bingham 1991), which enables it to smother its competition (Peters and Dunn 1971).

Previous research shows that large crabgrass is hard to control, as a single plant can produce up to 150,000 seeds, accumulating in the soil from years of infestation (Peters and Dunn 1971; Molinar and Elmore 2009). Various competition studies have been conducted on popular crops such as alfalfa (Peters and Dunn 1971), which document reduced crop yields in the presence of large crabgrass. For example, Peters and Dunn (1971) investigated competitive relationships between alfalfa and large crabgrass to find that not only was alfalfa yield decreased when crabgrass was present, but alfalfa tissue phosphorus (P) was lowered as well. Further competition studies on large crabgrass should be investigated. In particular, the competitive relationship between

crabgrass and the prominent biofuel feedstock, switchgrass; which should be further investigated in regions where large crabgrass is native, to determine if a long-term effect of competition exists.

CONCLUSIONS

With the current changes in global climate, environmental policy and general ecosystem changes, it is inevitable that a renewable energy alternative to fossil fuels must be found. The United States' Great Lakes region is heavily dependent on coal-fired power plants (Froese et al. 2010). As a perennial grass native to North America, switchgrass is a model bioenergy crop across suitable regions of the United States (U.S. Department of Energy 2005). Switchgrass holds great potential as a viable bioenergy crop within Michigan's Upper Peninsula because of its ability to succeed in marginal environments (Min and Kapp 2010). Future research is recommended to further investigate this promising species in Michigan's Upper Peninsula, other Great Lakes regions, and northern climates.

PURPOSE AND SCOPE OF TECHNICAL WORK

The overall objectives of this research are to investigate switchgrass establishment in the northern edge of its distribution through the effects of planting time and depth, and competition on the germination and establishment of switchgrass, through the developmental and competitive characteristics of Cave-in-Rock switchgrass and large crabgrass in Michigan's Upper Peninsula. This in turn, will determine if differences in initial conditions between switchgrass and large crabgrass affect the long-term outcome of competition. Specific above- and belowground studies will help to investigate the above- and belowground biomass allocation of competing switchgrass and large crabgrass, to determine if biomass allocation could affect the rate of switchgrass recovery. A greenhouse competition study investigated biomass allocation according to different densities of competing communities of switchgrass and large crabgrass, as well as root to shoot ratios. An indoor and outdoor seeding depth study was used to aid in establishing an optimal planting depth for switchgrass in Michigan's Upper Peninsula.

These studies will aid in determining the feasibility of growing switchgrass as a biofuel in Michigan's Upper Peninsula.

CHAPTER 2: THE EFFECT OF CRABGRASS WEED COMPETITION ON SWITCHGRASS BIOMASS PRODUCTION

ABSTRACT

While switchgrass (*Panicum virgatum* L.) is a perennial grass holding great promise as a biofuel resource, there is very little research exploring the possibilities of this southern grass in Michigan's Upper Peninsula, specifically, the initial interactions between switchgrass and competing weed species. Given that switchgrass requires an establishment period of about five years, the control of weeds plays a vital role in the economic success or failure of this species. Large crabgrass (*Digitaria sanguinalis* L.), is a weed of particular concern within Michigan cropping systems.

A randomized complete block design was installed June 2009 at two locations in Michigan's Upper Peninsula. Four treatments (0, 1, 4, and 8 plants/m²) of crabgrass were planted with one switchgrass plant. Treatments were replicated four times at each site. For the duration of the experiment, in-plot weed control was maintained through hand weeding and rototilling, with crabgrass weeds left to grow in year one and removed in year two. In October 2009 and 2010, switchgrass was harvested and aboveground biomass measured.

There was a significant difference between switchgrass biomass produced in year one, as a function of crabgrass weed pressure. There was no significant difference between the switchgrass biomass produced in year two versus previous crabgrass weed pressure. There is a significant difference between switchgrass biomass produced in year one and two. Thus, switchgrass showed no signs of a legacy effect of competition on biomass production. Overall, an antagonistic effect on switchgrass biomass yield during the establishment period has been observed as a result of increasing competing weed pressure.

The overall objectives of this research were to investigate switchgrass establishment in the northern edge of its distribution by investigating the effects of competition on the germination and establishment of switchgrass by the developmental and competitive characteristics of Cave-in-Rock switchgrass and large crabgrass in Michigan's Upper Peninsula. This work will develop a foundation for future research to examine if other economic implications of a legacy effect of competition on switchgrass as a biofuel for Michigan's Upper Peninsula, and northerly climates.

INTRODUCTION

The most basic definition of competition between plants can be described as a negative interaction that occurs among organisms, whenever two or more organisms require the same limited resource (Keddy 1989; Wedin and Tilman 1993). Competitors can reduce each other's growth, reproduction, or survival (Gause 1934) as they compete with desirable species by capturing nutrients, water, and solar radiation (Radosevich and Holt 1984; Aldrich and Kramer 1997). In agricultural cropping systems, these competitors are typically referred to as weedy species. A weedy species competing with a desired species is an example of interspecific competition (Connolly et al. 2001). Competition tends to be heavily affected by a plant's resource availability and population density (nearness and number of neighbors) (Murphy and Briske 1992). Grasses may develop several morphogenetic changes, such as reduced tillering and increased height, in order to adapt to reduced resource availability due to competition (Ballare et al. 1995). The long-term effects of competition on and from each species associated with perennial systems is very important to understand, as concentrations of limiting resources and differing plant traits can be responsible for differences in the resource reduction by each species (Wedin and Tilman 1993).

One of the common limitations associated with competition studies is the short time frame under which competition is often studied. Most competition studies, whether on both annuals and/or perennials, investigate plant parameters over a growing season or less (Law and Watkinson 1987; Sher 2000; Shainsky and Radosevich 1992). A one-year time frame may be suitable for an annual community, but competition dynamics within a

perennial community may vary greatly over a longer period of time (Tarasoff 2006; Bennett et al. 2011). Additionally, the length of time that a weed can remain within a desired cropping system, and eventually be removed with no resultant deleterious effects on quantity and quality of crop yield, is important in determining if a legacy effect of competition is present. If the effect of competition does not go away once the competing plant is removed, there may be a lingering (or legacy) effect of competition. Previous studies have investigated how long specific weeds of concern can remain in annual cropping systems without negative effects on the quantity and quality of the yield (Hager et al. 1998; Shainsky et al. 1992; Sher et al. 2000), but studies that evaluate perennial species over longer periods of time are lacking (Tarasoff pers. comm. 2011; Bennett et al. 2011).

Switchgrass (*Panicum virgatum* L.) requires a long establishment period; therefore, the early control of weeds will play a vital role in the success or failure of this species, ultimately determining whether this species is economically viable in northern climates (McLaughlin et al. 1999; Parrish and Fike 2005; Schmer et al. 2006; Perrin et al. 2008). Weed control in switchgrass establishment can cost an investor about twenty-five percent of the total establishment cost (Duffy and Nanhon 2002; De La Torre Ugarte et al. 2003), but these costs are most likely offset by a shortened establishment period (Tarasoff pers. comm. 2010). Therefore, a long-term investment will be required to reach maximum growth rates. This translates into a greater need to control weeds earlier, during the establishment period in the cropping cycle (Parrish and Fike 2005; Schmer et al. 2006; Wolf and Fiske 2009). Delays in switchgrass establishment can be attributed to competition from undesirable grassy and broadleaf weeds in the cropping system (Mitchell et al. 2008), poor seeding vigor and switchgrass seed dormancy (Gibson and Barnhart 2007). *Digitaria sanguinalis* L. (large crabgrass), is a fast growing, prostrate annual that is of particular concern within current, and potential switchgrass, cropping systems in Michigan's Upper Peninsula (Min pers. comm. 2009). Large crabgrass is known as an excellent competitor because of its early emergence, resulting in rapid

vegetative growth (Chism and Bingham 1991), which enables it to smother its competition (Peters and Dunn 1971).

However, very little research has been conducted to determine the legacy effect ('long-term' or 'lingering' outcome), of competition on growth rates of perennial species and/or annual species that have different growth strategies; in particular, studies relating the competitive interaction of large crabgrass and switchgrass in Michigan's Upper Peninsula and other northern regions. In addition, the long-term effect of early weed competition on establishment rates of switchgrass is unknown. The competitive relationship between large crabgrass and the promising biofuel crop, switchgrass, should be further investigated in regions where large crabgrass is already established, to determine if initial and/or long-term effects of competition exist. The objectives of this research are to investigate switchgrass establishment in the northern edge of its distribution by examining the effects of competition on the germination and establishment of switchgrass by the developmental and competitive characteristics of Cave-in-Rock switchgrass and large crabgrass in Michigan's Upper Peninsula. This work will develop a foundation for future research to examine if there are other economic implications of a legacy effect of competition on switchgrass as a biofuel for Michigan's Upper Peninsula, and northerly climates.

MATERIALS AND METHODS

FIELD STUDY

Year 1

Cave-in-Rock switchgrass (June 1, 2009) and large crabgrass (June 20, 2009) seeds were planted in styroblocks with 84 ml cavities (10.9 cm depth x 3.6 cm cavity top) (Beaver Plastics, Acheson, Alberta, Canada) at Michigan Technological University, Houghton, MI, under optimal greenhouse conditions ($32 \pm 2^{\circ}\text{C}$ with a 16:8 light:dark cycle) (Masiunas and Carpenter 1984). The switchgrass seed was supplied by the USDA-Natural Resource Conservation Service Elsberry Plant Materials Center (Elsberry, MO). The large crabgrass seed was supplied by the Columbia Basin Agricultural Research

Center (Pendleton, OR). Plants were watered as needed and fertilized with a 20N-20P-20K (Scotts Miracle-Gro Company, Marysville, OH) solution once every two weeks. On July 8, 2009, plants were moved outside for hardening.

The plants were transplanted to two locations in the Michigan's Upper Peninsula: "Miller Site", Houghton County, MI, (47.15°N, 88.70°W; Munising-Yalmer complex, dissected, 1-12% slopes; Munising—loamy till deposits; Yalmer—sandy outwash over loamy till deposits) and the Michigan State University Extension (MSUE), Upper Peninsula Experiment Station, "Chatham Site", Alger County, MI (46.34°N, 86.92°W; Eben very cobbly sandy loam; sandy-skeletal, mixed frigid Pachic Hapludolls) (Figure 2.1). Prior to transplanting, both sites were first chemically prepared with an application of glyphosate (N-(phosphonomethyl)glycine) (Roundup) (76.9 ml/3.8 L) (Monsanto, Creve Coeur, MO), followed by multiple tillages. The Miller Site was planted on July 16, 2009, (switchgrass seedlings were 46 days old and crabgrass seedlings were 26 days old), and the Chatham site was planted on July 20, 2009, (switchgrass seedlings were 50 days old and crabgrass seedlings were 30 days old). Switchgrass plants were approximately 13 cm tall with an average of 2 tillers (a tiller is defined by having 2 full leaves), and an average dry weight of 0.30 grams. A randomized complete block design was used. In each treatment one switchgrass was transplanted with 0, 1, 4, or 8 competing crabgrass plants. A 0.5 m² template was used and spacing between all seedlings was approximately 20 cm. Each treatment was replicated four times at each site (Figure 2.2). At the time of transplanting, all plants were well watered, and for 10 days following planting, all plots were watered daily if no natural precipitation occurred. For the duration of the experiment, in-plot weed control was maintained through hand weeding and rototilling.

Switchgrass was harvested at the Miller Site on October 9, 2009, and at the Chatham site on October 11, 2009. The plants were harvested at 15 cm and oven dried for 36 hours at 65°C (Sanderson and Reed 2000). Due to mortality, a total of 27 successfully established plots (Table 2.1) were used in this study. During harvest, the annual large crabgrass was left to die, and the perennial switchgrass was left to grow weed free for the remainder of the experiment.

Onset HOBO Microstation data loggers (Onset Computer Corp., Cape Cod, MA) were installed at the Miller Site June 5, 2010 and Chatham site May 28, 2010. The data loggers recorded air temperature, soil moisture (2 and 10 cm), and soil temperature (2 cm) at 30-minute intervals (Table 2.2).

Year 2

Competition sites were fertilized with nitrogen (56.1 kg/0.40 hectare) in both spring and fall, using 1.4 grams per 0.5 m² plot at the Miller Site on June 1 and August 23, 2010. The Chatham Site was fertilized on June 3, 2010, and not fertilized in the fall. For the duration of the experiment, in-plot weed control was maintained through hand weeding and rototilling, including crabgrass remains from the previous year.

Switchgrass was harvested at the Miller Site on October 6, 2010, and at the Chatham site on October 10, 2010, following the same procedures as year one.

GREENHOUSE STUDY

Using seed from the same source as above, a single switchgrass seed was planted with 0, 1, 4, or 8 competing crabgrass seeds in a 2.6 L pot (16 cm x 18 cm x 13 cm) filled with soil from the already established Miller research site. Seeds were planted using a circular template (radius=5.5 cm; area 95 cm²) on May 4, 2010, (8 replicates of each density 1, 4, and 8; and 12 replicates of 0, the control) and June 27, 2010, (12 replicates of each density 1, 4, and 8; and 24 replicates of 0, the control) (Figure 2.3). Plants were grown under optimal greenhouse conditions (32 ± 2°C with a 16:8 light:dark cycle) (Masiunas and Carpenter, 1984). Pots were watered as needed. Due to mortality and inconsistent germination, multiple pots contained unplanned numbers of competing crabgrass weeds; these pots were still utilized in the data analysis. A total of 56 successfully established pots (24 in May, and 34 in June) were used in this study (Table 2.3).

After 97 days, all plants were extracted from the pots; roots and above ground biomass were separated and grouped by species. Roots were washed and oven dried at 65°C for 72 hours. Shoot length, dry weight shoot and root biomass, and number of

tillers for both species were measured. Root to shoot ratio was calculated for switchgrass.

DATA ANALYSIS

Field Study

Following each of the two seasonal harvests, analysis of variance (ANOVA) tests were conducted comparing annual biomass yield by weed competition density, with site as a blocking factor. In addition, year one and two average overall biomass and switchgrass growth differences by weed competition density were compared. Comparisons between all treatments were conducted using Tukey-Kramer HSD test, with differences at $P < 0.05$ considered significant. All analyses were conducted using JMP (version 9.0.2, from SAS Institute Inc., Cary, NC, U.S.A.).

Greenhouse Study

Regression analysis were conducted using the two greenhouse trials, to investigate the relationship between weed competition density and switchgrass biomass yield, total root biomass, and root to shoot ratio. All analyses were conducted using JMP (version 9.0.2, from SAS Institute Inc., Cary, NC, U.S.A.).

RESULTS

ENVIRONMENTAL PARAMETERS

The average water content (2 and 10 cm), air and soil temperature differences between sites were similar, both throughout the entire growing season (May – Oct.) as well as within individual months (Table 2.2).

FIELD STUDY

There was a significant difference between switchgrass biomass produced in year one and crabgrass weed pressure. Mean switchgrass biomass decreased from 3.08 g per plant (± 0.81) with no competition to 2.11 g (± 0.37) with one competitor. With additional, increasing competition, biomass decreased even more to 0.91 g (± 0.76) and 0.80 g

(± 0.76) with crabgrass weed pressures of 4 and 8 plants, respectively ($P=0.0014$, $\alpha=0.05$) (Figure 2.4A, Table 2.4). There was no significant difference between the switchgrass biomass produced in year two, versus crabgrass weed pressure ($P=0.9143$, $\alpha=0.05$). Mean switchgrass biomass was 234.76 g (± 36.91) with no competition from the previous year, and 227.07 g (± 39.86) with eight previous competitors (Figure 2.4B, Table 2.5). There was a significant difference between switchgrass biomass produced in year one and two ($P<0.001$).

GREENHOUSE STUDY

A greenhouse competition study was performed to analyze above- and below-ground switchgrass responses to increased crabgrass weed pressure. The two trials were combined for analysis. The regressions were transformed to meet the assumptions of regression. The best-fit line for all regressions was a second-degree polynomial.

A negative relationship exists between aboveground switchgrass biomass accrual, and increasing crabgrass weed pressure; as crabgrass weed pressure increases, aboveground switchgrass biomass decreases ($P<0.0001$, $R^2=0.50$) (Figure 2.5):

$$M_s = 3.12 - 0.7158 N_g + 0.1128 N_g^2$$

M_s = switchgrass biomass (g)

N_g = number of crabgrass weeds

A negative relationship exists between switchgrass root biomass accrual, and increasing crabgrass weed pressure; as crabgrass weed pressure increases, belowground switchgrass root biomass decreases ($P<0.0001$, $R^2=0.37$) (Figure 2.6):

$$M_s = 1.908 - 0.349 N_g + 0.057 N_g^2$$

M_s = switchgrass biomass (g)

N_g = number of crabgrass weeds

A positive relationship existed between switchgrass root to shoot ratio, and increasing crabgrass weed pressure; as crabgrass weed pressure increases, switchgrass root to shoot ratio increases ($P < 0.0044^*$, $R^2 = 0.19$) (Figure 2.7). Variability also increased as large crabgrass weed pressure increased (Figure 2.7).

$$M_s = 0.604 + 0.097 N_g + 0.001 N_g^2$$

M_s = switchgrass biomass (g)

N_g = number of crabgrass weeds

DISCUSSION

FIELD STUDY

The results of this study support past research that weedy competition within cropping systems reduces crop yields (Hager et al. 1998; Shainsky et al. 1992; Sher et al. 2000). For example, the differences in switchgrass biomass yield in year one can be explained by the presence and increasing density of crabgrass competition (Figure 2.4A). Our result is similar to Peters and Dunn (1971) who investigated the effects of crabgrass on alfalfa. The switchgrass biomass yield in year one provides data that shows aboveground switchgrass biomass is negatively affected by increased crabgrass weed pressure. Not only is there a negative relationship, but also just one large crabgrass weed can reduce aboveground switchgrass biomass by up to 82%. Switchgrass not only requires a long establishment period (Parrish and Fike 2005), but its establishment can be delayed due to competition from grassy weeds (Mitchell et al. 2008). Therefore, crabgrass presence/competition in year one, and complete absence in year two, likely contributes to the overall lack of switchgrass growth/biomass yield demonstrated during

year one. Switchgrass is a perennial, with an extensive root system; it typically invests more growth efforts into belowground attributes during the first year of establishment (McLaughlin et al. 1999; Parish and Fike 2005). Large crabgrass, an annual weed with early emergence and rapid growth (Chism and Bingham 1991) could be an obvious competitive threat to a switchgrass seedling. Because biofuel production is focused on maximum biomass yields, a focus on weed control in these/switchgrass cropping systems is important, especially during the first year establishment period. However, maintaining weed-free cropping systems post establishment should be important as well, as weedy species are known to have deleterious effects on overall crop yields (Connolly et al. 2001). In general, large crabgrass is prevalent throughout Michigan's Upper Peninsula, as well as other Northerly climates, and could compete with potential/future switchgrass cropping systems.

The results of this study also support previous switchgrass research in Canada, where the first year of establishment only producing 30 to 40 percent of the maximum potential production, and the second growing season producing 70 to 80 percent (Girouard et al. 1999). Therefore, our low switchgrass biomass yield from the first year of establishment, and large yield in the second year of growth is typical. In addition, the lack of significant differences between the treatments in year two demonstrates that the switchgrass was able to fully recover after weed removal regardless of initial weed density. Thus, switchgrass showed no signs of a legacy effect of competition on biomass production.

General guidelines have evolved from studies as to relative competitiveness of weeds with various crops (Fleming et al. 1988; Hashem et al. 1998; Moechnig et al. 2003), the weed-free time needed following crop emergence (Hager et al. 1998), and the appropriate time of weed removal to prevent loss of crop quantity and quality (Park et al. 2003; Ni et al. 2004). Information of this nature which pertains to switchgrass production, are lacking, especially for northern climates. Thus, more long-term studies are needed to fully understand long-term plant responses to weed pressure and subsequent control. The data do not support past research (Tarasoff et al., 2008) that suggested a legacy effect of weed competition might exist within plant communities. However, this disconnection

could be explained due to the differences in species studied and their associated growth strategies.

As demonstrated in current studies by Bennett et al. (2011), destructive sampling should be done in the future to investigate belowground competitive aspects in the field, as well as soil community characteristics over long time periods. Long-term competition studies, as well as annual versus perennial plant competition studies are generally lacking. Thus, while this study demonstrated that weed competition affected yields in year one, and had no significant influence in year two, belowground influences are still not clear.

GREENHOUSE STUDY

This study enabled destructive sampling, which was not possible in the field study, to provide insight into the belowground effects of increasing large crabgrass densities on shoot and root parameters.

The results of this study support past research as well as our field experiment, which demonstrated that competition from weedy species, have a negative effect on crops (Hager et al. 1998; Shainsky et al. 1992; Sher et al. 2000). For example, the significant linear relationships between increasing weed competition and decreasing above- and below-ground switchgrass biomass (Figure 2.6 and 2.7) support previous research in which morphogenetic changes are known to occur in grasses in order to adapt to resource availability, due to competition (Ballare et al. 1995).

It is typical for annual grasses to produce less belowground biomass than aboveground biomass, while perennial grasses, such as switchgrass, produce more belowground biomass than aboveground biomass in the first year of establishment (Dalrymple and Dwyer 1967). Our root to shoot ratio results for switchgrass competing against eight crabgrass weeds averaged 1.48 ± 0.43 g after about 13 weeks of growth (Figure 2.7); previous studies by Dalrymple and Dwyer (1967) found switchgrass grown root to shoot ratios to range from 1.9 and 2.0 g, between 12 and 15 weeks of growth, respectively, with no competition. Thus, our average roots to shoot ratios were lower than

previously studied monocultures of switchgrass, demonstrating the negative effects of competition on root shoot ratios.

Generally 70 to 90 percent of the roots of perennial forage crops are located in the upper 20 cm of the soil (Bolinder et al. 2002); the majority of the switchgrass roots in the greenhouse experiment were root bound, and located at the bottom 16 to 18 cm of the grow pots, (which were 18 cm deep) (Yatso personal observation). Thus, the data do not support past work that often demonstrated a trend towards a larger proportion of roots in the upper layers of the soil, as the age of the perennial forage crop increases (Troughton 1957). There could be many possible reasons for our results. First, switchgrass is a perennial species, and it is known to have slow establishment (McLaughlin et al. 1999; Parish and Fike 2005). The location of the switchgrass roots could be in part due to the competition from the shallow-rooted annual, large crabgrass (Chism and Bingham 1991), and/or the size limitations of the grow pots. As the large crabgrass grew more rapidly than the switchgrass (Yatso personal observation), the shallow roots could have dominated the upper layers/depths of the potted soil, thus forcing the switchgrass to root more deeply in order to compete and survive in the artificial environment (Ballare et al. 1995).

The greenhouse study provided data that complemented the field competition studies that increased weed pressure negatively affects switchgrass growth, especially during the critical stage of emergence. This study also provided a glimpse into the belowground aspects of competition between switchgrass and large crabgrass. Further research should investigate specific rooting patterns and resource allocation of switchgrass when grown in competition.

CONCLUSIONS

This study investigated the developmental characteristics and competitive associations of switchgrass and large crabgrass, to determine if a legacy effect of competition exists between these species in Michigan's Upper Peninsula. Specific above- and below-ground studies determined that increasing weed competition negatively affects aboveground switchgrass biomass accrual, but if competitive weeds are removed after

first-year switchgrass establishment, the rate of switchgrass recovery in biomass yield is not affected; thus, no legacy effect of competition from the establishment year to the second year of growth exists between switchgrass and large crabgrass in Michigan's Upper Peninsula.

Continuing studies will investigate belowground influences of competition on switchgrass cropping systems in Michigan's Upper Peninsula. Our work will develop a foundation for future research to examine the economic implications of planting switchgrass as a biofuel crop in Michigan's Upper Peninsula, as well as other northern climates.

FIGURES

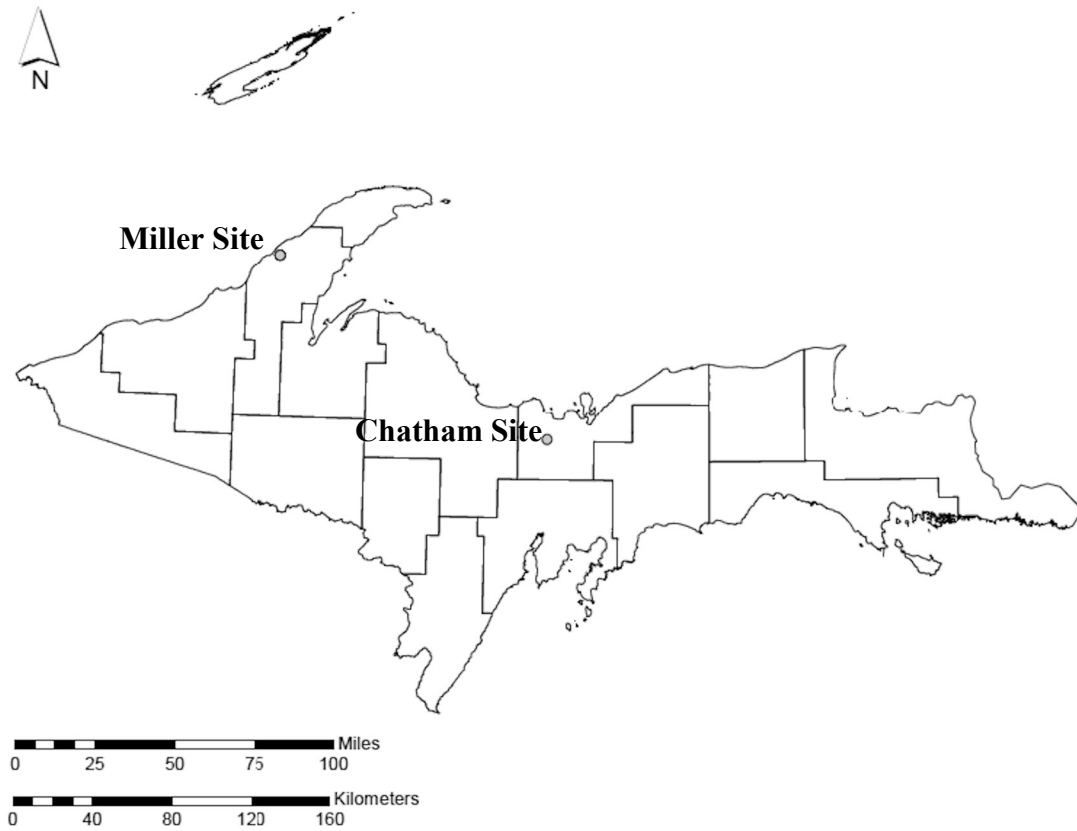


Figure 2.1. Competition study sites in Michigan's Upper Peninsula: Miller Site, Houghton County, MI, and Chatham Site, at the Michigan State University Extension (MSUE), Upper Peninsula Experiment Station, Chatham study site, Alger County, MI.

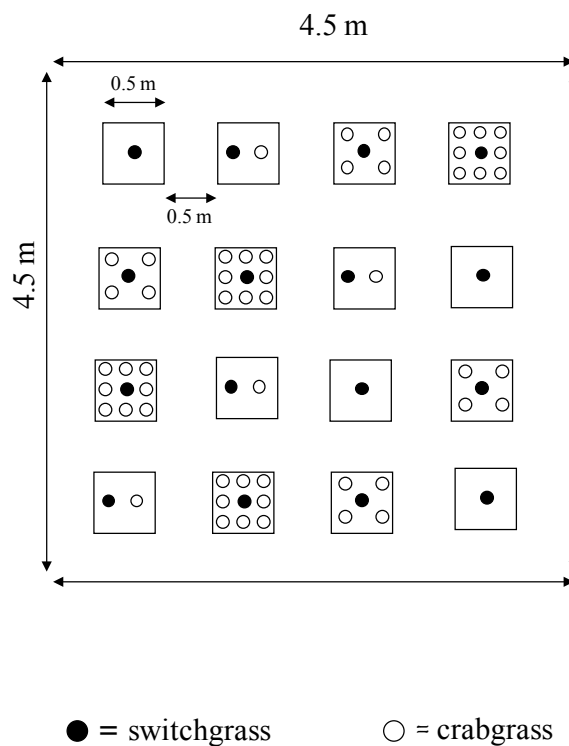


Figure 2.2. Diagram of Miller Site competition plot in each treatment one switchgrass was transplanted with 0, 1, 4, or 8 competing crabgrass plants ($n = 4$). A 0.5 m template was used and spacing between all seedlings was approximately 20 cm. The planting layout for the Chatham site was the same only it had 2.5 m alleyways for rototiller use.

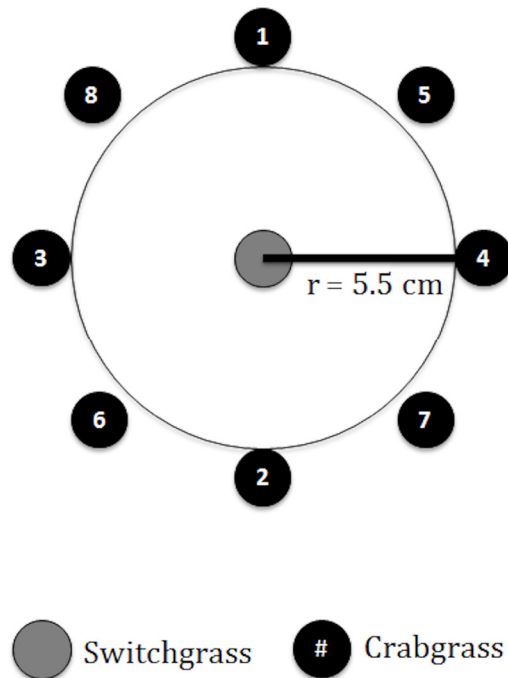


Figure 2.3. Circular template used to plant monocultures of switchgrass and combinations of increasing weed pressure from 0, 1, 4, or 8 competing crabgrass plants on May 4, 2010, and June 27, 2010 in greenhouse experiment. Number, according to the seed placement dependent on competition pressure, labels crabgrass.

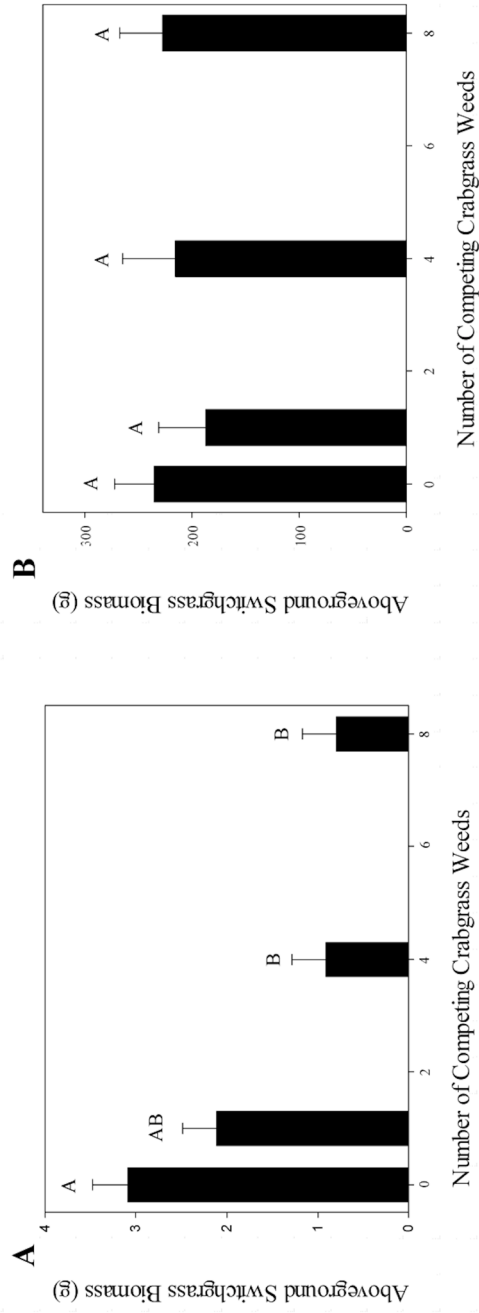


Figure 2.4. Effect of crabgrass weed competition in field study, on aboveground switchgrass biomass year one, 2009 (A) and year two, 2010 (B). Columns labeled with the same letters are not significantly different at $\alpha = 0.05$. Vertical bars at the top of the columns represent standard error of the mean.

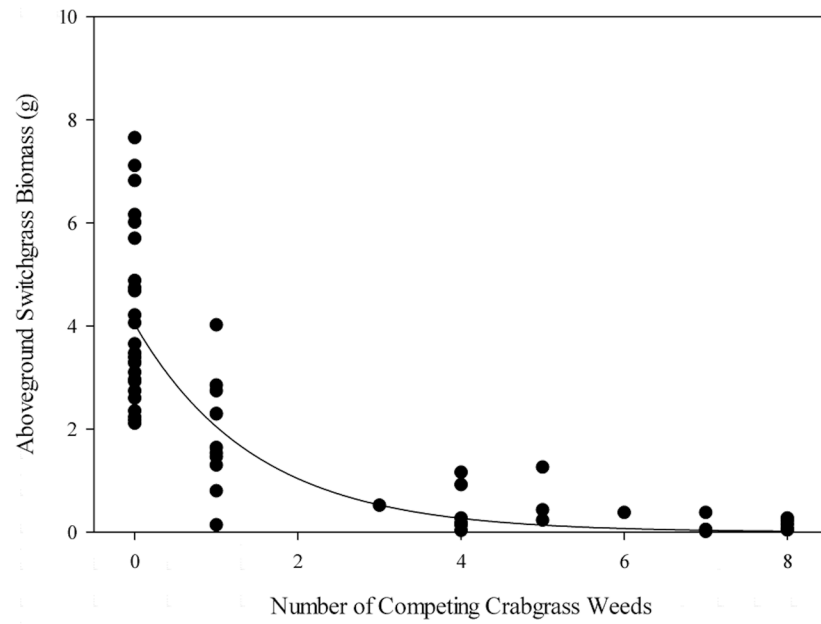


Figure 2.5. Effect of greenhouse crabgrass weed pressure on switchgrass biomass yield.
 $M_s = 3.12 - 0.7158 N_g + 0.1128 N_g^2$. M_s = switchgrass biomass (g), N_g = number of crabgrass weeds.

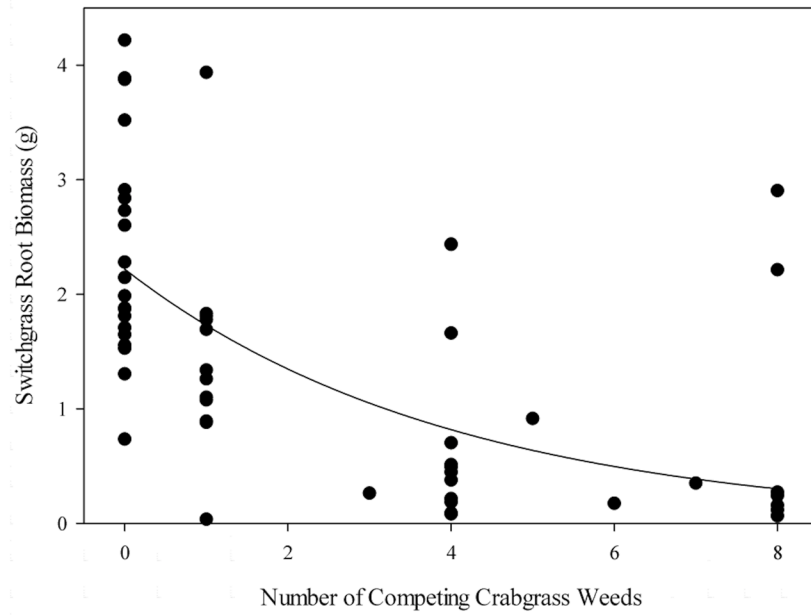


Figure 2.6. Effect of greenhouse crabgrass weed pressure on switchgrass root biomass accrual. $M_s = 1.908 - 0.349 N_g + 0.057 N_g^2$. M_s = switchgrass biomass (g), N_g = number of crabgrass weeds.

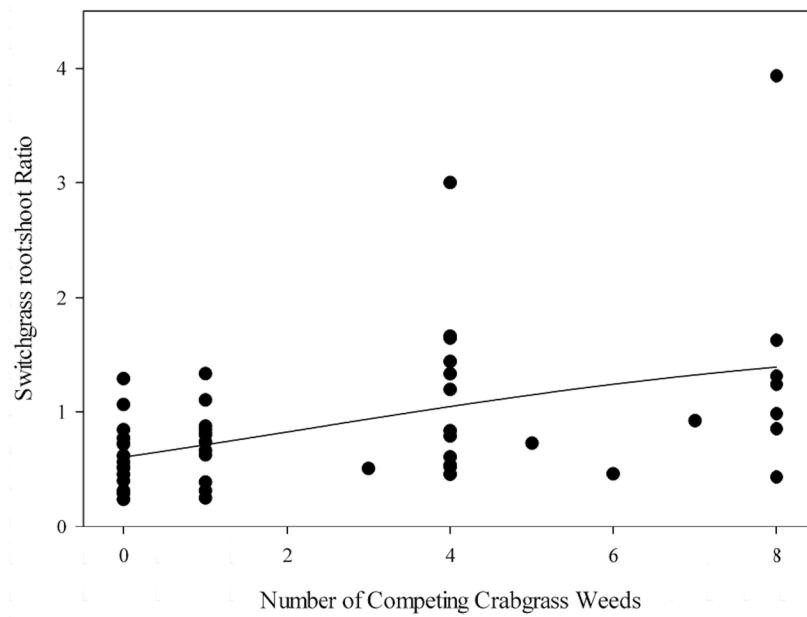


Figure 2.7. Effect of competing crabgrass on switchgrass root:shoot ratio, in a greenhouse environment. $M_s = 0.604 + 0.097 N_g + 0.001 N_g^2$. M_s = switchgrass biomass (g), N_g = number of crabgrass weeds.

TABLES

Table 2.1.
Field trials for switchgrass seedlings.

	Number of Replicates Planted		“Surviving” Replicates	
Weed Density	Chatham	Miller	Chatham	Miller
0	4	4	4	4
1	4	4	3	4
4	4	4	3	3
8	4	4	4	2
Total	16	16	14	13
Grand Total	32		27	

Table 2.2.
2010 averages from HOBO Microstation weather data.

Month	Avg. Soil Water Content, m ³ /m ³ at 10 cm		Avg. Soil Water Content, m ³ /m ³ at 2 cm		Avg. Soil Temp, °C		Avg. Air Temp, °C	
	Chatham	Miller	Chatham	Miller	Chatham	Miller	Chatham	Miller
June	0.08	0.17	0.15	0.20	14.93	15.24	17.36	18.06
July	0.05	0.13	0.15	0.17	19.84	20.47	21.77	21.61
Aug	0.03	0.10	0.11	0.16	20.01	20.21	22.03	20.37
Sept	0.11	0.12	0.16	0.19	11.69	11.13	14.69	13.19
Oct	0.12	0.11	0.16	0.20	8.24	7.49	11.25	9.04
Period Avg.	0.07	0.13	0.14	0.18	16.35	16.43	18.72	17.91

Table 2.3.
Greenhouse trials for switchgrass seedlings.

Weed Density	Number of Replicates Planted		“Surviving” Replicates	
	May 4	June 27	May 4	June 27
0	12	12	9	11
1	8	12	7	6
2	-	-	-	-
3	-	-	1	-
4	-	-	3	9
5	8	12	1	-
6	-	-	1	-
7	-	-	1	-
8	8	24	1	6
Total	36	60	24	33
Grand Total	96		56	

Table 2.4.
ANOVA results for switchgrass biomass (g) year 1.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Site	1	0.841972	0.841972	0.7579	0.392
Density	3	25.658838	8.552946	7.6989	0.0008*
Model	4	27.021807	6.75545	6.0809	
Error	26	28.88427	1.11093		
C. Total	30	55.906077			0.0014*

Table 2.5.
ANOVA results for switchgrass biomass (g) year 2.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Site	1	2117.6704	2117.6704	0.2124	0.6508
Number of Competing Crabgrass Weeds	3	7384.7774	2461.592467	0.2469	0.8624
Model	4	9401.23	2350.31	0.2357	
Error	17	169512.11	9971.3		
C. Total	21	178913.34			0.9143

CHAPTER 3: SEEDLING EMERGENCE AND BIOMASS PRODUCTION FOR SWITCHGRASS (*Panicum virgatum* L.) AS INFLUENCED BY PLANTING DEPTH AND DATE IN NORTHERN CLIMATES

ABSTRACT

Switchgrass (*Panicum virgatum* L.) is a perennial grass holding great promise as a biofuel resource. While Michigan's Upper Peninsula has appropriate land base and climatic conditions, there is little research exploring the possibilities of switchgrass production. The main objectives of this research were to determine optimum planting depths and timing for switchgrass in Michigan's Upper Peninsula.

A randomized complete block design was installed at two locations in Michigan's Upper Peninsula; on seven planting dates, 25 seeds were planted 2 cm apart along 0.5 m rows at depths of: 0.6 cm (0.25 in), 1.3 cm (0.5 in), and 1.9 cm (0.75 in). The number of emerged seedlings was tallied weekly, until harvest in October 2010. Emergence and biomass yields were compared by planting date and depths. A greenhouse seeding experiment was established in pots, using the same planting depths and parameters as the field study. The number of seedlings was tallied daily for 30 days.

Planting switchgrass in Michigan's Upper Peninsula should be done in the spring (May or June). Planting in May will produce more biomass yield in the first year, whereas planting in June will have more emergences and survivorship; making June more appropriate. Both the field and greenhouse experiments determined that there is no significant difference between planting switchgrass at 0.6 cm, 1.3 cm, and 1.9 cm.

The main objectives of this research were to determine optimum planting depths and timing for switchgrass in Michigan's Upper Peninsula. These results will lead to future establishment of switchgrass planting guidelines for Michigan's Upper Peninsula and other Northern climates.

INTRODUCTION

Currently, perennial, warm-season (C4) grasses are considered to be both the most efficient and most sustainable biofuel energy crops in temperate regions, due to their potential for high yields on marginal lands (Adler et al. 2007; Karp and Shield 2008;

Russi 2008; Lee et al. 2009; Williams et al. 2009; Dauber et al. 2010). Of the C4 grasses, the perennial species, switchgrass (*Panicum virgatum* L.), is one of the most popular and promising biomass crops in the southeastern and central United States (Cundiff and Marsh 1996; Vogel et al. 2002; Teel and Barnhart 2003; Parrish and Fike 2005; Comis 2006). Switchgrass has received widespread attention due to its high productivity, low site impact, low energy input requirements, and limited vulnerability to pests and diseases (Froese 2007; Wolf and Fiske 2009; Min and Kapp 2010). Being a native species, switchgrass has been exposed to North American pathogens for decades, and possesses a broad genetic background (Parish and Fike 2005; Mitchell et al. 2008; Wolf and Fiske 2009). Because switchgrass has widely adapted and favorable traits, it is of particular interest in the northern, Great Lakes Region of the United States for biofuel production.

Research has been conducted on depth and seeding requirements of native warm-season grasses, including switchgrass when managed for biofuel crop and grazing in the Great Lakes Region. The results of these trials have recently been summarized through Michigan State University's Extension Service (Mitchell et al. 2011). In brief, *Panicum virgatum* L. var. *virgatum* ('Cave-in-Rock' switchgrass variety) is able to survive the harsh winters of Michigan's Upper Peninsula; this variety also consistently has the highest yields, averaging 5.73 dry metric tons per hectare per year (Min and Kapp 2010). Therefore, other northerly locations have become candidates for switchgrass production.

Limited research information is available on planting schedules and requirements for switchgrass in Michigan's Upper Peninsula. Studies in the Great Lakes Region suggest that switchgrass seeds should be planted anywhere from 0.6 cm to 1.3 cm deep, but no deeper because of soil moisture requirements and seed size (Wolf and Fiske 2009). Switchgrass seed is very small and dormant at harvest (Gibson and Barnhart 2007; Wolf and Fiske 2009); germination typically occurs within a week after planting (Wolfe and Fiske 2009), though it can be slow if soil temperatures are below 16°C. Switchgrass should be planted in the spring, within two to three weeks of before or after the recommended date for planting corn (*Zea mays*) in a region where switchgrass has not been planted (Wolf and Fiske 2009; Min and Kapp 2010; Mitchel et al. 2011). For the state of Michigan, corn is typically planted from late April to early June (Mitchel et al.

2010). Wolf and Fiske (2009) also suggest that while early June is ideal for planting switchgrass, planting even earlier is appropriate if weeds are an issue. Switchgrass will grow until the first killing frosts in the fall. Single harvests should take place during the fall of a growing season, and are recommended to increase switchgrass productivity and survival (Mitchell et al. 2011). As a crop, approximately three years are required to reach maximum productivity (Parish and Fike 2005; Gibson and Barnhart 2007). During the first year, the plant will grow to only one third of its potential (McLaughlin et al. 1999; Parish and Fike 2005), but once fully established the plant is quite vigorous (Gibson and Barnhart 2007; Wolf and Fiske 2009).

Information on optimum planting depths and timing for switchgrass is not available for switchgrass in Michigan's Upper Peninsula, and is generally lacking for northern climates. The main objectives of this research were to determine optimum planting depths and timing for switchgrass in Michigan's Upper Peninsula. Our results will lead to the establishment of switchgrass planting guidelines for northern climates.

MATERIALS AND METHODS

FIELD STUDY

This research was conducted at two locations in Michigan's Upper Peninsula, the "Miller Site", Houghton County, MI (47.15°N, 88.70°W) and the "Gierke Site", Houghton County, MI (46.97°N, 88.48°W) (Figure 3.1). Soil types were Munising-Yalmer complex (dissected, 1-12% slopes; Munising—loamy till deposits; Yalmer—sandy outwash over loamy till deposits) at the Miller Site, and Munising loamy fine sand (1-8% slopes) at the Gierke site. Cave-in-Rock switchgrass seed was supplied by the USDA-Natural Resource Conservation Service Elsberry Plant Materials Center (Elsberry, Missouri). Onset HOBO Microstation data loggers (Onset Computer Corp., Cape Cod, MA) were installed at the Miller Site on 5 June 2010, and Gierke Site on 6 June 2010, recording air temperature, soil moisture (2 and 10 cm), and soil temperature (2 cm) (Table 3.1). The data loggers were removed 6 October 2010, the date of harvest. On three dates throughout the study 12 soil cores were taken at each site to determine average gravimetric soil water contents (Table 3.2); 15 May, 2010: 6 samples at 8 cm depths; 1

June and 25 July, 2010: 6 samples each at 2 and 10 cm depths. Gravimetric soil moisture was calculated using the following percent soil water content formula:

$$\%SWC = 100 \times (ww / dsw)$$

$$\% \text{ Soil water content} = \%SWC$$

$$\text{Water weight (g)} = (\text{wet weight} - \text{dry weight}) = ww$$

$$\text{Dry sample weight (g)} = (\text{dry weight} - \text{weighing tin weight}) = dsw$$

The experimental design at both sites was a completely randomized design within a 22 m × 6.5 m plot (Figure 3.2). Each row was 0.5 m long. A 1 m fence was installed along the perimeter of the research plot to prevent herbivory. On seven planting dates (5 and 19 Sept., 1 Oct. 2009, 1 and 15 May, 1 and 15 June, 2010), 25 switchgrass seeds were planted 2 cm apart along a 0.5 m row, 0.6 cm (~0.25 in), 1.3 cm (~0.5 in), and 1.9 cm (~0.75 in) deep. Seeding depths were obtained by making a furrow in the soil with a marked meter stick, to predetermined depths, 0.6, 1.3, and 1.9 cm. Seed was placed uniformly by hand, then covered with surrounding soil to fill the furrow and establish the predetermined planting depth. Soil was then compacted after planting. Each treatment was replicated three times at each site. The number of emerged seedlings was tallied weekly. For the duration of the experiment, in-plot weed control was maintained through weekly hand weeding. On 6 October 2010 aboveground biomass was harvested by row and oven dried for 3 d at 65°C (Sanderson and Reed 2000).

GREENHOUSE STUDY

A greenhouse seeding experiment was established at Michigan Technological University, Houghton, MI, under optimal greenhouse conditions (32 ± 2° C with a 16:8 light:dark cycle) (Masiunas and Carpenter 1984). Within a large rectangular (62×21×19 cm) container, 25 switchgrass seeds were planted 2 cm apart, along a 0.5 m row at depths of 0.6 cm (~0.25 in), 1.3 cm (~0.50 in), or 1.9 cm (~0.75 in). Seeding depths were obtained by making a furrow in the soil with a marked meter stick, to predetermined depths, 0.6, 1.3, and 1.9 cm. Seed was placed uniformly by hand, then covered with

surrounding soil to fill the furrow and establish the predetermined planting depth. Soil was compacted after planting. Four replications of each depth were planted on 7 July and then again on 9 August 2010. Cave-in-Rock switchgrass seed was supplied by the USDA-Natural Resource Conservation Service Elsberry Plant Materials Center (Elsberry, Missouri). Professional growing mix (SunGro Sunshine Germinating Mix #3) was used in all replications. The pots were watered daily. Emergence was tallied daily for 30 days.

DATA ANALYSIS

Field Study

Switchgrass emergence and biomass yield were analyzed using analysis of variance (ANOVA) between planting date and depth. An ANOVA test was performed on the percent total switchgrass survival to harvest, and then compared to the percent of total emergence. Percent total switchgrass survival to harvest was calculated by:

$$((S / 25) / 49\%) \times 100$$

S = number of surviving seedlings at harvest

25 = number of seedlings planted per row

49% = switchgrass viability

Percent total emergence was calculated by:

$$((E / 25) / 49\%) \times 100$$

E = largest number of seedlings counted during the entire study

25 = number of seedlings planted per row

49% = switchgrass viability

Percent survivorship of switchgrass by depth was calculated by dividing the number of emerged seedlings, by the amount of total seeds planted multiplied by 49% seed viability (provided by the USDA-Natural Resource Conservation Service Elsberry Plant Materials

Center). All analyses were conducted using JMP (version 9.0.2, from SAS Institute Inc., Cary, NC, U.S.A.).

Greenhouse Study

Switchgrass total emergence by planting depth was analyzed using analysis of variance (ANOVA). Descriptive statistics were used to investigate the effect of depth on switchgrass rate of emergence. Percent survivorship, days until the appearance of the first coleoptiles, and number of days until the last emergence, was calculated for switchgrass by planting depth. Percent survivorship of switchgrass by depth was calculated by dividing the number of emerged seedlings, by the amount of total seeds planted multiplied by 49% seed viability (provided by the USDA-Natural Resource Conservation Service Elsberry Plant Materials Center). All analyses were conducted using JMP (version 9.0.2, from SAS Institute Inc., Cary, NC, U.S.A.).

RESULTS AND DISCUSSION

ENVIRONMENTAL PARAMETERS

The average air and soil temperature between sites were similar, both throughout the entire growing season (May – Oct.) as well as within individual months (Table 3.1). At 2 cm, the overall and average monthly water content was higher at the Miller site, but the average water content (m^3/m^3) at 10 cm showed negligible differences between sites. Moisture content at shallow depths can be variable, especially when being measured by only one probe. Thus, the moisture difference between sites should be acknowledged (Table 3.1 and 3.2), as there was a site interaction present for switchgrass spring planting dates and biomass yield (Figure 3.4).

FIELD STUDY

Though there was initial emergence (counted on 19 Sept.) from the 5 Sept. planting date, an infinitesimal amount of the seedlings survived through Sept. and the winter. There was a significant difference ($P < 0.001$) between the four spring planting dates: 1 and 15 of May and June. Therefore, the spring planting dates were used for all further analysis. There was no interaction between site and planting depth ($P = 0.0899$)

for switchgrass emergence; Therefore switchgrass emergence was grouped for analysis of spring planting dates. There was no significant difference between planting depths (0.6 cm = 7; 1.3 cm = 2; 1.9 cm = 11) in switchgrass emergence ($P = 0.0502$) (Table 3.4).

There was a significant difference in biomass yield ($P < 0.001$) between planting switchgrass in the fall (Sept. and Oct.) and the spring (May and June) in Michigan's Upper Peninsula. Biomass yield for switchgrass was analyzed by site, as there was interaction present between depth and site ($P = 0.0114$), though there was no interaction between date and site ($P = 0.1196$) (Table 3.5).

There was no interaction between planting depth and site ($P = 0.3351$), and no significant difference between seeding depths ($P = 0.4433$) for switchgrass percent emergence and total survival; Therefore switchgrass emergence was grouped for analysis of spring planting dates. There was a significant difference ($P < 0.001$) between spring planting dates for percent total emergence of switchgrass (Figure 3.5, Table 3.6).

The results of this study support our hypotheses that spring planting dates are favorable for switchgrass emergence and biomass yield in Michigan's Upper Peninsula (Figure 3.3 and 3.4). Our results also support previous research, which states that the best time to plant switchgrass in other northerly latitudes is in the spring (Girouard et al. 1999, Min and Kapp 2010, Mitchell et al. 2010). For example, Girouard et al. (1999) suggest planting in between 15 May and 10 June in eastern Ontario, and Wolf and Fiske (2009) suggest early June or even sooner in the Great Lakes Region.

While fewer switchgrass seedlings emerged in May (1 and 15 May = 3.39 ± 0.38), the plants produced more biomass in the first year of establishment (1 May = 127.51 ± 22.90 g; 15 May = 106.96 ± 19.16 g, respectively); the June plantings had more emergence (1 June = 5.41 ± 0.39 ; 15 June = 5.06 ± 0.38) (Figure 3.3), but produced less biomass (1 June = 58.04 ± 6.45 g; 15 June = 56.75 ± 6.67 g, respectively) during the first year of establishment (Figure 3.4). This could be explained in part because the June plantings had one fewer months to grow prior to the October harvest; this month, and its warmer temperatures, likely made a significant difference. Michigan's Upper Peninsula is

known for long, cold winters, with annual minimum temperatures ranging from -28.9°C to -31.6°C (USDA 2011) . The average dates for Houghton County's first fall frost are between 1 and 30 of Sept. (USDA 2011). While a May planting date would allow more time for switchgrass to grow during the short growing season, it could provide added weather-related risks, such as late frosts or colder soil temperatures, characteristic of northern climates. Thus, although May proved to be more productive for switchgrass biomass yields, June planting dates had more overall emergence; percent emergence and total percent survival was higher as well (Figure 3.3). Therefore, June planting dates would be more appropriate, providing more individuals for the second year of growth, as switchgrass is not harvested during the first year of establishment.

While the results of this study support past research of switchgrass planting depths between 0.5 cm and 1.3 cm (Girouard et al. 1999; Wolf and Fiske 2009), significantly better switchgrass germination and yields at 1.9 cm add critical information to the literature. Small seed size and moisture requirements of switchgrass support shallower seeding depths (Girouard et al. 1999; Wolf and Fiske 2009). A previous study by Newman and Moser (1988) found that switchgrass seed emergence percentage was higher than most grasses at depths as deep as 6.0 cm. Switchgrass emergence was the highest between depths of 1.5 and 3.0 cm (Newman and Moser 1988), further supporting our results, as well as a deeper planting depth. In fact, the results of our study show no significant difference in either switchgrass emergence ($P=0.0622$) (Table 3.4) or biomass yield ($P=0.1196$) (Table 3.5), between planting at the shallowest suggested depth (0.6 cm) and deepest (1.9 cm) (Figure 3.6). Thus, the necessity for precision in planting depth may not be as essential when planting switchgrass in northern climates, as there is no significant difference between planting at 0.6 cm and 1.9 cm depths (Figure 3.6); though planting at a 1.9 cm depth might be an added benefit of drought resistance in the future.

Although switchgrass seed is small, there may be advantages to deeper plantings. For example, there could be increased soil moisture available to the seed and/or less of a risk of desiccation, or the extra depth could provide protection from predation or inclement weather during the seed's sensitive emergence stage. It is important to observe

and follow weather trends in Michigan's Upper Peninsula; weather can be variable, resulting in unusually cold springs, late snow melts, and colder spring soil temperatures. The average dates for Houghton County's last frost are 1 to 30 May (USDA 2011), keeping in mind that switchgrass germination can be delayed if soil temperatures are below 16° C (Wolfe and Fiske, 2009). Additionally, the planting timing of switchgrass can be impacted by a window of rainfall forecast or soil moisture level, rather than fixed calendar dates, especially when dealing with variable, northern climates (Min pers. comm. 2011). The deepest planting depth of 1.9 cm also had the highest average germination (41%) (Table 3.3). Deeper planting depths could potentially translate into less monetary loss to a farmer from seed mortality.

GREENHOUSE STUDY

The results of this study support the findings of our field experiment, as well as previous research (Girouard et al. 1999; Wolf and Fiske 2009). As previously mentioned, planting depths over 1 cm have not been supported by previous research (Girouard et al. 1999; Wolf and Fiske 2009), but our greenhouse study provided further support that switchgrass could be planted at 1.9 cm, with no risk of lower emergence rates (Figure 3.7). The average switchgrass germination for the greenhouse study also supports planting at any of the three depths, as switchgrass germination ranged from 81% at 0.6 cm, to 71% at 1.3 cm (Table 3.7). As expected, the germination for the greenhouse study was higher than that of the field study across all planting depths (Table 3.3 and 3.7).

The daily monitoring of emergence enabled our study to investigate the effect of planting depth on other aspects of switchgrass germination, such as the appearance of the coleoptiles and days until the last switchgrass seedling emergence. For all three planting depths, no emergence was noted until day 5. The depth of planting affected the amount of days until the last seedling emergence. The days until the last seedling were inversely proportional to depth; the shallowest depth had seedlings emerge up to 27 days after planting, whereas the deepest depth had seedlings emerge until 18 days after planting (Figure 3.8 and Table 3.7). While planting depth does not affect when the first seedlings emerged, it does impact the amount of time between first and last emergence, with the

shallowest depth (0.6 cm) emerging over the longest time period (27 days) (Table 3.7). If seeds are emerging over longer periods then they are at higher risk to variable weather, threats of herbivory/predation, or other factors. In the field, a shorter establishment period could allow for a longer growing period for the seedlings, potentially increasing biomass yields. However, a variable, or staggered, emergence strategy could be beneficial potentially preventing the farmer from relying on just a two week emergence time period. If the farmer is using irrigation, the shorter emergence strategy (deeper depths) could be more beneficial, enabling a more predictable timeframe for when the majority of the seed will emerge; thus, allowing shorter watering times, translating into monetary gain. However, if the farmer is not using an irrigation system, then planting deeper (resulting in a staggered emergence), could be better if the weather is variable or involves dry spells that would wipe a single crop out; later emerging seeds would be able to survive and produce profits for the farmer.

CONCLUSION

In Michigan's Upper Peninsula, and potentially other Northern climates, the optimal planting time for Cave-in-Rock switchgrass is in the spring months of May or June; Planting within the first two weeks of May will produce more aboveground biomass, whereas planting within the first two weeks of June will have a higher survivorship. There is no significant difference in biomass production or emergence between the planting depths of 0.6 cm and 1.9 cm in the field trials. Soil type will be a key factor in determining an appropriate depth for switchgrass planting anywhere. Our research concludes that Cave-in-Rock switchgrass should be planted in June at any depth ranging from 0.6 cm to 1.9 cm in Michigan's Upper Peninsula, and/or other similar northern climates. In addition, it should be recognized that switchgrass planting timing can be impacted by a window of rainfall forecast or soil moisture level, rather than fixed calendar dates, especially when dealing with variable, northern climates.

Current research and literature on establishing switchgrass cropping systems in the Great Lakes Region is lacking. Other credible data on switchgrass establishment in Michigan's Upper Peninsula will be fundamental in determining switchgrass prices,

locations, and quality and quantity of biomass for investors and developers associated with this emerging bioenergy market. Our research supports previous research concluding that managing switchgrass for bioenergy in the Midwest is an option as an environmentally sustainable production system. Our results will lead to the establishment of switchgrass planting guidelines for other northern climates as well.

FIGURES

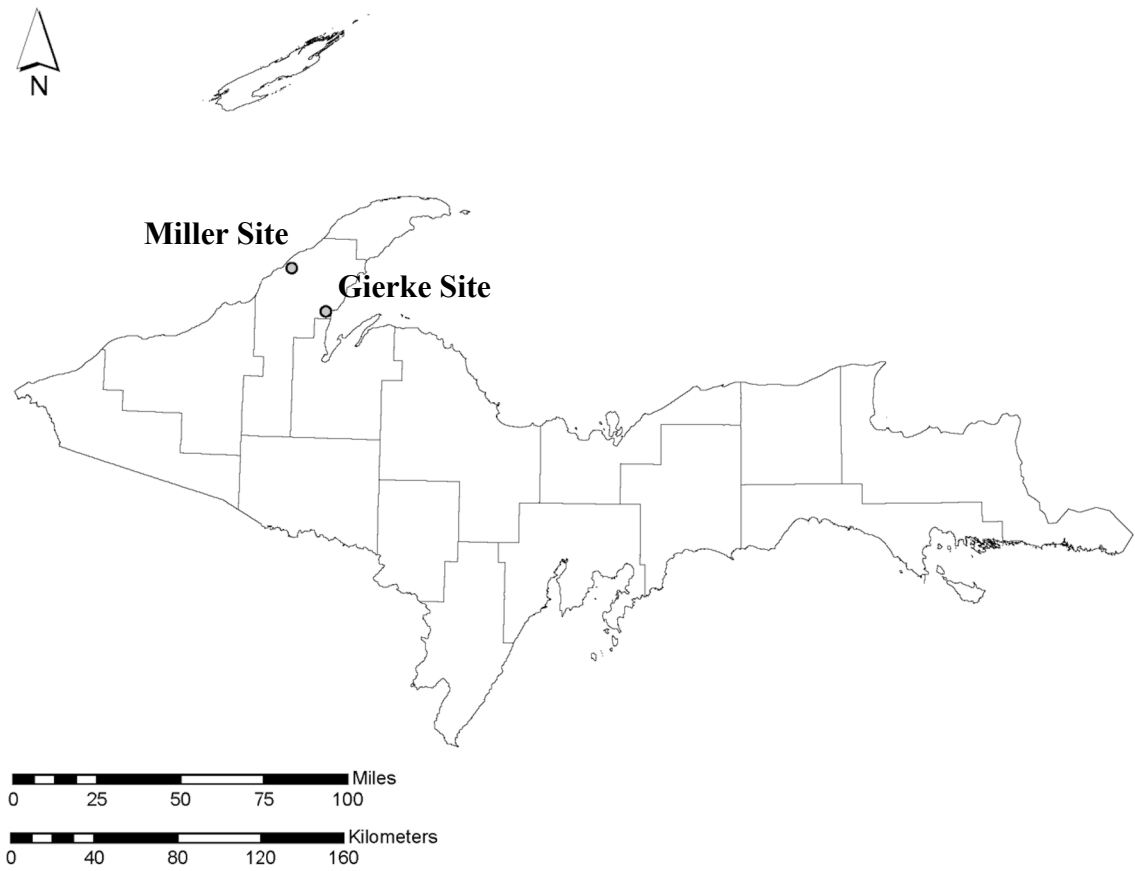


Figure 3.1. Study sites in Michigan's Upper Peninsula: Miller Site and Gierke Site, Houghton County, MI.

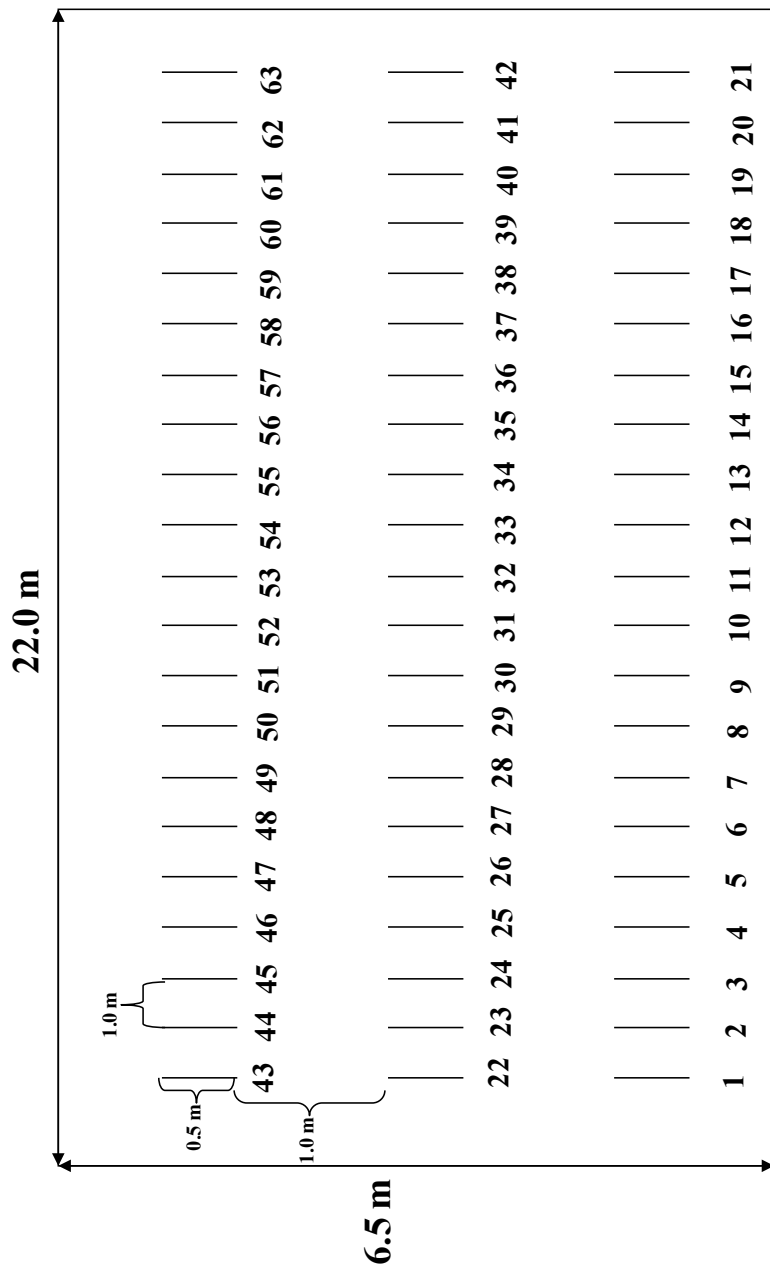


Figure 3.2. Completely randomized design at Miller and Gierke sites.

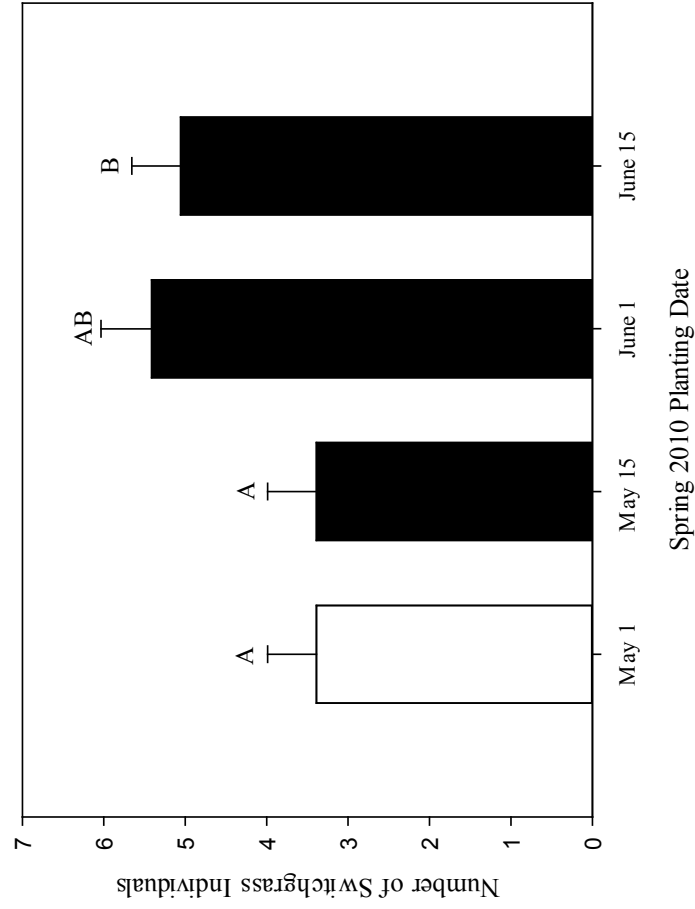


Figure 3.3. Effect of spring planting date for switchgrass emergence. Mean values reported. Columns labeled with the same case letters are not significantly different at $\alpha = 0.05$. Vertical bars at the top of the columns represent standard error of the means.

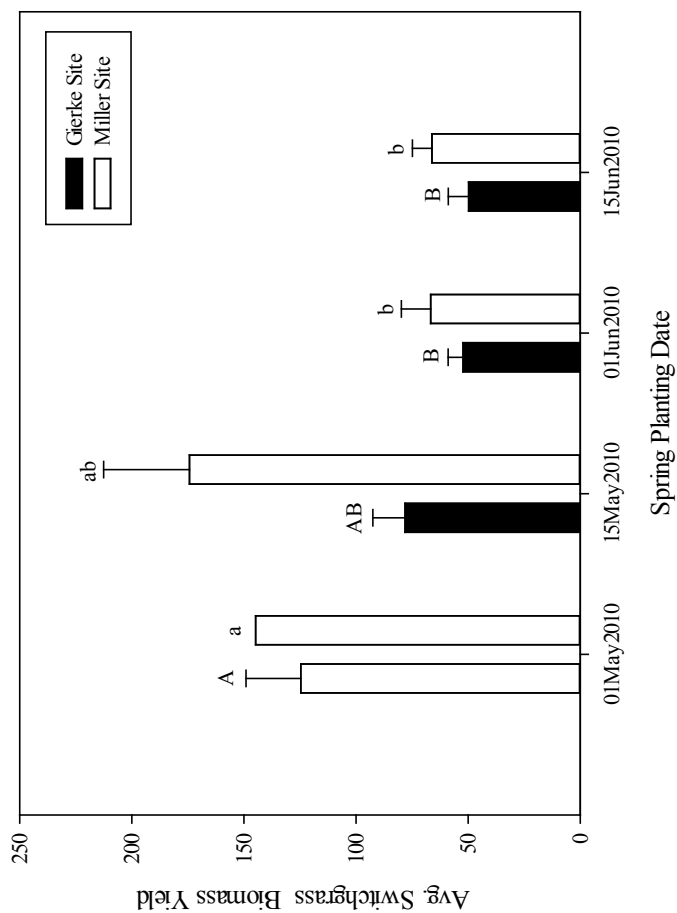


Figure 3.4. Effect of spring planting date on switchgrass biomass yield, by site for the field study. Mean values reported. Columns labeled with the same case letters are not significantly different at $\alpha = 0.05$. Vertical bars at the top of the columns represent standard error of the means.

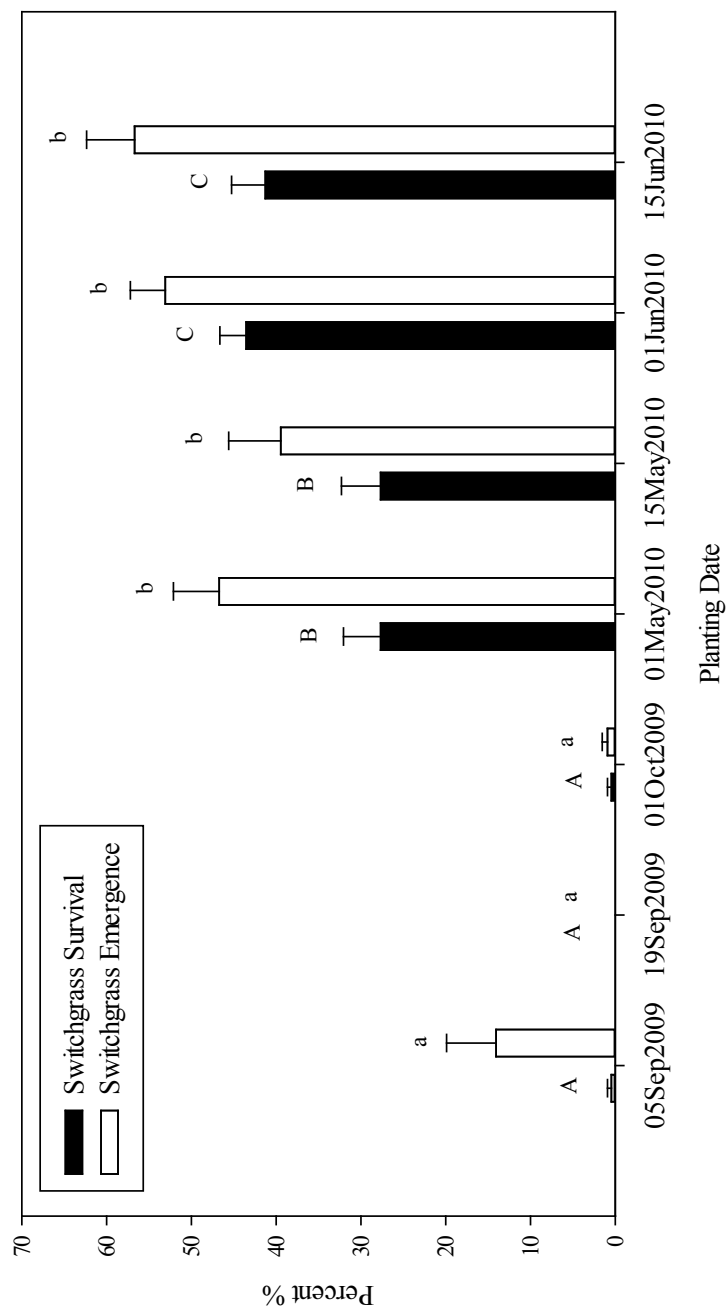


Figure 3.5. Percent switchgrass survival and switchgrass emergence by planting date. Mean values reported. Columns labeled with the same letters are not significantly different at $\alpha = 0.05$. Vertical bars at the top of the columns represent standard error of the means.

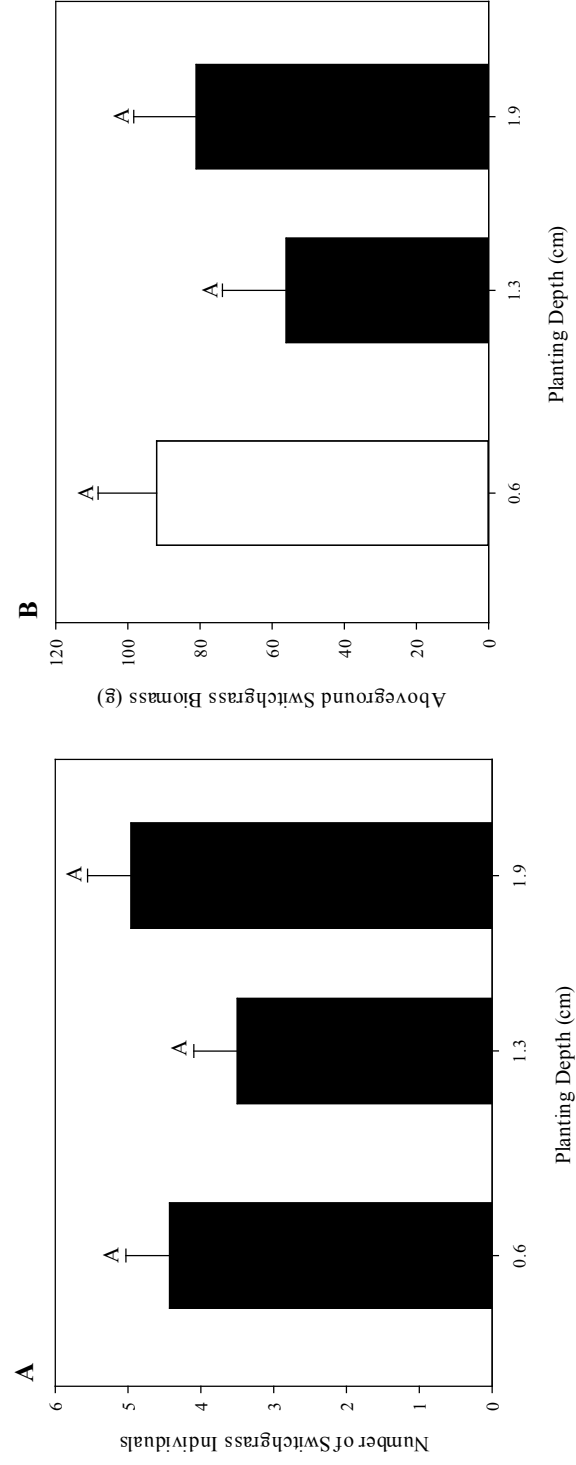


Figure 3.6. Effect of planting depth on switchgrass emergence for the field study. Mean values reported. Columns labeled with the same letters are not significantly different at $\alpha = 0.05$. Vertical bars at the top of the columns represent standard error of the means.

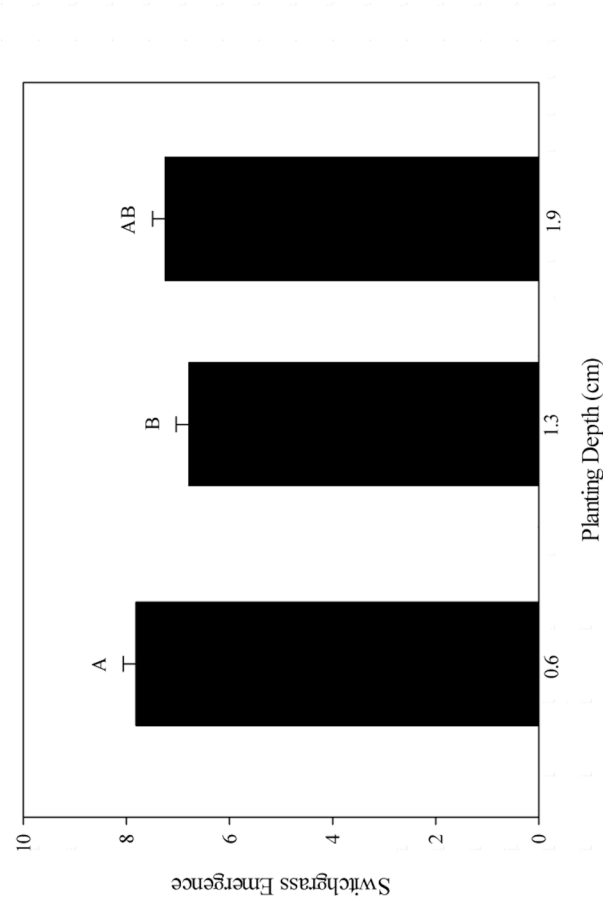


Figure 3.7. Effect of planting depth on switchgrass emergence for the greenhouse trials. Mean values reported. Columns labeled with the same letters are not significantly different at $\alpha = 0.05$. Vertical bars at the top of the columns represent standard error of the means.

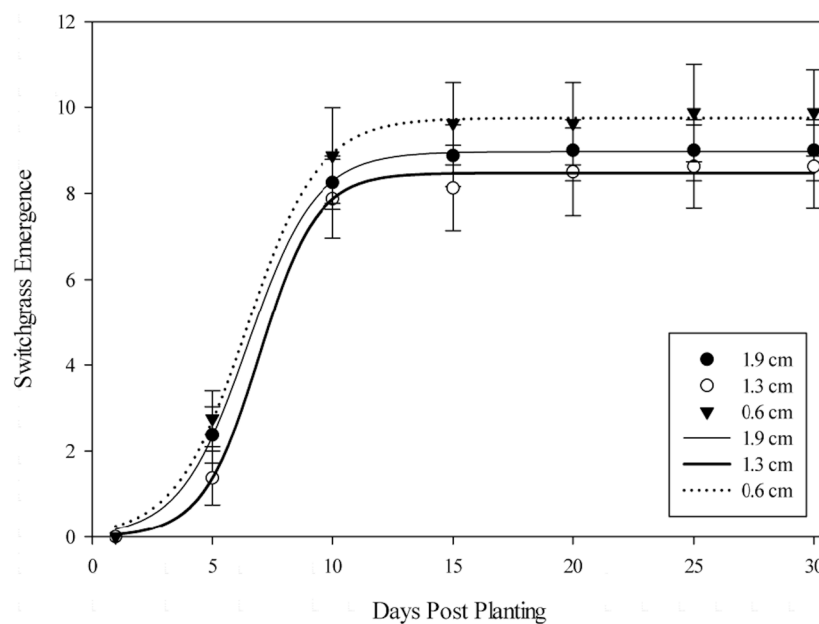


Figure 3.8. Effect of planting depth on rate of emergence for the greenhouse trials. Mean values reported for that day, every five days. Vertical bars represent standard error of the means.

TABLES

Table 3.1.
2010 Averages from HOB0 Microstation weather data.

Month/Site	Ave. Water Content, m ³ /m ³ at 10 cm			Ave. Water Content, m ³ /m ³ at 2 cm			Ave. Soil Temp, °C		Ave. Air Temp, °C	
	Gierke	Miller		Gierke	Miller		Gierke	Miller	Gierke	Miller
June	0.12	0.17		0.10	0.20		15.71	15.24	18.08	18.06
July	0.10	0.13		0.06	0.17		20.40	20.47	22.03	21.61
Aug	0.06	0.10		0.02	0.16		20.29	20.21	21.59	20.37
Sept	0.12	0.12		0.07	0.19		11.52	11.13	14.16	13.19
Oct	0.14	0.11		0.08	0.20		8.36	7.49	10.45	9.04
Period Ave.	0.10	0.13		0.06	0.18		16.66	16.43	18.63	17.91

Table 3.2.
Average gravimetric soil water contents by site.

Date	Depth (cm)	Gierke	Miller	Total Avg.
May 15, 2010	10	$14 \pm 1 \%$	$27 \pm 2 \%$	21 %
June 1, 2010	2	$4 \pm 0 \%$	$14 \pm 2 \%$	9 %
June 1, 2010	8	$10 \pm 2 \%$	$22 \pm 1 \%$	16 %
July 25, 2010	2	$8 \pm 0 \%$	$13 \pm 1 \%$	11 %
July 25, 2010	8	$11 \pm 1 \%$	$22 \pm 1 \%$	16 %
Total Avg.	6	$9 \pm 1 \%$	$20 \pm 1 \%$	15%

Table 3.3.
Average percent switchgrass survivorship for field trials.

Planting Date	Avg. Percent Survivorship by Planting Depth		
	0.6 cm	1.3 cm	1.9 cm
September 5, 2009	1.36 ± 1.36	0.00 ± 0.00	0.00 ± 0.00
September 19, 2009	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
October 1, 2009	0.00 ± 0.00	1.36 ± 1.36	0.00 ± 0.00
May 1, 2010	31.29 ± 9.05	20.41 ± 5.48	31.29 ± 8.28
May 15, 2010	29.93 ± 4.04	20.41 ± 10.05	32.65 ± 9.19
June 1, 2010	39.46 ± 6.80	42.18 ± 4.43	48.98 ± 4.71
June 15, 2010	43.54 ± 4.55	31.29 ± 6.80	48.98 ± 7.89

Table 3.4.
ANOVA results for switchgrass emergence.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Depth (cm)	2	26.521056	13.260528	3.1332	0.0502
Date	3	61.513916	20.50463867	4.8448	0.0042*
Model	5	87.69214	17.5384	4.144	
Error	65	275.09659	4.2323		
C. Total	70	362.78873			0.0025*

Table 3.5.
ANOVA results for switchgrass biomass (g) by site.

Source	DF	Sum of Squares	Mean Square Error	F Ratio	Prob > F
Gierke Site					
Depth (cm)	2	6403.696	3201.85	2.7549	0.0837
Date	3	24975.395	8325.13	7.1631	0.0013*
Model	5	30754.974	6150.99	5.2924	
Error	24	27893.325	1162.22		
C. Total	29	58648.299			0.002*
Miller Site					
Depth (cm)	2	4402.472	2201.24	1.8737	0.2037
Date	3	31790.776	10596.93	9.02	0.0034*
Model	5	35359.472	7071.89	6.0195	
Error	10	11748.257	1174.83		
C. Total	15	47107.73			0.008*

Table 3.6.
ANOVA results for switchgrass percent total emergence.

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
			Error		
Planting Depth (cm)	2	2069.11	1034.56	1.8475	0.1622
Planting Date	6	134000.01	22333.34	39.8833	<0.0001*
Model	8	136069.12	17008.6	30.3744	
Error	117	65516.16	560		
C. Total	125	201585.28			<0.0001*

Table 3.7.
Summary of switchgrass trials by planting depth, for the greenhouse.

Planting Depth (cm)	Avg. Percent Survivorship	Days until first coleoptiles	Days until last emergence
0.6	81	5	27
1.3	71	5	24
1.9	74	5	18

THESIS CONCLUSIONS

The objectives of the studies described herein were to investigate switchgrass establishment in the northern edge of its distribution through: investigating the effects of competition on the germination and establishment of switchgrass, and determining the optimum planting depths and timing for switchgrass in Michigan's Upper Peninsula.

Through the developmental and competitive characteristics of Cave-in-Rock switchgrass and large crabgrass (*Digitaria sanguinalis* L.) in Michigan's Upper Peninsula, it was determined that no legacy effect of competition exists between switchgrass and large crabgrass in Michigan's Upper Peninsula between the first and second year of establishment. In addition, specific above- and below-ground studies determined that increasing weed competition negatively affects aboveground switchgrass biomass yields, but if competitive weeds are removed after first-year switchgrass establishment, the rate of switchgrass recovery in biomass yield is not affected.

Planting Cave-in-Rock switchgrass in Michigan's Upper Peninsula should be done in the spring (May or June) at any depth ranging from 0.6 cm to 1.9 cm. Planting in May will produce more biomass yield in the first year, where planting in June will have more emergences and higher percent survival. Rainfall or soil moisture level, rather than fixed calendar dates, could additionally determine the timing of switchgrass planting, especially when dealing with variable, northern climates. This study is unique in the sense that it is one of the few that has investigated specific planting aspects of switchgrass in Michigan's Upper Peninsula, a region in which both literature and research on this subject are lacking.

The data collected from the studies listed above will aid in establishing planting guidelines for switchgrass production in other northern climates. It may also be used in future research to determine the economic implications of weed competition on biofuel production of switchgrass in Michigan's Upper Peninsula, and fully determine the feasibility of growing switchgrass as a biofuel in northern climates.

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