Summer August 2014

ASSESSING BEST MANAGEMENT PRACTICES FOR IMPROVING SWITCHGRASS ESTABLISHMENT AND PRODUCTION

Amir Sadeghpour
University of Massachusetts Amherst

ASSESSING BEST MANAGEMENT PRACTICES FOR IMPROVING SWITCHGRASS ESTABLISHMENT AND PRODUCTION

A Dissertation Presented

by

AMIR SADEGHPOUR

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2014

Department of Plant and Soil Science

ASSESSING BEST MANAGEMENT PRACTICES FOR IMPROVING SWITCHGRASS ESTABLISHMENT AND PRODUCTION

A Dissertation Presented

by

AMIR SADEGHPOUR

Approved as to style and content by:

Masoud Hashemi, Chair

Stephen Herbert, Co-chair

Timothy Randhir, Member

Michelle DaCosta, Member

Wesley Autio, Department Head
Plant and Soil Sciences

DEDICATION

I dedicate my dissertation work to my family. A special feeling of gratitude to my loving parents, Gholamreza Sadeghpour and Lida Malek who have given me love and a strong will to encounter the challenges of everyday life. My brother Babak who has always encouraged me in my academic pursuits and in loving memory of my Grandmothers, Batool Karami and Soghra Ramzi who raised me and taught me the value of education when I was a child.

ACKNOWLEDGMENTS

I would like to express my deepest appreciation to my committee chair, Dr. Masoud Hashemi who believed in me at the first place. Thank you for giving me the opportunity to come to the University of Massachusetts as a graduate student and for helping me to experience working not only on switchgrass establishment and production, but also on a wide range of agronomic crops. Special thanks go to my committee co-chair, Dr. Stephen Herbert for his unbelievable patience, belief, time, and support. I would not be where I am now without you. I thank Dr. Timothy Randhir, who introduced me to the world of modeling and simulation and taught me how complex the ecosystems are. Special thanks go to Dr. Michelle DaCosta for her invaluable advice and support. Many thanks to Dr. Sarah Weis for her endless support both in lab and field works. I would like to thank Dr. Allen Barker for inspiring me to work hard and improve myself. I want to thank Dr. Wesley Autio for supporting me as the graduate director and for answering to my endless statistical questions. Thanks go to my best friend Emad Jahanzad for being there for me every time I needed him. Life was much easier with your presence. I would like to thank Ali Farsad and Leryn Gorlitsky who helped me to adapt to the academia in USA and gave me helpful advice. Special thanks go to Neal Woodard for his invaluable assistant in my field works and for improving my work by his critical advice. Thanks go to Mallory Ottariano, Jaqui Carlevale, Edward Bodzinski, and Madeline Magin for assisting me in conducting my experiments. Special thanks go to Micky Spokas for her kind support and advice.

There are several people outside of academia who made this journey possible. Thanks go to my aunts, Lili and Farah Malek and Monir Sadeghpour for encouraging me to focus to continue my studies. Thanks go to my wonderful cousins and friends Shiva and Maryam Kalantari, Parinaz Maghferat, Amir Azadi, Mahsa Siavashpouri, Amin Nikravan, Yashar Zeinali, Maryam Shafii, Hamed Attar, Iman Arefzadeh, and Margaret Engesser who made my life so happy and joyful. Most importantly I want to thank my family: Gholamreza and Babak Sadeghpour and especially my mother, Lida Malek. I owe everything in my life to you.

ABSTRACT

ASSESSING BEST MANAGEMENT PRACTICES FOR IMPROVING SWITCHGRASS ESTABLISHMENT AND PRODUCTION

MAY 2014

AMIR SADEGHPOUR, B.A., AZAD UNIVERSITY OF VARAMIN

M.S., UNIVERSITY OF TEHRAN

Ph.D., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Dr. Masoud Hashemi

Switchgrass (*Panicum virgatum* L.) is a C_4-grass indigenous to North America being considered as the "model" energy crop. Switchgrass is difficult to establish and first-year stand failure often challenge the large scale production of switchgrass. Reliable establishment methods and effective weed management practices to produce a harvestable biomass in the establishment year are required. Also, to maximize the economic viability of switchgrass production, appropriate nutrient management and harvests are needed. Thus, we conducted researches to improve switchgrass establishment and production. These studies ranged from finding the most promising switchgrass variety to adjusting switchgrass seeding rate, determine the most appropriate seeding date, seeding methods, weed management, nitrogen application, and harvest management.

Currently Cave-in-Rock is a highly suggested upland variety for northern region of United States. Results of our variety trials both at establishment and production level

indicated that Carthage and Shawnee could also be considered as promising varieties in northern regions of United States. In a four-year study, Carthage consistently produced higher biomass yield compared with other varieties. A vigor test trial was suggested for adjusting switchgrass seeding rate and we found significant differences between the required seeding rate for producing acceptable first-year biomass in fertile soils and marginal soils. While approximately 7 kg ha^{-1} seeding rate might be sufficient for fertile soils, 15 kg ha^{-1} might be required to produce enough established seedling for the same biomass production in a marginal soil. An early planting of switchgrass was not as effective as a late planting in weed suppression but plants were more advanced morphologically thus, produced acceptable biomass yield with root system which ensures successful second-year production. Among cover crops, oat outperformed others (Fallow and Rye) with both suppressing weeds and improving switchgrass establishment. Results suggested drastic differences between no-till planting and seeding with cultipacker seeder where no-till planting into oat produced significantly higher biomass yield compared with cultipacker seeder. A firm seedbed is also another desirable method of planting where significantly improved switchgrass establishment and production was observed with 2 times rolling/cultipacking after seeding. Our findings indicated that application of herbicides is strongly required in the establishment year where a Broad Spectrum application of atrazine, quinclorac, 2,4-D, and dicamba improved switchgrass establishment through effective control of weeds. We found a late-fall harvest could improve switchgrass quality for combustion (less moisture, ash, and nutrient content) without yield reduction for many years. When switchgrass was harvested in late-fall, no response to N application was found.

Overall, it is proposed that a no-till planting of switchgrass into oat cover crop with herbicide application planted in early-June could provide a successful stand and later, a late-fall harvest without any N application could maintain crop productivity with acceptable biomass yield and quality for several years.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Establishment and production of switchgrass grown for combustion: A review

Abstract

Switchgrass (*Panicum virgatum* L.) is a C_4-grass with deep fibrous root systems indigenous to North America. In recent years switchgrass has been considered to be a "model" energy crop due to its high productivity, perenniality, and adaptability to various sites and soils. This paper specifically reviews published works on the effect of cultural management practices on switchgrass establishment, biomass production and composition, dynamic of nutrient and non-structural carbohydrates (NSC) translocation from above-ground to roots and nitrogen-use efficiency (NUE).

Introduction

In recent years notably interest has been paid to biomass-based energy production due to economic and environmental issues related to fossil fuel (Colbran and Eide, 2008). Use of grain corn (*Zea mayes* L.) as the common feedstock for ethanol production has raised serious concerns about its sustainability. These concerns are mainly related to environmental pollution due to increased soil erosion and high agricultural inputs including chemical fertilizers and herbicides. Therefore, use of perennial species (grasses and woods) as more environmentally friendly sources of bioenergy production (Navik et al., 2010). A ten-year study that began in the 1980's at Oakland Ridge National Laboratory identified switchgrass as an ideal species for bioenergy production due to variety of its desirable characteristics (Parrish and Fike, 2005). Consequently, dedicated research effort over the last thirty years, has led to significant progress in developing switchgrass as a biofuel crop (Shastri et al., 2012). The ultimate use of switchgrass is commonly either ethanol or heat (Balan et al., 2012); however, when cultivation land is limited, energy production through combustion seems more feasible (Gorlitsky et al., 2012). In this article the challenges associated with establishment, survival, and production of switchgrass grown for combustion are discussed.

Switchgrass plant overview

Switchgrass is a warm-season (C_4), sod-forming perennial tall grass native to North America (Lemus et al., 2009) with deep fibrous roots which can reach up to 3 m deep (Ma et al., 2000). The species has been evolving since approximately two million years ago and its dispersal from tropical regions to Central and North America created an extensive genotypic variation among the crop species leading to high adaptation of switchgrass to a wide range of growing conditions (Parrish et al., 2012). Latitudinal differences are most responsible for variation among switchgrass populations. Latitude of origin has been reported to have a significant impact on productivity, survival, and adaptation traits of switchgrass (Sanderson et al., 1999; Casler et al., 2004). In 1966, porter categorized switchgrass populations between two distinct ecotypes; "upland" and "lowland." Lowland ecotypes occur in lower hydric conditions in lower latitudes, whereas upland varieties occur in drier, elevated conditions and are more common at higher latitudes (Hultquist et al., 1996). Lowland ecotypes are more tolerant of wet conditions than upland types and grow taller and faster, but are more sensitive to drier conditions (Forberg, 2009). The leaves of lowland switchgrass are bluish-green and coarser and thicker than upland varieties. Additionally, the ligules are longer and the panicles are larger than upland types (Casler, 2005). Upland ecotypes have thin stems, are generally less productive than the lowland varieties, often grow in a bunch form and are adapted to dry conditions (Christian and Elbersen et al., 1998). Although lowland ecotype is less tolerant to dry conditions, the extensive root systems of switchgrass allow for both ecotypes to be more drought tolerant than other herbaceous crops such as Miscanthus (*Miscantus giganteum* L.). Elberson et al. (2001) determined that latitudinal differences were the main factor influencing adaptability, when southern varieties had higher yields in the north than northern varieties. When grown too far north however, southern varieties could be winter-killed (Parrish and Fike, 2005). In general, Northern ecotypes have a longer winter dormant period with better winter survival than southern ecotypes when grown at the same latitude (Jefferson and McCaughey, 2012). Conversely, planting Northern varieties in southern locations does not necessarily maximize the yield because these varieties cease growth sooner in the fall due to their adaption to shorter growing season (Van Esbroek et al., 2003). Figure 1 illustrates biomass yield differences between upland and lowland cultivars within an ecotype (Wullschleger et al., 2010). Among lowland ecotypes, the most productive cultivars were Alamo, SL941, SL931, Kanlow, NL942 and SL932 with average biomass production of 12.2 to 14.8 Mg ha^{-1} (Fig. 1). Within upland ecotypes, Cave-in-Rock, NE Late, HDMDC3, Late-Synthetic-HY, Shelter, and NU94 were the highest yielding cultivars with median rates of annual biomass production that ranged from 9.6 to 11.4 Mg ha^{-1} (Fig. 1).

Establishment management

One of the important challenges in switchgrass production is seedling establishment (Shastri et al., 2012; Monti et al., 2001). Similar to many warm-season perennial grasses, switchgrass has been known to be difficult or slow to establish (Evers and Butler, 2000; Monti et al., 2001; Sadeghpour et al., 2013). Poor establishment in the planting year directly relates to reduced stand vigor and yield in succeeding years and limits large scale crop adoption (Mitchell et al., 2008 and 2010; Berti and Johnson, 2013). It is estimated that a stand failure costs growers over \$300 ha^{-1} (Perrin et al., 2008).

Switchgrass initially allocates energy to establishing an extensive root system in the first and second year and will consequently only reach 33 and 66% of its maximum production capacity, respectively (McLaughlin and Kszos, 2005). Due to the allocation of energy to the development of root structures, switchgrass will not reach its full yield potential until the third year (Madakadze et al. 1998). This extended establishment time has dissuaded many growers and entrepreneurs from planting switchgrass given the lack of financial return in the first two years; however with proper planning, switchgrass can be profitable endeavor for growers.

Establishment of switchgrass specifically in the establishing year can be influenced by several factors including high seed dormancy and weed pressure, improper planting technique or seedbed preparation, and adverse environmental conditions (Moser and Vogel, 1995; Monti et al., 2001; Parrish and Fike, 2005).

Seed dormancy

Seed dormancy is one of the major challenges in establishment of switchgrass (Mitchell et al., 2008). Switchgrass seed has been proven to be highly dormant at seed dispersal (Harper et al., 1983; Hopkins and Taliferro, 1997). Innate seed dormancy can be caused by many chemical or physical inhibition mechanisms; however, it is most often due to the immaturity of the seed embryo at (Zhang and Maun, 1989; Zegada-Lizarazu et al., 2012). Chemical inhibition is caused by hormones that restrict germination (Zhang and Maun, 1989) whereas; physical inhibition is caused by seed coat barrier (Sautter et al. 1962). One strategy to increase germination rates for maximum stand establishment is to reduce seed dormancy (Parrish and Fike, 2009). Dormancy reduction can be achieved through various methods. Two common approaches are stratification and after-ripening (Shen et al., 2001). Studies concluded that stratification or a wet pre-chilling treatment at 5 °C for two or more weeks reduced dormancy rates (Zarnstorff et al., 1994; Smart and Moser, 1997). Averaged over two Cave-In-Rock seedlots, Shen et al. (2001) found that stratification at 5 °C 14 days increased germination from 7 to 75%. Zhang and Maun (1989) also found that germination rates could be increased from 3% to anywhere from 88-98% by scarification of the seed coat. Although this method was successful, in a review article, Parrish and Fike (2005) stated that seed priming, scarification and hormonal treatments may not be applicable strategies on large-scale switchgrass production. One seed dormancy-breaking technique that is more feasible for large-scale production is after-ripening, storage of seeds for one or more years in a warm environment, which has shown positive practical effects on the reduction of dormancy in switchgrass (Shen et al., 1999).

Sowing rate

Variable germination rates of switchgrass due to seed dormancy can confound determination of sowing rate (Forberg, 2009). Several studies have developed, various planting rate recommendations have been made based on different calculation methods. Whether based on mass per area or number of “pure live seeds” per area, there have been many points of confusion regarding this matter (Parrsih and Fike, 2005). Pure live seed

(PLS) refers to seed that is viable, including both dormant and non-dormant seeds (Berti and Johnson, 2013). In a standard germination test (AOSA, 1993), results would be lower than in a viability test for PLS because dormant seeds will not necessarily germinate (Gutormson and Patin, 2002). Seed distributors often test their seeds for viability (PLS), germination rate, weed seed contaminations and inert matter and include the test results on the seed packaging. Using the distributor's test results for PLS (%) or germination (%) to calculate planting rates will lead to an inaccurate planting rate (Mitchell and Schmer, 2012). Due to reduction in dormancy rates over time, current germination percentages do not necessarily correspond with supplied information. Conversely, seed testing laboratories will present inflated test data collected from controlled environment that do not accurately represent the stressed conditions that might occur in the field. In summary, the use of seed distributors' test results for determination of sowing rate should be avoided. Forberg et al. (2009) concluded that it is more practical to implement a vigor test and then compensate for restricted germination by adjusting sowing rates.

Precise planting rates are crucial for a successful and economical planting of switchgrass as a bioenergy crop (Mitchell and Vogel, 2012). A low stand frequency will limit yield and too high of a stand frequency will waste seed (Vogel and Master, 2001). The average recommended planting rate is 4 to 10 kg ha^{-1} PLS (Moser and Vogel, 1995; Vogel, 2000; Teel et al., 2003). Alternatively, recommendations have been made based on number of established plants per m^{-2}. Teel et al. (2003) recommended 20 plants per m^{-2} as an adequate established stand for bioenergy usage; however, it is difficult to plant at a rate targeted for number of established plants per area. Forberg (2009) found 30-50% seedling mortality after emergence across four varieties (Blackwell, Carthage, Cave-in-

Rock, and Dacotah) grown in Massachusetts. He also observed higher seedling mortality with higher seeding rates. Jung et al. (1990) planted 600 PLS m^{-2} and achieved stand densities of 278 plants m^{-2} (Parrish and Fike, 2005). Ultimately, desired stand frequency or density is the principle consideration for the determination of planting rates. Vogel and Masters (2001) designed a frequency grid with which stand density of switchgrass could be determined. In their previous switchgrass establishment research, frequency-grid-measured switchgrass stands of 40 to 50% or greater indicated a successful stand, frequencies between 25 to 50% were marginal to adequate, and frequencies <25% indicated partial stands that need replanting (Schmer et al., 2006; Mitchell and Schmer, 2012). Mitchell and Schmer (2012) reported that in most cases, poor seed quality resulted in poor stand establishment that required re-planting.

Other factors that affect the establishment of switchgrass include soil preparation and seeding methods, seed placement, planting date, weed control, and environmental conditions (Elbersen et al. 1998; Monti et al. 2001).

Seeding methods

Methods of seedbed preparation for planting switchgrass typically include: conventional, and no-till planting into killed sods or bare soil (Parrish and Fike, 2005). Although several reports have indicated the preference of conventionally tilled seedbeds over no-till planting (Oldfather et al., 1989; Potvin, 1993; Teel et al., 2003), no-till planting of switchgrass has also been proven to be useful in some circumstances (Wolf et al., 1989). There is limited information regarding the suitability of various seedbed preparations for switchgrass cultivation in different conditions (Parrish and Fike, 2005).

McKenna et al. (1991) and Teel et al. (2003) suggested that planting into an herbicide-killed sod is possible with proper equipment, but they also stated that switchgrass stands planted using this method may be reduced compared with switchgrass stands planted into conventionally tilled seedbeds. Similarly, Oldfather et al. (1989), Potvin (1993), Evers and Butler (2000) suggested that switchgrass planted through direct drilling into killed sod was a less reliable method when compared with conventional tillage. In another approach, Monti et al. (2001) showed that establishment of switchgrass was enhanced when conventionally prepared seedbeds were rolled or compacted after seeds were broadcasted. It is now well documented that switchgrass emergence increases greatly in a firm seed bed (Venturi et al., 1999; Evers and Butler, 2000; Monti et al., 2001; Sadeghpour et al., 2013). Venturi et al. (1999) showed greatest germination in two varieties of switchgrass in well-tilled soil that was compacted before and after planting. They found lowest germination in tilled treatments without any compaction. Sadeghpour et al. (2013), similarly reported that greatest germination rate, stand density, and biomass production was found when switchgrass was compacted two times after planting either with a roller or a cultipacker. In dry conditions, increasing seed-soil contact could also enhance germination through higher available moisture to the seeds. In contrast, other reports indicated no yield advantage from conventional tillage over no-till planting. For example, Rehm (1990) found no switchgrass yield difference between no-till and conventional planting methods. King et al. (1989) compared no-till with conventional planting of switchgrass at two locations in Nebraska and found that the yield advantage of one tillage system over the other was dependant on season and location. Harper et al. (2004) in a series of studies in Tennessee reported a 50 to 150% increase in switchgrass seedlings in a no-till system compared with a conventional seedbed preparation. Sadeghpour et al., (2013) found significant advantage of no-till planting over conventional tillage when precipitation was low during the growing season. In the same study, they used cereal cover crops, which are known to be fast growing and able to suppress weeds and provide N for the subsequent crop (Sadeghpour et al., 2013; Hashemi et al., 2013) to control weeds and enhance switchgrass establishment and found oat as the most effective cover crop for switchgrass establishment (Sadeghpour et al., 2013). Parrish and Fike (2005) and Wolf et al. (1989) concluded that the advantage that no-till planting of switchgrass has over conventional tillage is partly due to soil and water conservation and also to the potential for earlier planting. It is yet to be determined which planting method should be preferred due to various results in different locations.

Depth of Planting

Depth of seed placement is critical in emergence and the establishment of switchgrass (Parrish and Fike, 2005). In general, planting depths of 1 to 2 cm have been recommended to growers based on several studies (Moser and Vogel, 1995; Evers and Butler, 2000; Teel et al., 2003; Berti and Johnson, 2013). Newman and Moser (1988) found no significant difference between switchgrass emergence in plantings depths at 1.5 and 3 cm. However, they observed a 40% emergence reduction when they increased the sowing depth to 4.5 cm. It has also been suggested the emergence can affected by soil texture in conjunction with planting depth and moisture level. Aiken and Springer (1995) found that soil texture and seed size among switchgrass cultivars had a greater effect on emergence than differences in planting depths within < 2 cm. Planting depths < 1 cm in sandy soils may result in low seedling survival under drought stress condition.

Conversely, seedlings established in a clay soil at the same depths showed high survival at the same level of water stress (Evers and Parsons 2003). In a recent greenhouse study, Berti and Johnson (2013) observed significant differences on switchgrass emergence between surface planting (0 cm) and planting at the depth of 1.3 cm; however, did not find any significant differences in planting depths of 1.3 to 6.4 cm. In a field study the same authors found silty-clay soil as a more suitable media for switchgrass emergence compared with fine-silty and coarse-loamy soils in North Dakota, USA. In a greenhouse study, we also found a shallow planting < 3 cm could be suitable for switchgrass planting.

Seed size is also a factor in seedling emergence and vigor (Parrish and Fike, 2005). In several studies, larger seeds produced more vigorous seedlings in a shorter duration than smaller seeds; however, seedlings from smaller seeds would eventually be comparable in size (Aiken and Springer, 1995; Smart and Moser, 1999). In contrast, Zhang and Maun (1991) found no difference after eight weeks between seedlings from small or large seeds.

Date of Planting

Successful establishment of switchgrass acquires a sufficient stand that will maximize yield in subsequent years (Sanderson et al., 2012). Planting dates can vary from November to July depending on several factors including geographical region; weed control methods; soil temperature; and rainfall patterns (Hsu and Nelson, 1986a,b; Monti et al., 2001; Parrish and Fike, 2005). In warmer climates with longer growing seasons, switchgrass can be planted earlier than in cooler climates. However, planting early in the spring in most climates will cause slower seedling emergence than later plantings due to extreme temperature fluctuation and weed competition (Forberg, 2009). Optimal soil temperature for germination of a wide range of switchgrass cultivars have been suggested to be between 27-30 °C. However, according to Hsu et al. (1986a), a soil temperature of 20 °C is sufficient for switchgrass emergence and growth. In a field study in Missouri, Hsu and Nelson (1986a, b) found emergence to be more rapid at later planting dates in a set of treatments from April to June. Similarly, in Massachusetts, we found faster emergence in June and July plantings compared with November and May. However, earlier-planted switchgrass was taller, and had more advanced root systems. In agreement with our findings, in Nebraska, Smart and Moser (1997) found much larger seedlings and more vigorous stands in the earlier planting treatments spanning from March to late May. When comparing fall and spring plantings in a Mediterranean climate, Monti et al. (2001) found slightly more emergence in spring plantings. Planting in a cool season could benefit seedling establishment by breaking dormancy in seeds by stratification. Hsu et al. (1985) found that germination of dormant seeds increases in cool planting conditions. In several other studies, spring plantings of highly dormant seed yielded greater germination than later plantings; (Sanderson et al., 1996; Teel et al., 2003) however, this directly depends on the weather conditions. We found that in a mild winter with low amount of precipitation, emergence did not increase whereas; a cold and wet winter resulted in significant increase in switchgrass germination (Sadeghpour, unpublished data). When rainfall proliferates in the spring, early plantings of switchgrass could be successful with proper weed control. But in many climates, weed pressure is high in early spring given warm temperature and increased rainfall (Moser and Vogel, 1995; Evers and Butler, 2000). Weed pressure in the establishment year can be reduced by avoiding planting at a time when weed emergence is high. Many annual weed species have a short period of emergence in the spring; therefore, delaying planting by two weeks could have positive effects on establishment (Buhler et al., 1998). In northern climates weed pressure is highest in the spring and thus planting should be delayed until early summer. There must be a balance between a delayed planting date for weed pressure avoidance while still allowing for enough growing season for adequate stand establishment (Buhler et al., 1998).

Weed Control

A relatively small seed size, high dormancy rate, and slow germination often makes switchgrass a weak competitor with many summer annual grass and broadleaf weeds (Boydsten et al., 2010; Curran et al., 2011). As a result, crop establishment and early growth is often delayed (Mitchell et al., 2010). A poor switchgrass stand during the seeding year can limit yield and large scale crop adoption (Mitchell et al., 2008 and 2010; Berti and Johnson, 2013). Weeds reduce yields of switchgrass by competing for nutrients, water, light, and space (Dawson and Rincker, 1982; Kelly, 1988; Peters and Linscott, 1988). Additionally, some weed species produce toxins and growth inhibitors that can cause negative effects on switchgrass (Putnam, 1988). Switchgrass seedlings grow slowly in the first several months and can be out-competed by fast growing annual weeds (Sadeghpour et al., 2013). Additionally, a major obstacle in weed management in perennial grasses is the lack of registered herbicides approved for this use (Parrish and Fike, 2005). In order to avoid stand failure, weed management must be a primary consideration in the establishment year of switchgrass (Sanderson et al., 2012). Cool-season grassy weeds that germinate in cooler temperatures are most threatening to newly emerging switchgrass seedlings. Hsu and Nelson (1986a) found that crabgrass (*Digitaria sanguinalis* L.), a very problematic weed species, can grow more rapidly than switchgrass at equal temperature. Crabgrass produced up to 20 times more biomass per seedling than switchgrass when grown side by side. In our field trials in Massachusetts, crabgrass was also the most problematic weed in establishment of switchgrass which resulted in a significant reduction in stand density and yield (Sadeghpour et al., 2013). The most effective weed management strategy in the establishment year could be herbicide application (Mitchell et al., 2010). Efficacy of weed pressure reduction through herbicide application has been documented by several researchers (Boydsten et al., 2010; Mitchell et al., 2010; Curran et al., 2012; Sadeghpour et al., 2013). For conventionally-tilled plantings, many studies have shown success with pre-emergent triazine herbicides, notably atrazine [6-chloro-N-ethyl-N'-(1-methylethyl)- 1,3,5-triazine-2.4-dimine] (Mitchell et al., 2010; Curran et al., 2011; Sadeghpour et al., 2013). Switchgrass is one of the most tolerant grass species to atrazine (Buhler et al., 1998). Atrazine effectively controls many annual weed species when grown with perennial warm-season grasses (Martin et al., 1982; Bahler et al., 1984; McKenna et al., 1991). Problematic weeds such as crabgrass, fall panicum (*Panicum dichotomiflorum* L.), foxtail species (*Setaria* spp.), and barnyardgrass (*Echinochloa crus-galli* L.) are less susceptible to atrazine treatments and require additional herbicide treatments for effective control. With similar growth habits to switchgrass, the control of these grassy weeds is crucial to avoid detriment to switchgrass stands (Masters, 1995). Sadeghpour et al. (2013) found sufficient weed control by using a combination of 1.1 kg a.i. ha^{-1} atrazine and 0.37 kg a.i. ha^{-1} quinclorac

(3, 7-dichloro-8-quinolinecarboxylic acid). Quinclorac (Paramount) is highly effective at controlling annual warm-season grassy weeds as well as some broad leaf weeds and has recently been registered for use in switchgrass production (Boydsten et al., 2010; Curran et al., 2011). Mitchell et al. (2010) reported that a combination of quinclorac and atrazine provided satisfactory weed control for establishing both lowland and upland switchgrass cultivars in the Central and Northern Great Plains. Boydsten et al. (2010) reported switchgrass yield and stand loss as a result of post-emergent application of quinclorac however, application of this herbicide in controlling grasses has been found to be very effective (Boydsten et al., 2010; Curran et al., 2012; Sadeghpour et al., 2013). In a study at Wisconsin, Miesel et al. (2012) reported that a mixed application of imazapic (±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-methyl-3-pyridinecarboxylic acid] and glyphosate [N-(phosphonomethyl) glycine] at 0.07 kg a.i. ha^{-1} provided the best grassy weed suppression and resulted in the highest yield compared with different rates of glyphosate alone (1.12 kg a.i. ha^{-1}) or in combination with 2,4-D [(2,4-dichlorophenoxy)acetic acid] at 1.06 kg a.i. ha^{-1}. Kering et al. (2013) studied the effect of various herbicides on switchgrass establishment and reported that when quinclorac was mixed with foramsulfuron [1-(4,6-dimethoxypyrimidin-2-yl)-3-(2-dimethylcarbamoyl-5-formamidophenyl-sulfonyl)urea)] and pendimethalin (3,4-Dimethyl-2,6-dinitro-N-pentan-3-yl-aniline) efficacy of weed control was more than 70% and switchgrass establishment was improved 13 to 26% compared to untreated control, however, their findings suggest that establishment was marginal and should be improved.

Broadleaf weeds in switchgrass can be controlled by an application of dicamba (3,6-dichloro-o-anisic acid) and 2,4-D (Curran et al., 2008). In a recent study, Curran et al. (2012) reported that a broad-spectrum post-emergence application of atrazine, quinclorac, dicamba and 2,4-D significantly reduced the weed pressure in the establishment year of switchgrass. Findings of Sadeghpour et al. (2013) are in line with earlier reports by Curran et al. (2011, 2012), showing the effectiveness of a broad-spectrum application of atrazine, quinclorac, dicamba and 2,4-D. Further research is needed on herbicide application rates and their effect on switchgrass varieties.

One of the modern approaches to increase the success of herbicide application, reduce herbicide injury and enhance switchgrass establishment is seed safening (Rushing et al., 2013). Herbicide safeners can prevent herbicide damage of specific crops by reducing the binding abilities of molecules to affect target sites of plants (Rushing et al., 2013). This can be accomplished through safener-induced stimulation of herbicide catabolizing enzymes, or by safener-enhanced metabolism of herbicides to immobile metabolites (Anderson, 1996; Rushing et al., 2013). Previously, seed safeners were proven to be effective in protecting several forage plants including sorghum (*Sorghum biocolor* L. Moench), perennial ryegrass (*Lolium perenne* L.), and sand bluestem (*Andropogon hallii* hack) from herbicide injury. To reduce the injury of switchgrass from pre-emergence application of metolacholor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(methoxy-1-1methyllethyl) acetamide], Rushing et al. (2013) used two methods of seed-safening with fluxofenim (coating vs. controlled hydration). They reported that the controlled hydration (comination of 25, 50, or 100% fluxofenim) resulted in greater yields compared with the coating technique. Before this attempt, Butler et al. (2012) was failed to safen switchgrass seeds in greenhouse experiments using fluxofenim.

In no-till plantings of switchgrass, weeds can be controlled effectively with a non-selective herbicide most notably glyphosate before the emergence of switchgrass (Sanderson et al., 2012).

As discussed earlier, planting date has a significant effect on weed pressure. Delaying seeding to allow weed emergence before final seed bed preparation will reduce weed pressure (Peters and Linscott, 1988). Curran et al. (2012) found that delaying the planting until late June, resulted in weed pressure reduction.

Production management

Harvest

Harvesting strategy is dependent upon expected yield, quality and stand maintenance (Sokhansanj et al., 2009). Frequency and time of harvest are the most important harvest management practices followed by cutting height (Sadeghpour et al., 2013).

Switchgrass harvesting frequency ranges from single-cut to multiple cuttings. Multiple harvests have been a viable strategy for forage agronomists to increase annual yield (Parrish and Fike, 2005). Commonly, after plants reach their maximum biomass, they can be harvested before the end of a growing season to allow for re-growth and increase total yield; however, many studies on switchgrass have shown multiple harvests results in yield reduction in succeeding years (Madakadze et al., 1999; Sanderson et al., 1999; Reynolds et al., 2000; Smart et al., 2004; Parrish and Fike, 2005). Madakadze et al. (1999) found that a single end-of-season harvest was a more sustainable management practice compared with two or three cuttings. In the south-central USA, Sanderson et al.

(1999) reported that a single harvest at approximately 260 days of year provided the maximum biomass yield. They also concluded that multiple harvests (three or more) reduced yields over a 4-yr study. Generally, mid-summer harvests remove N and other nutrients from the shoots which would otherwise be translocated into the roots and crowns for successful re-growth in the following year. In a 5-yr study in Tennessee, Reynolds et al. (2000) found no yield advantage of two-harvesting system (mid-summer and late-October) over a single-cut in late-October. Similarly, in a trial comparing numbers of harvests, Smart et al. (2004) reported the benefits of a single harvest with respect to yield production. They found higher yields in one-cut compared with total biomass produced by a three cutting system. An additional reason for yield reduction in long term studies is tiller density reduction (Smart et al., 2004; Thompson et al., 2005). Parrish and Fike (2005, 2009) and Fike et al. (2006) concluded that only a single or at most two-cut management could be appropriate to maximize biomass output.

In addition to harvest frequency time of harvest also influences switchgrass production (Adler et al., 2006; Guretzky et al., 2011) and perhaps is the most important harvest management practice (Mitchell and Schmer, 2012). Recommendations for the ideal time to harvest switchgrass to produce consistent maximum yield varies from site-to-site. A Mid-September harvest was reported by Sanderson et al. (1999) and Vogel et al. (2002) for maximum biomass yield. Adler et al. (2006) found 40% reduction in switchgrass biomass production when the harvest was delayed until spring. Reports from Jannasch et al. (2001) and Herbert et al. (2012) were in line with findings of Adler et al. (2006) where they found a 30% yield reduction from spring harvest. In contrast, Parrish and Fike (2005) found no yield differences between November and February harvests in

Virginia. Generally, biomass yield was reduced when harvest was delayed until after killing frost (Mitchell and Schemer, 2012; Herbert et al., 2012); however, later harvest may ensure stand productivity and persistence of switchgrass. In north-central USA, harvesting after killing frost produced the highest yields (Mulkey et al., 2006). In the same location, Casler and Boe (2003) found that a mid-August harvest reduced switchgrass stand density over time. According to Mitchell and Schmer (2012) switchgrass should not be harvested within 6 weeks of the first killing frost to ensure NSC translocation to the plant crowns for setting new tiller buds and maintaining stand productivity.

Cutting height is another important harvesting management practice that may influence final biomass yield (Trócsányi et al., 2009). Limited data is available on the influence of cutting height on the biomass production of switchgrass in the Northeast region of the United States. Existing reports suggest cutting heights between 15 to 25 cm will ensure switchgrass re-growth in the following year (Kiss et al., 2007). According to Henry et al. (1976), the best switchgrass stand could be obtained from a cutting height of 23 cm in a single-cut system whereas in a two-harvest system, 8 cm would be the ideal harvesting height to gain maximum biomass yield. Several reports indicated that although cutting switchgrass as low as 5-8 cm compared with 20-25 cm may result in higher biomass yield in the short term, biomass will be lowered in the following years due to intensified weed infestation (Anderson et al., 1989; Kiss et al., 2007; Trócsányi et al., 2009). Mitchell and Schmer (2012) reported that cutting heights lower than 10 cm resulted in yield reduction due to stand vigor loss. In a three year period Sadeghpour et al.

(2013) reported that cutting height of 7.5 cm out yielded cutting at 15 cm by 1 Mg ha^{-1} without increasing weed pressure.

Quality parameters of switchgrass as biofuel feedstock include energy content of grass, moisture, nutrients, and ash. Higher moisture and ash both reduce energy content, since higher moisture requires excess energy input to burn, and ash creates fouling in combustion equipment (McLaughlin et al., 1996). The presence of alkali metals and silicates in ash are major contributors to the production of slag, a thick black liquid material that forms when feedstock is burned at high temperatures. Slag coats the surfaces of machinery (furnaces, boilers, fluidized beds, etc.), causes fouling and prevents heat from being recovered (McLaughlin et al., 1996; Cassida et al., 2005), therefore making the burning process costly. Part of the appeal of switchgrass is that it can be used with existing technologies to supplement current energy production. It is imperative that the end product be used without causing high external costs to existing systems.

Harvesting management of switchgrass such as time of harvest may alter the concentration of unwanted nutrients present in the grass and therefore influence feedstock quality for combustion purpose. There is a general conformity in the literature that delaying the harvest of switchgrass until killing frost (after senescence), reduces N, phosphorus (P), potassium (K), ash, and other nutrients in the grass (Madakadze et al., 1999; Yang et al., 2009; Waramit, et al., 2011). Lower ash content is associated with translocation of mobile nutrients from the above-ground tissue to the root structure (Herbert et al., 2012). It is reported that every 1% increase in ash concentration decreases the heating value by as much as 0.2 MJ kg ha^{-1} (Cassida et al., 2005). Nitrogen cycles down into the below-ground tissues at the end of the growing season (Wilson et al., 2013). This is due to the fact that switchgrass has evolved to go dormant at the onset of winter, translocates nutrients, including N, from above-ground tissues to the below-ground for re-growth in the succeeding season (Sadeghpour et al., 2013). Adler et al. (2006) found that delaying the harvest until spring resulted in higher energy content of the biomass because of moisture and ash content reduction. Direct baling of switchgrass requires moisture content of 15% or below (McLaughlin et al., 1996). In a multi-harvest study, Gorlitsky et al. (2013) found 30% moisture reduction when harvest was delayed from mid-September to mid-November; however, the moisture content from the delayed harvest was still high (29%) which makes it unsuitable for direct bailing. In another study (Sadeghpour et al., 2013) concluded that delaying harvest until spring (mid-April) can reduce moisture content to an acceptable level of 11 - 15%; however, this comes at the cost of a yield loss of about 25 to 30 % which questions the suitability of harvesting in spring. McLaughlin et al. (1996) reported a significant disparity of ash content of switchgrass across multiple locations ranging from 2.8 to 7.6%. Adler et al. (2006) showed that ash content reduced from 3.4 to 2.3% when the harvest was delayed until spring. Mulkey et al. (2006) and Waramit et al. (2011) concluded that reduction in ash concentration from time of anthesis to killing frost harvest was related mainly due to greater proportion of grass stems at late season which contains less silica, a major component of ash, compared to leaves.

Fertility management

Fertilization is perhaps the most unsettled aspect of switchgrass establishment and production (Parrish and Fike, 2005). Nitrogen fertilization is not recommended in the establishment year as it would encourage weed pressure and therefore not only increases establishment costs but also causes the economic risk associated with stand failure (Sanderson et al., 2012). Sanderson and Reed (2000) reported no biomass yield response to N application (22 and 112 kg ha^{-1}) during the establishment year of "Alamo" switchgrass. They concluded that lack of switchgrass response to N fertilization was due to the ability of switchgrass to use available N in the soil. Reports have also indicated no significant response of switchgrass to P and K (Parrish and Fike, 2009; Sanderson et al., 2012). This is mainly due to the adequate levels of these elements in most agricultural soils. However, P and K fertilizers and lime are recommended to maintain soil nutrient balance during establishment and throughout production years (Sokhansanj et al., 2009).

Nitrogen

Nitrogen is a critical nutrient for production of biomass and typically the most limiting factor to plants productivity (Lemus et al., 2008a). Managing N fertilizer application is important not only for optimum biomass production but also to maximize the NUE as well as feedstock quality. Excess N concentration in harvested switchgrass can be a liability by increasing the release of N oxide (NO and NO_2) compounds into the atmosphere when combusted (Lemus et al., 2008a; Parrish and Fike, 2005). Most of studies on N management have been conducted on lowland switchgrass varieties in the Midwest, southern, and upper southeastern U.S.A. Nitrogen fertilizer recommendation are site specific and depend on weather, soil fertility level and management practices (Sanderson et al., 2012). In a multi-location study throughout the upper southeastern USA, Lemus et al. (2009) found that in a single-cut system, 50 kg N ha^{-1} would be sufficient for biomass production of switchgrass; however, a split application of N (100 kg N ha^{-1}) is required in a 2-cut system to maintain grass productivity. Muir et al. (2001)

reported Alamo switchgrass yielded highest at N rate up to 224 kg ha^{-1}. In a season of higher-than-normal rainfall, production was maximized at 168 kg N ha^{-1}. Thomason et al. (2005) found 448 kg N ha^{-1} application in a 3-cut system as the most suitable for maximum biomass production of Kanlow variety. However, multiple harvests each year resulted in a significant yield reduction in the succeeding years and they reported that a single harvest system over a four-year period at one of the locations of their study produced higher biomass compared with the 3-cut system with 448 kg N ha^{-1} fertilization. While yields were highest (18.0 Mg ha^{-1}) with 448 kg N ha^{-1} applied all in April and three harvests, no N application and harvesting three times produced almost as much total biomass (16.9Mg ha^{-1}). This limited response to N is possibly explained by the evolution of switchgrass under low N conditions.

At the same location, Aravindhakshan et al. (2011) reported that a single-cut system with only 69 kg N ha^{-1} was the most economical management practice for producing the greatest biomass production. Vogel et al. (2002) tested N application rates up to 300 kg ha^{-1} for the Cave-in-Rock (a southern upland cultivar). They reported maximum yields at 120 kg N ha^{-1}. Guertsky et al. (2011) tested N up to 225 kg ha^{-1} at three harvest times (July, October, and December) and reported positive response of switchgrass biomass production to N fertilization. They found a 2-cut (July plus frost) harvest system the most productive however, higher N input was needed for this harvest system. In a recent multi-year-location study, Anderson et al. (2013) recommended 56 kg N ha^{-1} in late fall to 112 kg N ha^{-1} in early spring to optimize switchgrass production. Harvesting switchgrass once a year after frost (December) has been suggested by several researchers (Muir et al., 2001; Sanderson et al., 1999; Vogel et al., 2002; Waramit et al., 2011). In a study in Massachusetts on a 3-year old Cave-in-rock switchgrass Sadeghpour et al. (2013) found that for a late-summer harvest (September) only a 67 kg N ha^{-1} was required to maintain stand productivity. No significant response of switchgrass yield to N fertilization in late-fall (November) and spring (April) harvests was detected. They concluded that perhaps less than 67 kg N ha^{-1} would be sufficient for growing high-yielding switchgrass in the state of Massachusetts. In another recent study, Pedroso et al. (2013) found a linear response of switchgrass to N application where the greatest yields (9.7 and 13 Mg ha^{-1} yr^{-1}) were obtained from the highest N fertilization rates (300 kg ha^{-1}). They reported that the average NUE was between 30 to 44 kg biomass kg^{-1} N during 2009 and 2010 growing season. Sadeghpour et al. (2013), found the average NUE to be from 14 up to 33% which was much lower than the averages reported by Bransby et al. (1998). According to Parrish and Fike (2005) NUE can also be soil/site specific Lemus et al. (2008a) calculated different NUE for two different locations in Virginia. They reported that increasing the N rate at both sites could result in decreasing NUE at one site with no significant response in the other site. In a five-year experiment, Lemus et al. (2008b) in Iowa found 56 kg ha^{-1} an ideal N rate in terms of NUE. Overall, based on findings of Pedroso et al. (2013), greater N fertilization would be required to sustain biomass production in warm ecoregions with greater yield potential.

Phosphorus, Potassium and pH

Limited research has been conducted on response of switchgrass to P and K fertilization (Sanderson et al., 2012). Reports often suggested little (Jung et al., 1988; McKenna and Wolf, 1990) or no (Brejda, 2000; Muir et al., 2001) significant effect of these nutrients on switchgrass production which could be due to the inherent ability of switchgrass to use P that is available in the soil mainly through mycorrhizae symbiosis (Clark, 2002; Parrish and Fike, 2005). Mycorrhizae, by supplying the host plant with essential elements from the soil, can significantly increase plant growth (Clark et al., 1999). Mycorrhize increase a plant's ability to absorb water and growth limiting nutrients (notably P and N) through enhancing the root surface area in contact with the soil (Clark et al., 1999; Hosseinirad et al., 2013). According to Brejda et al. (1998) response of switchgrass to P and N was reduced when rhizosphere microflora was back to stem-sterilized soils. Muir et al. (2001) reported no response with P to Alamo switchgrass in a single-cut system at two experimental sites at Texas. In a recent study, Haque et al. (2013) found no influence of P on switchgrass productivity and suggested a 135/0 kg N-P ha^{-1} application as the most economically viable fertilization system for switchgrass production. McKenna and Wolf (1990) found small response of switchgrass to P fertilization when P levels in their soil test were low but only in the first year of their study.

Similar to P, switchgrass plants are efficient in their use of K (Parrish and Fike, 2009). Frequently little or no response of switchgrass to addition of K is reported (Hall et al., 1982; Brejda, 2000). In a greenhouse study, Friedrich et al. (1977) found no yield improvement with applying K at rates up to 896 kg ha^{-1}. In contrast, Tylor and Allinson (1982) reported that when K was applied in combination with N and P, switchgrass biomass was increased significantly. Similarly, Kering et al. (2013) reported that a combination application of 135 kg N and 68 kg K ha^{-1} produced the highest switchgrass biomass in Oklahama. They however, found no significant differences in biomass yield when comparing application of 68 kg K ha^{-1} alone with no fertilizer application.

There is a general conformity on tolerance of well-established switchgrass stands to many adverse environmental conditions including extreme pH. Reports on the influence of low pH on newly-established switchgrass seedlings are controversial. According to McLaughlin and Kszos (2005) greenhouse studies in North Dakota showed a significant reduction in seedling survival in soil pH < 4.0 or > 8.0. Jung et al. (1988) also reported 50% yield reduction on strong acidic (pH 4.3-4.9) soils compared with lime-treated soils. In contrast to these findings, Tylor and Allinson (1982), Harper and Spooner (1983), Bona and Belesky (1992), and Hopkins and Taliaferro (1997), found no limiting effect of soil acidity on switchgrass establishment.

Conclusion

In the last 30 years, significant progress through dedicated research efforts has been made in developing switchgrass as a bioenergy crop. Although there is an improved understanding of the biology and agronomy of switchgrass, a few aspects of switchgrass establishment and production need further investigation. Reliable establishment methods and effective weed management practices to produce a harvestable biomass in the establishment year, appropriate nutrient management to enhance fertilizer efficiency, and biomass conversion methods are yet not fully determined. Best agronomic management practices coupled with genetics will result in high-yielding quality switchgrass for more efficient conversion.

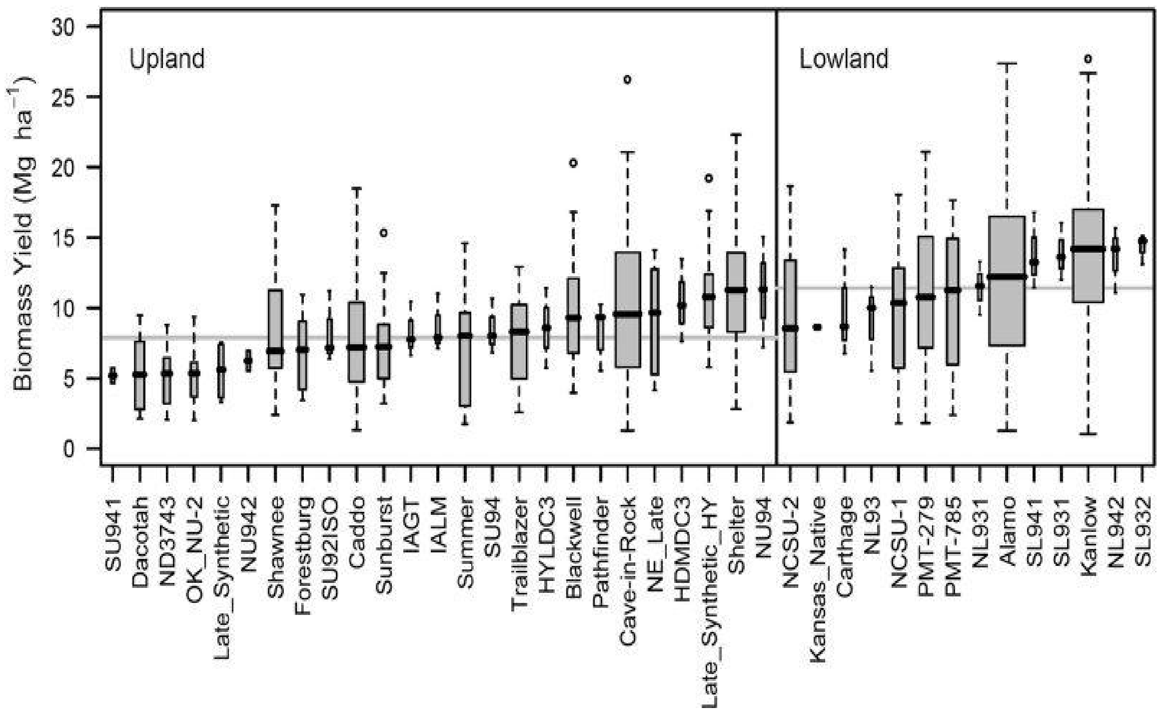


Figure 1: Biomass yield variation among upland and lowland switchgrass cultivars at several locations in the USA [adopted from Wullschleger et al. (2010), with permission, copyright American Society of Agronomy]

CHAPTER 2

A SIMPLE VIGOR TEST FOR ADJUSTING SWITCHGRASS SEEDING RATE IN FERTILE AND MARGINAL SOILS

Abstract

Calculating switchgrass (*Panicum virgatum* L.) seeding rate is misleading and often causes stand failure. Our objective was to introduce a simple vigor test to adjust the seeding rate and enhance switchgrass establishment and productivity in the establishment year in fertile and marginal soils. Seeding rate for four switchgrass varieties (Blackwell, Carthage, Cave-in-Rock, and Shawnee) was adjusted ranging from 25 to 125% based on a vigor test. Results indicated increase in seedling emergence and establishment with increasing the seeding rate. Higher established seedlings were recorded from the fertile soils (131 seedlings m^{-2}) compared with the marginal soil (78 seedlings m^{-2}). Based on our previous findings, 100 established seedlings often is considered as a successful establishment; therefore, a 50% (6.8 kg ha^{-1}) and 100% (13.8 kg ha^{-1}) adjusted seeding rates could provide sufficient stand density (111 and 94 seedlings m^{-2}) in the establishment year in fertile and marginal soils, respectively.

Key words: Seeding rate; seedling establishment; switchgrass.

Introduction

Producing renewable feedstock for biofuel has gained growing attention (Uwatoko *et al.* 2011). Switchgrass (*Panicum virgatum* L.) is a C_4 perennial grass and is considered as an important energy crop because of its high productivity with low input requirements (Herbert *et al.* 2012; Sadeghpour *et al.* 2014). However, switchgrass like other warm-season perennial grasses is difficult to establish mainly due to high seed dormancy, poor seed quality, weed competition, and improper planting methods (Hashemi and Sadeghpour 2013). Poor establishment in the first year directly relates to stand vigor in succeeding years (Mitchell and Vogel 2012). Therefore, a reliable establishment method is required to gain high switchgrass emergence. Adopting a suitable planting rate is an important consideration to improve switchgrass establishment (Forberg *et al.* 2009).

Commonly, farmers use the seed distributor's test results of percent pure live seed (PLS) or percent germination to calculate planting rates, but this information can be inaccurate. The rate of dormancy can reduce over time, and therefore recommended germination percentages could be higher than the original test results. Conversely, seed testing laboratories will present inflated results from highly controlled tests that may not represent typical field conditions affected by environmental stresses. Additional sources of misleading information can stem from significant variation in seed testing laboratory procedures (Hashemi and Sadeghpour 2013). Switchgrass seed distributors indicate percent germination, dormancy, and inert matter on the seed packaging. Overall seed quality is often expressed as percent pure live seed (PLS). This equals the sum of percent germination and percent seed dormancy (Mitchell and Vogel 2012). Basing planting rate determination on percent PLS can lead to an inaccurate determination of planting rates because dormant seeds that will not necessarily germinate are included. Seed and establishment costs for switchgrass are relatively high therefore, knowing the quality of a seed lot is critical before planting.

Simple alternatives to determine seed quality and to calculate planting rate are needed. In this research, a practical seed vigor test that growers can implement as a simple way to determine planting rate was evaluated. The basis of this test was to plant a constant number of seeds into a media promptly before field planting and evaluate germination over a fixed amount of time. In this research the term 'fast establishing seed' (FES) was defined as seeds that germinate within 14 days in the seed vigor test. Overall performance of fast establishing seed is defined as "seed quality". The objective of this study was to assess seed vigor as a predictor of seed germination in both fertile and marginal fields and seeding rate needed for rapid establishment of switchtgrass in seeding year.

Material and methods

Greenhouse experiment

This study was conducted at the University of Massachusetts Amherst in a greenhouse condition. Four switchgrass varieties (Blackwell, Carthage, Cave-in-Rock, and Shawnee) were tested at the depth of 5 cm and a coarse mason sand media in May 2011. Greenhouse experiment set up was based on findings of Forberg *et al*. (2009). Temperature was maintained at a 24/20 °C degree light/dark cycle. The greenhouse vigor test results were used as seed quality reference points for field planting rate evaluations. A germination test also was conducted to determine the differences between vigor test results and regular germination test that is often used by growers. For the vigor test, four, 25 cm x 50 cm x 10 cm rigid plastic trays with 0.5 cm drainage holes spaced 3 cm apart were used as containers to hold planting media. Paper towel was used in the bottom of each tray to retain dry media in the experiment setup. The media were steam sterilized at 100 degrees °C for 1.5 hrs to kill possible pathogens and weed seeds. Each tray contained four varieties planted in rows of 100 seeds. Each tray constituted one repetition. Media was watered daily on a need basis. Seedling emergence was recorded every day up to 25 days. Germination test was conducted at the Bowditch Hall at the University of Massachusetts. Germination test method was adopted from AOSA (2010).

Field experiment

The experiment was conducted at the Crops and Animal Research and Education Farm of the University of Massachusetts in South Deerfield (42°28′37″N, 72°36′2″W) during the 2011 growing season in two soil types (fertile and marginal). Fertile soil was a Hadley fine sandy loam which had the pH of 6.6, organic matter content of 3.7%, N, P, K, and Ca content of 7, 12, 38, and 1094 mg kg^{-1}, respectively. The chemical properties of the marginal soil (a mixed gravely coarse loam) were as follows: pH, 6.3; organic matter content, 1.5%; N, P, K, and Ca content, 3, 23, 211, and 382 mg kg^{-1}, respectively. Soil samples in the top 20 cm were taken prior to planting switchgrass in the beginning of June 2011.

The experimental design was a split-plot factorial with two locations (fertile vs marginal soil) as main plots. Five seeding rate treatments (25, 50, 75, 100, and 125% of the adjusted rate) were factorially combined with four switchgrass varieties (Blackwell, Carthage, Cave-In-Rock, and Shawnee). Plots were rolled first then planted in mid-July with a cultipacker broadcast seeder (Brillion drill). Seeds were planted at 0.5–1.5 cm depth. The following day, a combination of atrazine (2-Chloro-4-ethylamino-5-isopropylamino-1,3,5-triazine) and quinclorac (3,7-dichloro-8-quinolinecarboxylic acid) was sprayed at a rate of 1.1 kg ai ha^{-1} and 0.37 kg ai ha^{-1}, respectively. Seeds were planted into 3.1 x 3.1 m plots replicated four times in a randomized block design.

Planting rates in the treatments were calculated by dividing the target of 20 FES/0.1 m^2 by vigor test germination percentages (ex. 200/0.28 for 28% germinating seeds)/0.1 m^2. 100% Treatment: 100.0/0.1 = 714 seed m^{-2}

Each set of 100 seeds weights almost 0.17 g. The calculated seeding rates for the field experiment are presented in table 1.

Data was collected from two stand count stages; at seedling emergence (1–2 cm) and at plant establishment (30–40 cm). At establishment, healthy green plants shorter than 30 cm were included in the count. Counts were performed manually using a 0.1 m^2 wooden frame. Four subplot counts were taken from each plot systematically.

Statistical analysis

Number of emerged and established switchgrass data was analyzed using the ANOVA procedure and Proc GLM (SAS Institute 2009). Main effects were location (soil type), variety, and seeding rate. All main effects were considered as fixed and only block was treated as a random effect. Data for seeding rate were analyzed using Proc REG. Duncan multiple range tests were used for mean separations at $P<0.05$ significance level. Results were not averaged over location (soil type) when interactions of location by main effects were significant.

Results and discussion

Seedling emergence

Vigor test results indicated that Blackwell, Cave-in-Rock, and Shawnee had higher FES (28%) compared with Carthage (18%); thus, seeding rate adjusted for Carthage was different (Table 1). Results from regular germination test (AOAS) were different from vigor test results for Blackwell and Carthage varieties. Germination test results were 64 and 27 for simple germination test which were 36 and 9% higher than the vigor test results. Seedling emergence was significantly influenced by location (soil type), variety and seeding rate. Number of seedlings was significantly higher in fertile soils (561 seedlings m^{-2}) compared with the marginal soil (381 seedlings m^{-2}) (Table 2). Soil type has been suggested to significantly influence switchgrass emergence and production (Berti and Johnson 2013). Soils with higher gravels often impede the emergence of switchgrass and result in stand and biomass reduction (Hashemi and Sadeghpour 2013). Shawnee was significantly produced higher seedlings (643 seedlings m^{-2}) compared with Blackwell (348 seedlings m^{-2}), Carthage (417 seedlings m^{-2}), and Cave-in-Rock (477 seedlings m^{-2}) (Table 2). Herbert *et al.* (2012) reported all of the mentioned varieties as superior for the state of Massachusetts however; they observed Carthage to be the consistently the most productive upland variety. Regardless of soil type and variety, increase in seedling emergence with increasing seeding rate was in agreement with findings of Forberg *et al.* (2009) and Foster *et al.* (2013).

Seedling establishment

Results of analysis of variance indicated that number of established seedlings was significantly influenced by soil type (Fig. 2). Number of established seedlings was 67% higher in fertile soil compared with the marginal soil (Fig. 2). There was a significant linear relationship between seeding rate and number of established seedlings regardless of variety. The highest number of established seedling was resulted from 125% of adjusted seeding rate within each soil type whereas the lowest number of established seedling was recorded from 25% of adjusted seeding rate (Fig. 2). In this study we could not reach the target of 200 established seedlings m^{-2}. In general, however, one established seedling often produces between 3–4 tillers providing 300–400 tiller m^{-2} which suffices for producing more than 1 Mg ha^{-1} in the establishment year (Hashemi and Sadeghpour 2013). Figure 2 showed that in fertile soils a 50% adjusted seeding rate (averaged over varieties, 6.8 kg ha^{-1}) could produce enough seedlings to provide acceptable stand and therefore first-year harvestable biomass. In marginal soils, however, 100% adjusted seeding rate (average over varieties, 13.8 kg ha^{-1}) is required to provide sufficient stand density for harvestable biomass in the establishment year.

Table 1: Adjusted seeding rates (kg ha^{-1}) based on the seed vigor test for the field experiments

Seeding rate	Variety			
	Blackwell	Carthage	CIR†	Shawnee
	kg ha^{-1}			
25	3.03	4.72	3.03	3.03
50	6.07	9.44	6.07	6.07
75	9.10	14.16	9.10	9.10
100	12.14	18.88	12.14	12.14
125	15.17	23.60	15.17	15.17

†CIR, Cave-in-Rock

Table 2: Seedling emergence for four switchgrass varieties at five adjusted seeding rates in fertile and marginal soils.

Seeding rate	Variety							
	Blackwell		Carthage		CIR		Shawnee	
	Fertile	Marginal	Fertile	Marginal	Fertile	Marginal	Fertile	Marginal
	Emerged seedlings (m^{-2})							
25	120	85	140	125	285	155	195	135
50	250	130	405	165	400	395	640	375
75	455	360	560	320	605	395	760	525
100	580	415	725	475	705	485	895	760
125	540	545	860	395	800	545	1310	840
Linear	0.87	0.96	0.98	0.81	0.97	0.85	0.94	0.97
Quadratic	0.96	0.96	0.99	0.85	0.98	0.91	0.94	0.99
Mean	389	307	538	296	559	395	760	527

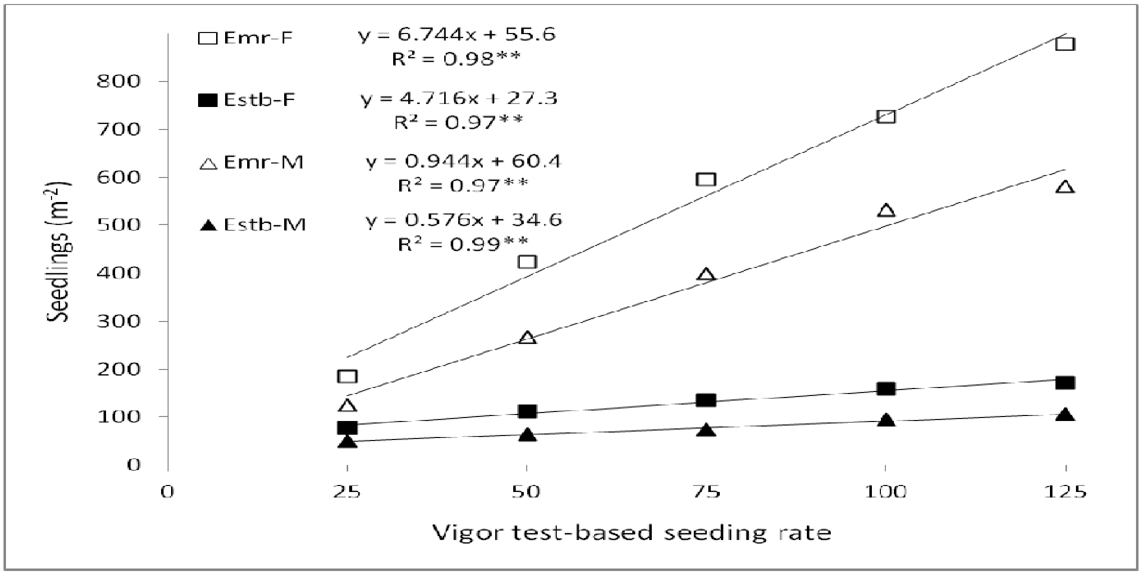


Figure 2: Influence of soil type and adjusted seeding rates on switchgrass establishment (averaged over varieties).

Emr-F, seedling emergence in fertile soil; Est-F, established seedlings in fertile soil; Emr-M, seedling emergence in marginal soil; Est-F, established seedlings in marginal soil.

**, significant at $P \leq 0.01$.

CHAPTER 3

SWITCHGRASS ESTABLISHMENT AND BIOMASS YIELD RESPONSE TO SEEDING DATE AND HERBICIDE APPLICATION

Abstract

Weed interference is a major challenge in the establishment of switchgrass. A field experiment was conducted in 2012 and replicated in 2013 to study the influence of seeding date (November, May, June, and July) and herbicide application [(A+Q; (atrazine + quinclorac) and broad spectrum; (atrazine + quinclorac + 2,4-D + dicambe)] on switchgrass establishment, production, and weed suppression in the establishment year. Switchgrass tiller density was increased with delaying the harvest until July (194 tiller m^{-2}) in 2012; however, no significant differences were observed among seeding dates in 2013. Switchgrass was more morphologically developed (plant height and adventitious root numbers) at earlier seeding dates (November and May) compared with later seeding dates (June and July). Weed biomass was reduced by 18% as a result of broad spectrum herbicide application compared with A+Q treatment. The highest weed biomass was recorded from May seeding date in both years. In 2012, switchgrass biomass yield was greatest in May (0.87 Mg ha^{-1}) which had no significant differences with June (0.66 Mg ha^{-1}) seeding date. Switchgrass biomass yield was significantly higher in 2013 with November (1.37 Mg ha^{-1}), May (1.38 Mg ha^{-1}), and June (1.22 Mg ha^{-1}) producing significantly higher biomass yield compared with July (0.71 Mg ha^{-1}) planting. Our results suggested that although higher tiller density and lower weed biomass was observed with later planting date, switchgrass was more morphologically developed and produced higher biomass yield in earlier seeding dates. To ensure a successful long-lasting switchgrass establishment an early seeding date (May) and a broad spectrum herbicide application could be a sustainable management practice.

Key words: Establishment, Seeding date, Switchgrass, Tiller density, weeds.

Introduction

Switchgrass (*Panicum virgatum* L.), a warm-season (C_4), sod-forming perennial tall grass native to North America, is perhaps the most ideal species for bioenergy production (Sadeghpour et al., 2014). Once established, switchgrass requires low input to produce high biomass yield (Hashemi and Sadeghpour, 2013) and is easy to harvest with conventional hay-making equipments (Herbert et al., 2012). However, establishment of swichgrass is often challenging and results in stand failure (Mitchell and Vogel, 2012). Small seed size, high dormancy rate which causes slow germination rate, and weed pressure as a result of slow seedling growth are often challenging factors in establishment of switchgrass (Foster et al., 2013). To ensure sufficient stand density to produce harvestable biomass in the establishment year, management practices such as seeding date and herbicide application are required (Curran et al., 2012). Seeding date not only can be used as an agronomic management practice to improve switchgrass emergence, it also can be applied as a management practice to reduce weed interference which is perhaps the major reason for switchgrass stand failure (Mitchell et al., 2010; Curran et al., 2012; Hashemi and Sadeghpour, 2013). Seeding date vary from November to July depending on several factors including geographical region; weed control methods; soil temperature; and rainfall patterns (Parrish and Fike, 2005; West and Kincer, 2011). We hypothesized that planting in November could improve switchgrass emergence as a result of winter-chilling effect. It is reported that a wet and cold weather can increase germination rate and thus enhance stand density (Hsu et al., 1985; Parrish and Fike, 2005). In a Mediterranean climate, Monti et al. (2001) found slightly more emergence in spring plantings. Hsu et al. (1985) found that germination of dormant seeds increased in cool planting conditions. However, planting early in the spring in most climates will cause slower seedling emergence than later plantings due to extreme temperature fluctuation and weed competition (Hashemi and Sadeghpour, 2013). In a field study in Missouri, researchers found emergence to be more rapid at later planting dates in a set of treatments from April to June (Hsu et al., 1986). In Nebraska, Smart and Moser (1997) found much larger seedlings and more vigorous stands in the earlier planting treatments spanning from March to late May. Literature lacks information on using seeding date as a management practice to control weeds (Curran et al., 2012). Curran et al. (2012) studied three seeding dates (early-May, late-May, and early-June) of switchgrass to determine the optimal time to plant switchgrass while controlling weed pressure in the establishment year. They suggested that planting relatively late (June) at a high seeding rate plus mowing annual weeds could be a sustainable weed control management practice.

Effective weed control for successful switchgrass establishment may not occur without a supplement of herbicide application (Curran et al., 2011; Miesel et al., 2012). Efficacy of weed pressure reduction through herbicide application has been documented by several researchers (Mitchell et al., 2010; Curran et al., 2012; Kering et al., 2013). For conventionally-tilled plantings, many studies have shown success with pre-emergent triazine herbicides, notably atrazine [6-chloro-N-ethyl-N'-(1-methylethyl)-1,3,5-triazine-2.4-dimine] (Hintz et al., 1998; Mitchell et al., 2010; Curran et al., 2012). Switchgrass is one of the most tolerant grass species to atrazine (Buhler et al., 1996). Atrazine effectively controls many annual weed species when grown with perennial warm-season grasses (Parrish and Fike, 2005). Problematic weeds such as large crabgrass (*Digitaria sanguinalis* L.) fall panicum (*Panicum dichotomiflorum* L.), foxtail species (*Setaria* spp.), and barnyardgrass (*Echinochloa crus-galli* L.) are less susceptible to atrazine treatments and require additional herbicide treatments for effective control (Hashemi and Sadeghpour, 2013). Quinclorac (Paramount) is highly effective at controlling annual warm-season grassy weeds as well as some broadleaf weeds and has recently been registered for use in switchgrass production (Boydsten et al., 2010; Curran et al., 2011). A combination of quinclorac and atrazine could successfully control weeds for establishing both lowland and upland switchgrass cultivars in the Central and Northern Great Plains (Mitchell et al., 2010). Boydsten et al. (2010) also reported that quinclorac could effectively control weedy grasses in switchgrass however, stand loss might occur as a result of post-emergent application of quinclorac. Kering et al. (2013) studied the effect of various herbicides on switchgrass establishment and reported that when quinclorac was mixed with foramsulfuron [1-(4,6-dimethoxypyrimidin-2-yl)-3-(2-dimethylcarbamoyl-5-formamidophenyl-sulfonyl)urea)] and pendimethalin (3,4-Dimethyl-2,6-dinitro-N-pentan-3-yl-aniline) efficacy of weed control was more than 70% and switchgrass establishment was improved 13 to 26% compared to untreated control, however, their findings suggest that establishment was marginal and should be improved. To control broadleaf weeds in switchgrass dicamba (3,6-dichloro-o-anisic acid) and 2,4-

D((2,4-dichlorophenoxy)acetic acid) can be effective (Hashemi and Sadeghpour, 2013). In a recent study, Curran et al. (2012) reported that a broad spectrum post-emergence application of atrazine, quinclorac, dicamba and 2,4-D significantly reduced the weed pressure in the establishment year of switchgrass. Our objectives were to evaluate the effect of (i) seeding date and (ii) herbicide application on switchgrass emergence, establishment, and production as well as weed control.

Materials and methods

Experimental site

Field experiments were conducted during 2011-2012 and continued into 2012-2013 growing season at the University of Massachusetts Agricultural Experiment Station Farm in South Deerfield located in the Connecticut River valley (42°28′37″N, 72°36′2″W). To facilitate presenting the study, 2011-2012 and 2012-2013 growing seasons will be considered as 2012 and 2013. The soil type was Hadley fine sandy loam (nonacid, mesic Typic Udifluvent). The soil pH was ranging from 6.3 to 6.6. Soil samples were taken from the top 20 cm at the experimental site.

Experimental design and cultural practices

The experimental design was split-plot design with four replications. The main plots consisted of four switchgrass seeding dates (mid-November, mid-May, mid-June, and mid-July). The sub-plots consisted of pre-emergence (PRE) application of atrazine (1.1 kg a.i. ha^{-1}) and quinclorac (0.37 kg a.i. ha^{-1}), or a broad spectrum application of atrazine (1.1 kg a.i. ha^{-1}) and quinclorac (0.37 kg a.i. ha^{-1}) as pre-emergence along with the post-emergence application of 2,4-D (0.28 kg a.i. ha^{-1}) and dicamba (0.28 kg a.i. ha^{-1}).

In this experiment, atrazine and quinclorac was applied as PRE due to lack of expected effectiveness on weed control in our previous studies. The plots were disked twice prior to seeding and rolled using a cultipacker after disking. Switchgrass variety ‘Cave-in-Rock’ was planted with a cultipacker seeder (Brillion drill) at the rate of 11 and 13 kg ha^{-1} pure live seed (PLS) at each seeding dates in 2012 and 2013, respectively. The seeding rate differences were due to planting a constant number of seeds into the soil according to standard seed germination test (AOSA, 2010). The plot size for each treatment in a replication was 1.5 × 6.1 m. The pre-emergence herbicide was applied one day after planting and the post-emergence herbicide treatments were applied approximately 6 weeks after planting. No irrigation was applied in this experiment, as that is not a common practice in Massachusetts due to adequate precipitation during the growing season (Hashemi et al., 2013). No N fertilizer was applied to avoid weed pressure competition in the establishment year.

Measurements, sampling and data collection

Tiller density was counted from the center rows of each plot approximately 5 weeks after each planting each year using a 0.1 m^{-2} quadrate. For November planting, stand density was counted the same time as May planting was counted. Weed and switchgrass biomass was determined in mid-September and late-October each year from a 0.5 m^{-2} area from the center rows using a hand mower (GS model 700, Black and Decker (U.S.) Inc, Towson, MD) at 10-cm stubble height. At the time of harvest the fresh weight was weighed and samples were placed in a forced air oven at 50°C for 72 hr to determine moisture content. At the time of harvest, 0.5 m^{-2} area from the center rows was used to measure plant height (5 randomly selected plants). A 15 ×15 cm cup cutter was used to dig out roots to measure number of adventitious roots for each treatment.

Statistical analysis

Data were analyzed using the ANOVA procedure and proc GLM (SAS Institute, 2009). Main effects were year, seeding date and herbicide application. All main effects were considered as fixed and only block was treated as a random effect. Where treatment differences were detected, means were compared using Duncan Multiple Range tests at the 5% level of significance. Results were not averaged over years when interactions of main effects were significant.

Results and discussion

Weather conditions

Cumulative growing degree days (GDD), observed from the Deerfield, MA, weather station, for 2012 and 2013 (November through October) were 3,074 and 2,774, respectively (Table 3). From November until April the GDD was lower in 2013 than that of 2012 which was more suitable for winter-chilling effect. Cumulative growing season precipitation was 864 mm in 2012, and 989 mm in 2013. Precipitation after the seeding month was quite different from year to year. In 2012, precipitation during June, July and August was 105, 0, and 15 mm respectively. In 2013, however, precipitation was 239, 103, and 72 mm for months of June, July, and August, respectively. Precipitation in moths from November until April was mostly rainfall in 2012 and snowfall in 2013.

Switchgrass morphological traits

Switchgrass tiller density was significantly influenced by year, seeding date and year by seeding date interaction (Table 4). An approximately threefold increase was observed in switchgrass tiller density in 2013 compared with 2012. This could be explained by the significant weather differences between the two year of study where cooler and higher precipitation in 2013 resulted in higher tiller density compared with the 2012 (Table 3). As expected delaying the seeding date increased tiller density with the highest tiller density recorded from July seeding date (269 tillers m^{-2}) (Table 5). We expected to observed higher tiller density with November planting however, lack of wet-cold weather in 2012 resulted in low tiller density thus, averaged over two years, only 157 tillers m^{-2} was recorded from November seeding date. Within each year, response of switchgrass tiller density to seeding date was quite different (Table 4). In 2012, November seeding produced considerably lower tillers (44 tillers m^{-2}) compared with other seeding dates. Tiller density did not significantly differ between May and June seeding dates in 2012 (Fig. 3). Foster et al. (2013) reported higher seedling density with later planting date (September) than early planting date (May). Our results were also in agreement with findings of Curran et al. (2012) who reported faster and more consistent emergence of switchgrass with later seeding dates. In 2013 although a slight increase was detected with delaying the seeding date from early seeding dates (November and May) to June and July seeding dates, no significant differences were observed between seeding dates. Successful establishment of switchgrass in 2013 could be attributed to optimal (moisture and precipitation) growth conditions (Foster et al., 2013).

Switchgrass height was significantly affected by year, seeding date and herbicide application (Table 4). Plant height was significantly higher in 2013 compared with 2012 which could be explained by the high amount precipitation in 2013 (Table 3). Delaying the seeding date until July resulted in considerably shorter plants (34 cm) compared with other seeding dates. The broad spectrum herbicide application improved switchgrass plant height by 10 cm compared with A+Q treatment which could be attributed to the reduction in switchgrass-weed competition as a result of effective suppression of weeds (Hashemi and Sadeghpour, 2013).

Response of switchgrass stand height to seeding date was different from year to year (Table 4). Excluding May seeding date, plants in 2012 were shorter to that of 2013 (Fig. 4). Plants were 24, 16, and 8 cm taller in November, June, and July seeding dates, respectively. Comparable plant height for May in both years could be due to less effectiveness of herbicides to control crabgrass which was most abundant in this seeding date. This could be justified by the significant interaction of seeding date and herbicide application (Table 4). Taller plants were observed when a broad spectrum herbicide was applied compared with A+Q treatment (Table 5). Plant height was remained at 77 cm in May seeding date regardless of herbicide application which could be explained by limited effectiveness of herbicides on controlling warm-season grassy weeds (Fig. 5).

There were significant differences in ARNs among seeding dates and herbicide treatments (Table 4). Seedlings from November and May plantings generally had greater ARN (15 ARN seedling^{-1}) than seedlings from the June (12 ARN seedling^{-1}) or July (9 ARN seedling^{-1}) (Table 5). In general, early planting dates are more advanced in morphological development (Smart and Moser, 1997). In current study, we observed that not only ARNs were greater in earlier plantings (November and May), they also were taller compared with especially the latest planting date (July). It could be concluded that July to October is a short duration for advanced morphological development of switchgrass. Although ARNs were slightly higher in 2013 compared with 2012, the differences were not found statistically significant. It is reported that ARNs are vital for switchgrass establishment and survival (Smart and Moser, 1997). According to Newman and Moser (1988) adventitious roots developed better when the soil moisture was sufficient. Perhaps, slightly higher ARNs were due to the fact that soil moisture was adequate in 2013 compared with 2012. Greater ARNs were observed with broad spectrum herbicide application (14 ARN seedling^{-1}) than A+Q treatment (13 ARN seedling^{-1}). There is currently no data available for response of ARN to these herbicide selections. These data suggested that to obtain advanced morphologically developed switchgrass seedlings planting early and broad spectrum herbicide application could be a more suitable management practice.

Switchgrass biomass

Switchgrass biomass yield (dry matter basis) was significantly influenced by year, seeding date, herbicide treatments, and year by seeding date (Table 4). Switchgrass biomass yield was 45% greater in 2013 compared with 2012 growing season (Table 5). This could be due to optimal (moisture and precipitation) growth conditions during 2013 growing season (Foster et al., 2013). Biomass yield was decreased with the delay in seeding where 0.5 Mg ha^{-1} biomass yield was obtained from July planting. Biomass yield was 56% greater for May planting compared with the July seeding (Table 5). No significant differences were found between November and June seeding dates. Response of biomass yield to seeding dates varied from year to year. In 2013 there were no significant differences between November, May, and July planting dates. In 2012 however, November produced as low biomass yield as July planting date produced (Fig. 6). This could be due to lack of wet-cold winter which resulted in low establishment of switchgrass in November planting date during 2012 growing season (Table 3). Foster et al. (2013) reported no significant differences between May and September planting dates. However, they reported significantly lower biomass yield when switchgrass was planted in February. Curran et al. (2012) also reported greater dry matter yield when switchgrass was planted earlier in May compared with mid-June planting. We found a significant quadratic relationship between switchgrass tiller density and biomass yield (averaged over two years, r^2= 0.85) (data not shown). While it seems that tiller density might be the main factor contributing in switchgrass biomass production, our data suggest that tiller size (plant height) could be a more pivotal factor in biomass yield where there was a significant linear relationship between plant height and biomass yield (averaged over two years, r^2= 0.94) (data not shown). These findings also emphasize on the importance of the advanced morphological development of the plant for successful establishment, growth, and production which was observed with earlier plantings.

Herbicide treatments had a significant effect on switchgrass biomass yield with 18% greater biomass yield was recorded with the application of broad spectrum treatment than A+Q treatment (Table 5). Herbicide application often reduces weed-crop competition and improve switchgrass biomass yield (Boydsten et al., 2010). Becker and Miller (1998) reported lower warm-season grass stands when weeds were allowed to compete in 2 of 3 years, particularly when soil moisture was limiting which could directly result in low biomass yield.

Weed biomass

Weed biomass significantly affected by seeding date and herbicide treatments (Table 4). As expected, average weed biomass was lowest (0.7 Mg ha^{-1}) in the latest seeding date (July) compared with other planting dates (Table 5). The greatest weed biomass was recorded from May seeding date which could be due to the presence of crabgrass as the dominant weed specifically in that time of growing season. We observed significantly less crabgrass interference in later planting dates which was perhaps the reason for lower weed pressure. Curran et al. (2012) also reported that later seeding date (mid-June) had lowest weed biomass compared with those of early and mid-May. In the second year of their study, they found greater weed biomass in the middle seeding date (mid-May) compared with the earlier (early-May) and later (mid-June) planting dates which could be due to lower tiller density of switchgrass in that seeding (mid-May) date. In current study, there was no significant linear relationship between switchgrass tiller density and weed biomass mainly due to greater weed biomass in May planting date although acceptable tiller density was counted earlier in the growing season. Excluding May seeding date, our finings confirmed the results reported by Curran et al. (2012) that adequate seedling density would be required to control weed pressure.

Greater weed biomass (1.6 Mg ha^{-1}) was recorded from A+Q treatment compared with broad spectrum treatment (1.4 Mg ha^{-1}). Curran et al. (2012) reported lower weed biomass for broad spectrum post application of atrazine, quinclorac, 2,4-D, and dicamba compared with only 2,4-D and dicamba treatment (Curran et al., 2012). Differences between herbicide applications are mostly due to the control of hairy vetch (*Vicia villosa* Roth) which was presented in the last seeding date which suggested that single application of A+Q would not be adequate for effective weed control depending on the weed species.

Curran et al. (2012) suggested that switchgrass performance can be assessed by calculating the ratio of switchgrass to weed biomass for each treatment. Response of swichgrass:weed biomass ratio was different from year to year. In 2012, similar to findings of Curran et al. (2012) later planting date (July) had significantly higher switchgrass:biomass ratio (Fig. 7). However, the highest switchgrass:weed biomass ratio in 2013 resulted from November (1.05) seeding date which had no significant differences with June (0.94) and July (0.95) planting dates (Fig. 7). The switchgrass:weed ratio reported in Curran et al. (2012) was higher than that of this study which could be explained by higher seeding rates, use of scarified seeds, and applying herbicides with the presence of surfactants.

Conclusion

In this study we addressed an integrated management of switchgrass establishment using planting date and herbicide application. We hypothesized that planting switchgrass in November could improve switchgrass stand density; however, this totally depends on the weather condition and we observed low stand density in a dry season with minimum snowfall during the winter. Later seeding date (July) always had lower weed pressure compared with November, May, and June seeding date but the stands were shorter, and the root system was less advanced with almost twice less ARN. This could result in limited stand productivity in the succeeding years. On the other hand, with optimal weather condition, earlier plantings produced acceptable harvestable biomass in the establishment year and due to greater ARNs could possibly produce higher biomass yields in the succeeding years. A mixed pre-emergence application of A+Q plus a post-emergence application of 2,4-D and dicamba promoted switchgrass establishment and resulted in the most effective weed control than just the A+Q treatment. Overall, considering switchgrass biomass yield, morphology to survive and stay productive, and weed biomass in the establishment year, an early planting (May) with the application of the broad spectrum herbicide could be suitable for switchgrass establishment.

Table 3: Monthly and total growth degree days (GDD_{10}°C) and precipitation (mm) from November 2011 to October 2013 at the University of Massachusetts experimental farm, South Deerfield.

Months	GDD_{10} □C		Precipitation (mm)	
	Year			
	2011-12	2012-13	2011-12	2012-13
November	38	6	82.5	7.8
December	4	0	118.6	72.9
January	0	0	76.2	54.6
February	0	0	17.8	45.7
March	87	0	21.2	44.9
April	91	64	65.0	51.8
May	385	301	125.2	172.5
June	483	528	105.0	239.5
July	745	790	0.0	103.9
August	692	591	14.8	75.2
September	386	350	138.2	75.7
October	158	142	99.3	44.9
Total	3069	2772	864.3	989.4

Table 4: ANOVA for influence of year, seeding date and herbicide application on switchgrass tiller density, plant height, adventitious root number, switchgrass biomass, weed biomass, and switchgrass:weed biomass.

SOV†	Tiller Density	Plant Height	ARN‡	SGB§	WB¶	SGB:WB#
Year (Y)	**	**	NS	**	NS	**
Seeding Date (SD)	**	**	**	**	*	**
Herbicide (H)	NS	**	**	*	**	**
Y×SD	**	*	NS	*	NS	**
Y×H	NS	NS	NS	NS	NS	NS
SD×H	NS	**	NS	NS	NS	**
Y×SD×H	NS	NS	NS	NS	**	**

†SOV, source of variation.
‡ARN, adventitious root number.
§SGB, switchgrass biomass.
¶WB, weed biomass.
#SGB:WB, switchgrass:weed biomass ratio.
NS, non-significant; *, significantly different at $P<0.05$; **, significantly different at $P<0.01$.

Table 5: Effect of year, seeding date, and herbicide application on switchgrass tiller density, plant height, adventitious root number, switchgrass biomass, weed biomass, and switchgrass:weed biomass ratio.

Treatment		Tiller Density	Plant Height	ARN†	SGB‡	WB§	SGB:WB¶
		(m^{-2})	(cm)	($seedling^{-1}$)	--- ($Mg\ ha^{-1}$) ---		
Year	2012	121b	51.9b	13.7a	0.62b	1.53a	0.53b
	2013	306a	64.6a	13.1a	1.12a	1.45a	0.87a
Seeding Date	November	157c	59.4b	15.5a	0.82b	1.22c	0.74a
	May	214b	76.7a	15.9a	1.13a	2.46a	0.47b
	June	214b	58.31b	12.8b	0.93b	1.57b	0.69a
	July	268a	36.6c	9.0c	0.58c	0.71d	0.91a
Herbicide	A+Q#	208a	52.8b	12.7b	0.78b	1.59a	0.54b
	Broad Spect.□	219a	63.3a	13.8a	0.95a	1.39b	0.86a

† ARN, adventitious root number
‡ SGB, switchgrass biomass
§ WB, weed biomass
¶ SGB:WB, switchgrass:weed biomass ratio
#A+Q, atrazine + quinclorac
□Broad Spect., Broad Spectrum (atrazine + quinclorac + 2,4-D + dicamba)
Means followed by the same letter are not significantly different at $P<0.05$ as determined by Duncan multiple range test.

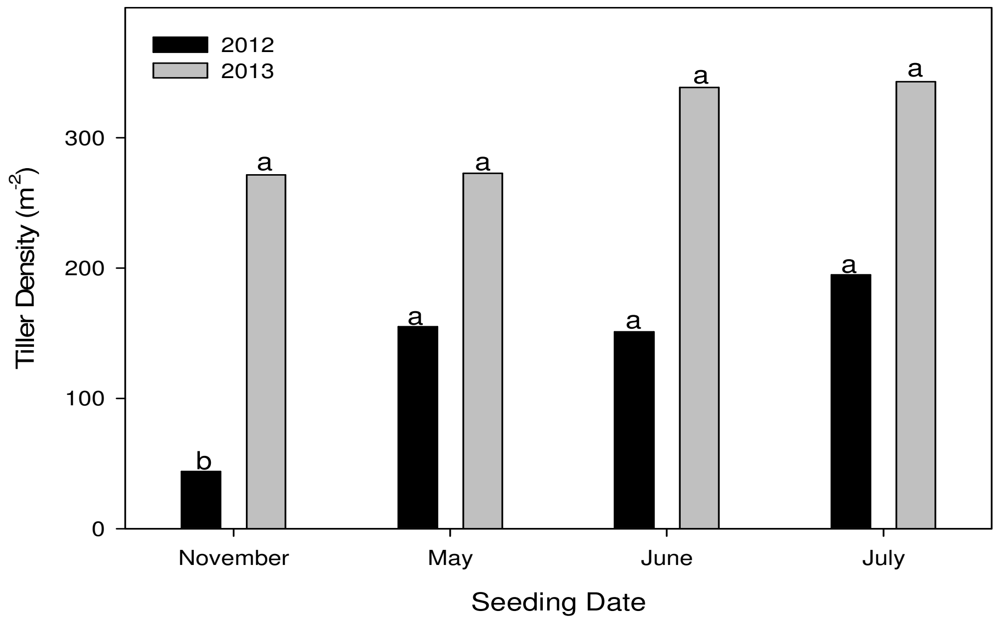


Figure 3: Switchgrass tiller density as influenced by seeding date in 2012 and 2013 growing seasons (averaged over herbicide treatments).

Means followed by the same letter are not significantly different at P<0.05 within each year as determined by Duncan multiple range test.

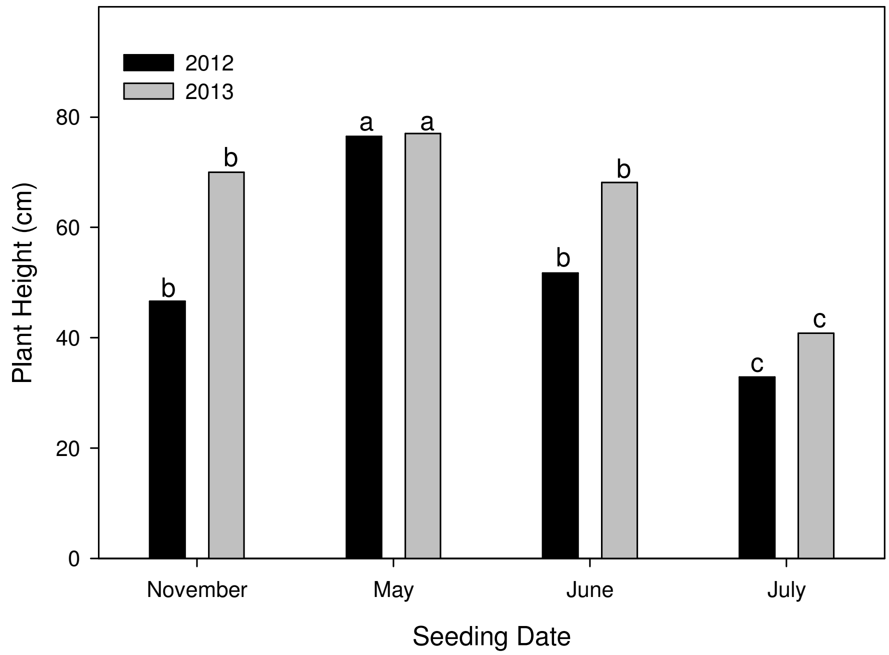


Figure 4: Effect of seeding date on switchgrass plant height in 2012 and 2013 growing seasons (average over herbicide treatments).

Means followed by the same letter are not significantly different at *P*<0.05 as determined by Duncan multiple range test.

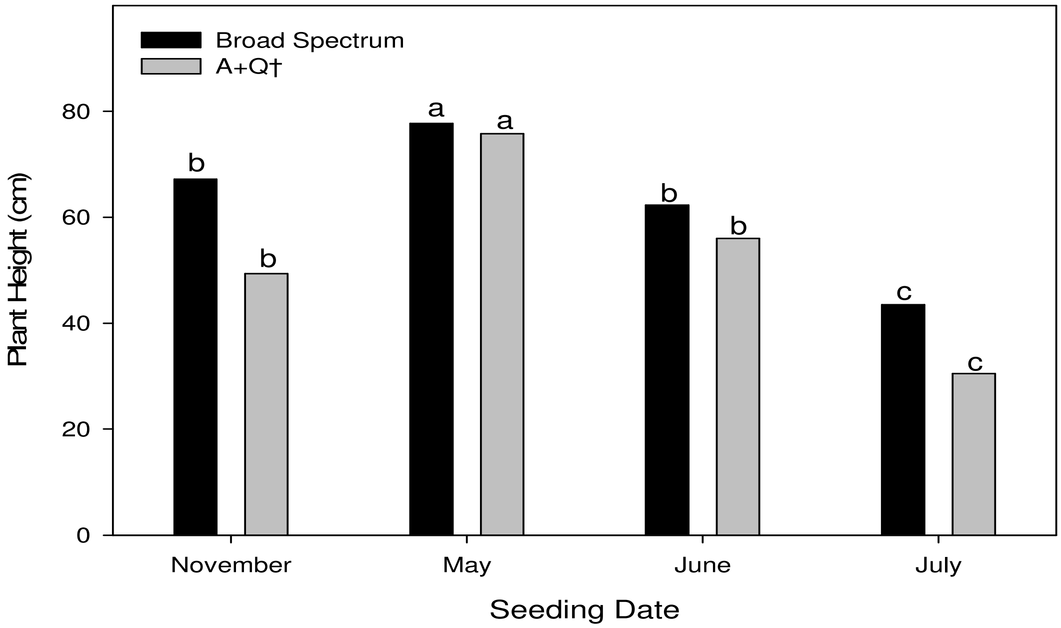


Figure 5: Switchgrass plant height as affected by seeding date and herbicide treatments (average over growing seasons).

Means followed by the same letter are not significantly different at $P<0.05$ within each planting date as determined by Duncan multiple range test.

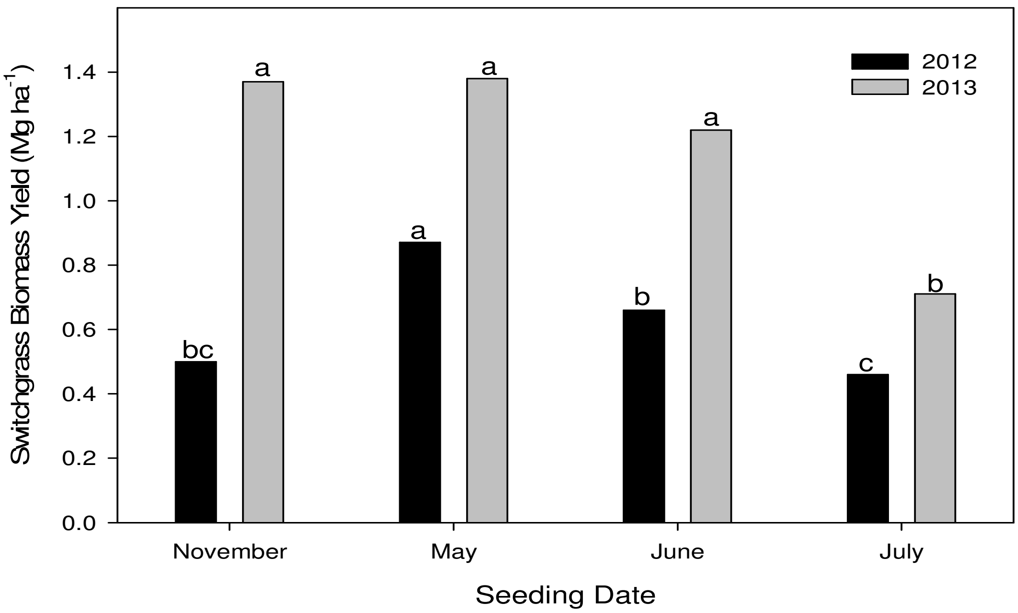


Figure 6: Switchgrass biomass yield as influenced by seeding date in 2012 and 2013 growing seasons (average over herbicide treatments).

Means followed by the same letter are not significantly different at $P<0.05$ as determined by Duncan multiple range test.

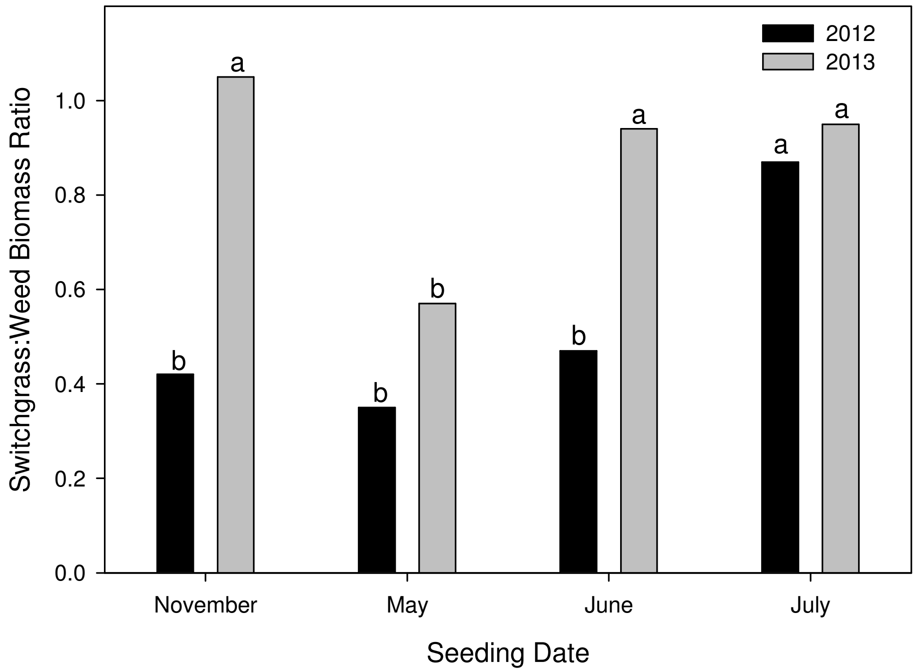


Figure 7: Effect of seeding date on switchgrass:weed biomass ratio in 2012 and 2013 growing seasons (average over herbicide treatments).

Means followed by the same letter are not significantly different at P<0.05 as determined by Duncan multiple range test.

CHAPTER 4

SWITCHGRASS ESTABLISHMENT INFLUENCED BY COVER CROPS, SEEDING METHODS, AND WEED CONTROL

Abstract

Successful establishment of switchgrass (*Panicum virgatum* L.) is often challenging. The objective of this study was to improve switchgrass stand establishment through integrated management practices that included cover crops, seeding methods and herbicide application. An experiment was conducted at the University of Massachusetts Agricultural Experiment Station in Deerfield during the growing season of 2012 and replicated in 2013. A split split-plot design with three replications was used in both experiments. The main plots consisted of three cover crop species [no cover crop, oat (*Avena sativa* L.), and rye (*Secale cereale* L.)]. The sub-plots were two seeding methods [no-till drill, and cultipacker seeder (Brillion)]. The sub sub-plots were herbicide treatments that consisted (i) pre-emergence (PRE) application of atrazine (A) and quinclorac (Q) and (ii) a Broad Spectrum application of PRE A+Q that was supplemented with post-emergence (POST) application of 2,4-D and dicamba. The no-till seeding method in both experiments resulted in higher stand density and biomass. Weed control was improved with the Broad Spectrum herbicide (0.90 Mg ha^{-1}) compared with A+Q treatment (1.3 Mg ha^{-1}). No-till seeding produced considerably higher tiller numbers (190 tiller m^{-2}) than other seeding methods which in turn resulted in significant weed suppression. In general, when planted after rye, switchgrass produced fewer tillers than after oat or no cover crop. No-till seeding into oat mulch with the application of Broad

Spectrum herbicides resulted in highest switchgrass yield (2098 kg ha^{-1}) in the establishment year.

Key words: Cover crops, Seeding methods, Switchgrass, Tiller density, Weed biomass.

Abbreviations: A, atrazine; GDD, growing degree days; NCC, no cover crop; PRE, pre-emergence; POST, post-emergence; Q, quinclorac.

Introduction

Switchgrass is the most promising second generation energy crop due to its low-input requirements and high biomass production in marginal lands (Sadeghpour et al., 2014). It is a warm season C_4 perennial grass with a deep fibrous root system native to North America (Herbert et al., 2012). A relatively small seed size, high dormancy rate, and slow germination often makes switchgrass a weak competitor with many summer annual grass and broadleaf weeds (Boydston et al., 2010; Curran et al., 2011). As a result, crop establishment and early growth is often delayed (Mitchell et al., 2010). A poor switchgrass stand during the seeding year can limit yield and large scale crop adoption (Berti and Johnson, 2013; Hashemi and Sadeghpour, 2013).

Weed control is one of the major challenges in the establishment of switchgrass (Mitchell et al., 2010). To reduce weed pressure and improve switchgrass stand establishment, an integrated management practice is required. Cover crops and organic mulches in combination with proper seeding methods are suggested practices for enhancing switchgrass establishment (King et al.,1989; Monti et al., 2001). The benefits of cover crops in controlling weeds in several row crops including corn (*Zea mays* L.), soybean (*Glycine max* L.), and southern pea (*Vigna unguiculata* L.) have been well documented (Johnson et al., 1993; Moore et al., 1994; Ateh and Doll, 1996; Burgos and Talbert, 1996; Yenish et al., 1996). Cereals are fast growing species which can grow fast, produce high biomass and suppress weeds (Sadeghpour et al., 2013). Rye (*Secale cereale* L.) is a commonly used cover crop that reduces density and biomass of several weed species in soybean (Liebl et al., 1992; Moore et al., 1994) and corn (Teasdale et al., 1991). Weed biomass reduction has also been reported with planting oat (*Avena sativa* L.) and other annual grass species such as Italian ryegrass (*Lolium multiflorum* L.) and wheat (*Triticum* spp.) (Weston, 1990; Moore et al., 1994; Burgos and Talbert, 1996). Hashemi et al. (2013) reported that planting a winter rye cover crop in early September in fall-manured fields produced optimum biomass for efficient nitrogen recovery and weed control in Massachusetts. In spring, cover crops can be killed by herbicide for no-till or incorporated into soil in a conventional tillage system. Cover crops can also be mowed prior to planting the main crop, leaving the organic mulch on the soil surface (Pullaro et al., 2006; Campiglia et al., 2012).

Seedbed preparation for planting switchgrass typically ranges from conventional to no-till, planting into killed sods or bare soil (Parrish and Fike, 2005). Although several reports have indicated the preference of conventionally tilled seedbeds over no-till planting (Oldfather et al., 1989; Potvin, 1993; Teel et al., 2003), no-till planting of switchgrass has also been proven to be useful in some circumstances (Wolf et al., 1989). However, there is limited information regarding the suitability of various seedbed preparations for switchgrass cultivation in different conditions (Parrish and Fike, 2005). McKenna et al. (1991) and Teel et al. (2003) suggested that planting into an herbicide-killed sod is possible with proper equipment, but they also stated that switchgrass stands planted in this method may be reduced compared with switchgrass stands planted into conventionally tilled seedbeds. Similarly, Oldfather et al. (1989), Potvin (1993), Evers and Butler (2000) suggested that switchgrass planted through direct drilling into killed sod was a less reliable method when compared with conventional tillage. In another approach, Monti et al. (2001) showed that establishment of switchgrass was enhanced when conventionally prepared seedbeds were rolled or compacted, after seeds were broadcasted. In contrast, other reports indicated that there was no yield advantage from conventional tillage over no-till planting. For example, Rehm (1990) found no switchgrass yield difference between no-till and conventional planting methods. King et al. (1989) compared no-till to conventional planting of switchgrass at two locations in Nebraska and found that the yield advantage of one tillage system over the other depended on season and location. Harper et al. (2004) in a series of studies in Tennessee reported 50 to 150% more switchgrass seedlings was obtained in a no-till system compared with conventional seedbed preparation. Parrish and Fike (2005) and Wolf et al. (1989) concluded that the advantage of no-till planting of switchgrass over conventional tillage is partly due to soil and water conservation and also to the potential for earlier planting.

Herbicidal control of weeds in conjunction with other management practices may significantly improve establishment success (Mitchell et al., 2010; Curran et al., 2012). Quinclorac controls a number of annual broadleaf and grass weeds, and has been recently registered for use in switchgrass (Curran et al., 2012; Kering et al., 2013). Atrazine can also be used in some states in U.S.A. to control broadleaf weeds in switchgrass (Martin et al., 1982; Bahler et al., 1984; Hintz et al., 1998). Mitchell et al. (2010) reported that a combination of quinclorac and atrazine provided satisfactory weed control for establishing both lowland and upland switchgrass cultivars in the Central and Northern Great Plains. Broadleaf weeds in switchgrass can also be controlled by an application of dicamba and 2,4-D (Curran et al., 2008). In a recent study, Curran et al. (2012) reported that a broad spectrum post-emergence application of atrazine, quinclorac, dicamba and 2,4-D significantly reduced the weed pressure in the establishment year of switchgrass. However, literature is lacking data on an integrated management practice for switchgrass establishment and there is currently no data available on establishment of switchgrass in Massachusetts. Our primary objective of this study was to improve switchgrass establishment through reducing weed pressure by implementing integrated management practices including use of cover crops, seeding methods and appropriate herbicide application.

Materials and methods

Experimental site

The experiment was conducted at the Crops and Animal Research and Education Farm of the University of Massachusetts in South Deerfield (42°28′37″N, 72°36′2″W), in 2012 and replicated in 2013. The soil type was a Hadley fine sandy loam (nonacid, mesic Typic Udifluvent) with a pH of 5.5, organic matter content of 1.3%, N, P, K, and Ca content of 3, 11.8, 109, and 616 mg kg^{-1}, respectively. Soil samples in the top 20 cm were taken prior to planting. To adjust the soil pH 1120 kg ha^{-1} was applied to the soil.

Experimental design and cultural practices

The experimental design was split split-plot design with three replications.The main plots consisted of three cover crop species [no cover crop, oat (*Avena sativa* L.), and rye (*Secale cereale* L.)]. The sub-plots were two seeding methods [no-till drill, and cultipacker seeder (Brillion)]. The sub sub-plots were herbicide treatments that consisted (i) pre-emergence (PRE) application of atrazine (A) (2-chloro-4-ethylamino-6-isopropyl-amino-s-triazine) at the rate of 1.1 kg a.i. ha^{-1} and quinclorac (Q) (3, 7-dichloro-8-quinolinecarboxylic acid) at the rate of 0.37 kg a.i. ha^{-1} and (ii) a Broad Spectrum application of PRE A+Q (1.1 and 0.37 kg a.i. ha^{-1}, respectively) that was supplemented with post-emergence (POST) application of 2,4-D ((2,4-dichlorophenoxy)acetic acid) (0.28 kg a.i. ha^{-1}) and dicamba (3,6-dichloro-o-anisic acid) (0.28 kg a.i. ha^{-1}).

Winter rye and oat were drilled in mid-September in each year of study at the rate of 112 and 96 kg ha^{-1}, respectively. Oat was winterkilled whereas winter rye and weeds in no cover crop plots were suppressed by an application of glyphosate [N-(phosphonomethyl) glycine] at a rate of 0.84 kg a.i. ha^{-1} in spring. Due to presence of high biomass in winter rye plots, a portion of rye residue was baled and removed from the field prior to seeding switchgrass. An upland switchgrass variety 'Cave-in-Rock' was planted at a rate of 9 and 11 kg ha^{-1} pure live seed on 28 June 2012, and 5 of July 2013. The plot size was 3 m wide and 6 m long. The pre-emergence herbicide was applied one day after planting and post-emergence herbicides were applied with a sprayer approximately 6 weeks after switchgrass was planted. In current study, no nitrogen fertilizer was applied due to lack of switchgrass response in previous studies in the study location. According to typical agronomic practices in Massachusetts, no irrigation was applied to the experimental sites (Farsad et al., 2012).

Measurements

Switchgrass tiller density was determined from the center rows using four 0.1 m^2 quadrats per plot approximately 6 weeks after post-emergence herbicide application. Weed biomass was collected from the center rows using four 0.1 m^2 quadrats per plot when tiller density was counted (Mid-September). Weed samples were dried in a forced air oven at 55 °C for 72 h and weighed. Switchgrass yield was determined from biomass samples collected in late October after a killing frost in 2012 and in early November in 2013 using five 0.1 m^2 quadrats per plot. Similar procedure to weed biomass was used to obtain dry matter yield of switchgrass.

Statistical analysis

All statistical was analyses were performed using proc GLM of SAS, Version 9.2 (SAS Institute, 2009), and proc REG was used for regression analysis. All data met the assumption of analysis of variance and no data were transformed. Main effects were year, cover crops, seeding methods, and herbicide treatments and only block was considered a random effect. Means were compared using the Duncan multiple range test. All differences reported are significant at $P \leq 0.05$ unless otherwise stated.

Results and discussion

Weather conditions

Cumulative growing degree days (GDD), observed from the Orange, MA, weather station, for 2012 and 2013 growing seasons (July through Oct) were 1983 and 1874, respectively (Table 6). Cumulative growing season precipitation was 163 mm in 2012, and 352 mm in 2013. Precipitation after the seeding month (August) was much higher (104 mm) in 2013 compared with 2012 (42 mm) which could explain the significant interaction of year by treatments.

Switchgrass density

Switchgrass tiller density was significantly differed from year to year (Table 7). Switchgrass tiller density was 42% higher in 2013 (198 tiller m^{-2}) compared with 2012 (113 tiller m^{-2}) which could be due to higher precipitation in 2013 than in 2012. Tiller density also was significantly influenced by cover crops, seeding methods and herbicide application treatments. When planted into oat cover crop, switchgrass tiller density was higher (195 tiller m^{-2}) than those of NCC (156 tiller m^{-2}) and rye (106 tiller m^{-2}) (Table 7). No-till drill produced significantly higher tillers (215 tillers m^{-2}) than that of cultipacker seeder (87 tiller m^{-2}) (Table 7). Tiller density was lower (125 tiller m^{-2}) in the A+Q treatment compared with the Broad Spectrum treatment (179 tiller m^{-2}) (Table 7). Tiller density was significantly affected by year×seeding methods, cover crops×seeding methods, and cover crops×herbicide treatments. Tiller densities were greater when no-till planted in 2013 (240 tiller m^{-2}) and were lowest when cultipacker seeder was used in 2012 (32 tiller m^{-2}) (Fig. 8). Our results indicated that oat was the most suitable cover crop when no-till planting was practiced with 278 tillers m^{-2}. However, there were no significant differences between oat and NCC when cultipacker seeder was used to plant switchgrass (Fig. 9). The lowest tiller density was recorded from planting switchgrass into rye cover crop using the cultipacker seeder (57 tiller m^{-2}) (Fig. 9). Sanderson et al. (2006) reported that little scientific information exists regarding cover crop selection to control weed and enhance switchgrass establishment. King et al. (1989) studied the effect of three seedbed preparation methods (untilled, disked, and oat residue) on dryland grass establishment and showed greater grass establishment occurred when oat residues were left on the soil surface. They concluded that in dry conditions, disking and/or oat residue can improve various grass stands. The lower switchgrass density after rye cover crop could be attributed to the allelopathic effect of rye on germination of switchgrass, but it requires further investigation. Previous studies have documented that using rye cover crop could reduce the germination of following crops including alfalfa (*Medicago sativa* L.) and tall fescue (*Festuca arundinacea* L.) (Miller, 1996). Weston (1990) also reported that increased weed suppression provided by a cover crop was accompanied by reduced row crop establishment, with greatest reductions observed in pasture grasses. Tiller density was greater when switchgrass was drilled into oat cover crop and followed by Broad Spectrum herbicide treatment (241 tiller m^{-2}) (Fig. 10). Overall, the lowest impact of Broad Spectrum treatment was observed in rye cover crop where tiller density increase from 99 (A+Q) to 113 (tiller m^{-2}) (Broad Spectrum). The major weeds in the switchgrass stands were crabgrass (*Digitaria sanguinalis* L.) and yellow foxtail (*Setaria glauca* L.), which significantly competed with germinated switchgrass seeds and seedlings. Some reports indicated that herbicide application may negatively impact the switchgrass stands.

For example Curran et al. (2008) and Boydston et al. (2010) showed that post-emergence application of quinclorac reduced switchgrass stand which might be attributed to higher herbicide rates (0.56 and 0.42 kg a.i. ha^{-1}, respectively) in their study compared to that used in this research (0.37 kg a.i. ha^{-1}). In the present study, the reduction in weed biomass resulting from Broad Spectrum treatment resulted in higher switchgrass tiller density compared with the recorded tiller density in A+Q treatment.

Weed biomass

Unlike what we expected, lower weed biomass was recorded from 2013 growing season which was wetter compared with 2012 (Table 7). This might be due to higher switchgrass stand density that was resulted from the favorable climatic condition in 2013 (Table 6) which perhaps suppressed weeds to some extent. There was a negatively linear relationship between switchgrass tiller density and weed biomass (r^2= 0.62) (Fig. 11). As expected, NCC had the greatest weed biomass (1.4 Mg ha^{-1}) than the other cover crop treatments (oat and rye) (Table 7). No-till drill significantly controlled weed pressure (0.80 Mg ha^{-1}) compared with cultipacker seeder (1.50 Mg ha^{-1}) (Table 7). The higher weed pressure in cultipacker seeder plots could be attributed to the soil disturbance before planting, which may encourage weed emergence from the soil seed bank. The most problematic weeds at this site were crabgrass and pigweed (*Amaranthus* spp.). Crabgrass did not emerge when switchgrass was planted in the no-till drilled plots, whereas disking of cultipack seeded plots increased the frequency of crabgrass as a major weed at this experimental site. In no-till drilled plots with less weed pressure in early stages of growth, switchgrass stands established successfully and were able to compete with the future weeds more effectively. Weed biomass was significantly lower in Broad

Spectrum herbicide treatment (0.90 Mg ha^{-1}) than that of A+Q (1.30 Mg ha^{-1}) (Table 7). Broadleaf weeds and volunteer legumes are often troublesome and result in switchgrass stand reduction (Hashemi and Sadeghpour, 2013). Boydston et al. (2010) and Mitchell et al. (2010) reported the effectiveness of using A+Q in controlling weeds and improving switchgrass establishment however, supplementing A+Q with 2,4-D and dicamba could significantly excel the efficacy of herbicide application and therefore, enhance switchgrass density through controlling weeds which are primary reasons for switchgrass stand failure (Curran et al., 2012). Boydston et al. (2010) concluded that quinclorac was the most promising herbicide for switchgrass establishment and suggested that quinclorac should be applied in lower rates than 56 kg a.i. ha^{-1} to effectively reduce the weed pressure without reducing the switchgrass stand.

Weed biomass also significantly influenced by year×seeding methods, cover crop×seeding methods, and seeding methods×herbicide treatment. Weed biomass response to no-till drill method was similar in 2012 (0.76 Mg ha^{-1}) and 2013 (0.84 Mg ha^{-1}). However, significantly higher weed biomass was recorded from cultipacker seeder method in 2012 (1.8 Mg ha^{-1}) compared with 2013 (1.2 Mg ha^{-1}) (Fig. 12). Year to year variation in cultipacker seeder method could be explained by higher tiller density in 2013 which probably resulted in improved weed suppression. Weed infestation was reduced significantly when switchgrass was no-till drilled into winterkilled oat residues (0.58 Mg ha^{-1}) and was at its peak when cultipacker seeder was used to drill switchgrass into NCC (1.67 Mg ha^{-1}) which interestingly did not differ from cultipacker seeder and oat cover crop treatments (1.54 Mg ha^{-1}) (Fig. 13). As expected a combination of no-till drill and Broad Spectrum herbicide application provided acceptable weed suppression (0.58 Mg ha^{-1}). On the other hand, combination of cultipacker seeder and A+Q treatment had the highest weed biomass (1.6 Mg ha^{-1}) (Fig. 14).

Switchgrass biomass

Switchgrass biomass yield was significantly influenced by cover crops and seeding methods but not by herbicide treatments (Table 7). Switchgrass biomass yield was greatest when planted into oat cover crop (1.2 Mg ha^{-1}) whereas there were no significant differences between rye and NCC (Table 7). This could be due to higher tiller density in oat observed in oat cover crop plots (Table 7). There was a significantly positive linear correlation (r^2= 0.87) between switchgrass tiller density and biomass yield (Fig. 11). No-till drill seeding of switchgrass yield was threefold higher than the cultipacker seeder method (Table 7). The significant differences between the no-till drill seeding and the cultipacker seeder methods could be explained by the greater water conservation benefits from no-till as well as successful weed suppression. Our findings differ from some other reports and add to the contradictory reports in regard to switchgrass establishment (Sanderson et al., 2004; Parrish and Fike, 2005). Oldfather et al. (1989) and Potvin (1993) suggested that direct drilling switchgrass into a killed sod was less reliable method than conventional tillage. Many other reports, however, suggest no yield advantage of conventional tillage over no-till seeding. For example, Rehm (1990) found no yield difference between no-till and conventional seeding methods. King et al. (1989) compared no-till versus conventional planting of switchgrass at two locations in Nebraska and found that the yield advantage of one tillage system over the other was depended on season and location. Parrish and Fike (2005) in their review indicated that warm-season grasses could be successfully established in a no-till system mainly due to better conserving soil and water. Our findings confirmed that no-till seeding of switchgrass is a preferred method for switchgrass cultivation. Recent reports indicated that biomass production of more than 1 Mg ha^{-1} during the establishment year often results in a high crop yield in the succeeding years (Mitchell et al., 2010; Mitchell and Vogel, 2012; Curran et al., 2012; Miesel et al, 2012). The biomass production during the establishment year in present study was above 1 Mg ha^{-1} when no-till drill method was used (1.39 Mg ha^{-1}). Averaged over two years, a combination of no-till drill, oat cover crop and Broad Spectrum herbicide treatments produced acceptable establishment year biomass (1.9 Mg ha^{-1}).

Curran et al. (2012) suggested that switchgrass performance can be assessed by calculating the ratio of switchgrass to weed biomass for each treatment. Six-fold higher swichgrass:weed ration was obtained from no-till drill method (1.80) compared with cultipacker seeder (0.30) (Table 7). When Broad Spectrum herbicide was applied, greater switchgrass:weed biomass ratio (1.10) than A+Q (0.60) was recorded (Table 7). The ratio was greatest when switchgrass was no-till planted into oat cover crop (3.70) (Fig. 15). However the ratios were lower than those reported by Curran et al. (2012) (6.90) in the establishment year, possibly due to their higher seeding rates and use of scarified seeds.

Conclusion

In this study we addressed the integrated management of switchgrass establishment using cover crops, tillage systems and herbicide application. No-till drill seeding resulted in most efficient weed control and therefore highest switchgrass establishment. Although rye and oat cover crops controlled weeds to a greater extent than no cover crop when used as mulch, rye reduced switchgrass stand density whereas oat mulch provided weed suppression as well as satisfactory switchgrass establishment. Application of a Broad Spectrum herbicide (A+Q+ 2,4-D, and dicamba) is highly recommended for successful switchgrass establishment. Overall, highest weed suppression, switchgrass tiller density, and switchgrass biomass yield was achieved with the no-till drill seeding of switchgrass into a winter killed oat mulch with the application of the Broad Spectrum herbicide.

Table 6: Monthly and total growing degree days (GDD_{10} °C) and precipitation (mm) during 2012 and 2013 at the University of Massachusetts experimental farm, South Deerfield.

Month	GDD_{10} °C		Precipitation (mm)	
	2012	2013	2012	2013
July	745.7	790.2	14.5	123.7
August	692.7	591.1	42.2	104.1
September	386.7	350.5	37.3	98.5
October	158.7	142.6	69.6	25.9
Total	1,983.8	1,874.4	163.6	352.2

Table 7: Influence of cover crop, seeding methods, and herbicide application on switchgrass tiller density and biomass, weed biomass, and switchgrass:weed biomass ration in 2012 and 2013 growing seasons.

Treatment		Tiller density	SG† Biomass	Weed Biomass	SG:W‡ Biomass
		m^{-2}	$Mg\ ha^{-1}$		
Year	2012	113b	0.90a	1.3a	1.4a
	2013	198a	0.96a	1.0b	1.3a
Cover crop	Fallow	156b	0.84b	1.4a	0.9a
	Oat	195a	1.20a	1.1b	1.1a
	Rye	106c	0.81b	1.0b	1.1a
Seeding methods	No-till	215a	1.39a	0.8b	1.8a
	Cultipacker	87b	0.47b	1.5a	0.3b
Herbicide	A+Q§	12b	0.86a	1.3a	0.6b
	Broad Spectrum	179a	1.00a	0.9b	1.1a

† SG, switchgrass
‡ SG:W Biomass, switchgrass:weed biomass ration
§A+Q, atrazine + quinclorc
Different letters next to the treatment means indicate significant difference (P<0.05).

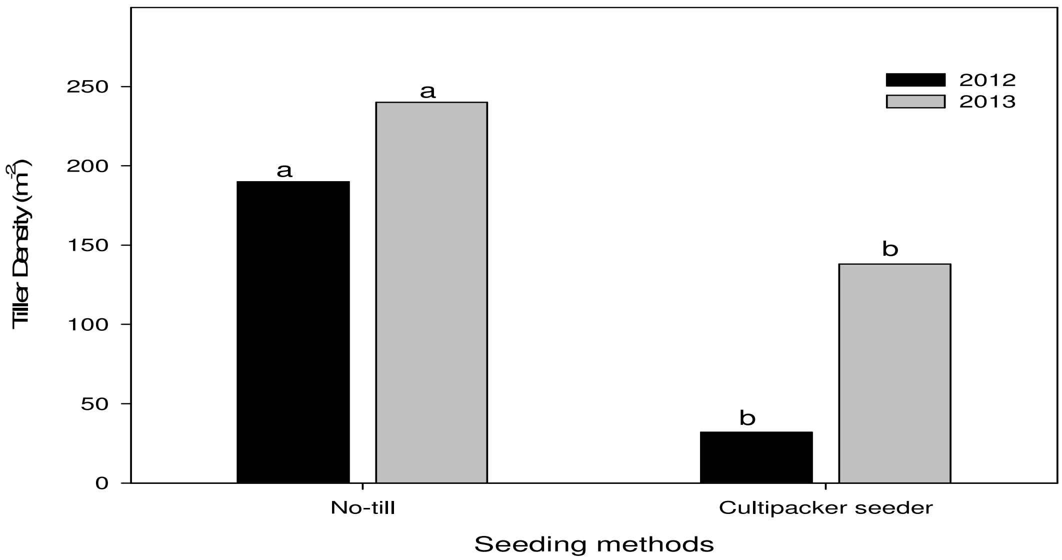


Figure 8: Switchgrass tiller density as affected by seeding methods in 2012 and 2013 growing seasons (averaged over cover crop species and herbicide treatments). Mean values in each column followed by different letters differ significantly at $P<0.05$.

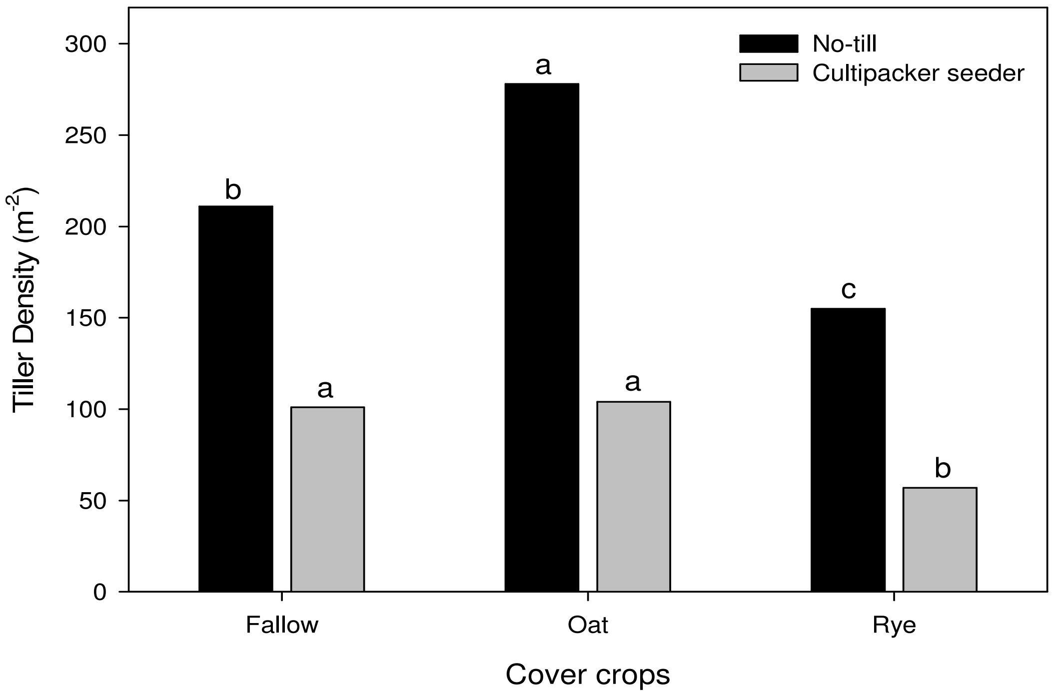


Figure 9: Effect of cover crop species and seeding methods on switchgrass tiller density (averaged over years and herbicide treatments).

Mean values in each column followed by different letters differ significantly at $P<0.05$.

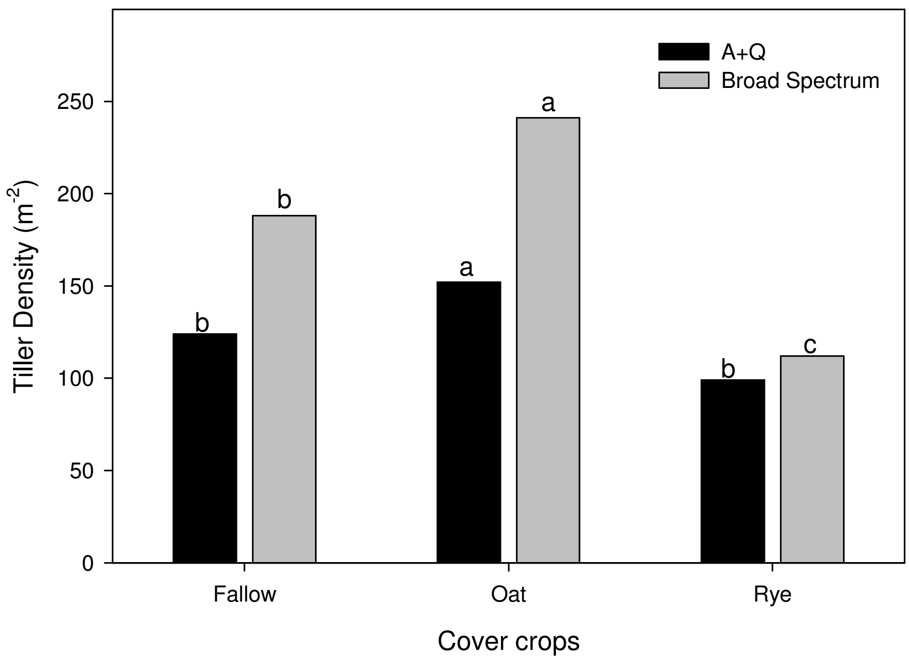


Figure 10: Influence of cover crop species and herbicide treatments on switchgrass tiller density (averaged over years and seeding methods).

†A+Q represents for atrazine + quinclorac.

Mean values in each column followed by different letters differ significantly at P<0.05.

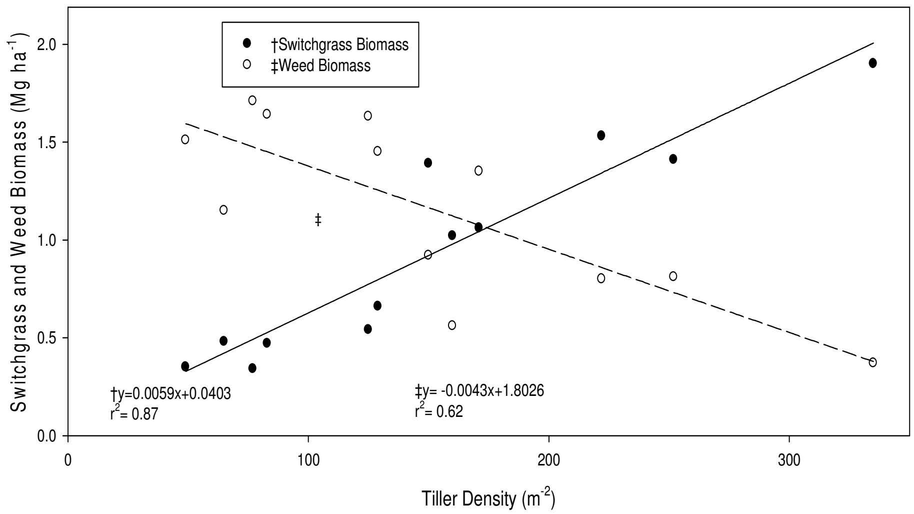


Figure 11: Correlation between switchgrass tiller density with switchgrass and weed biomass.

Regression analyses were conducted with mean values for treatments, and therefore, r^2 values were based on means.

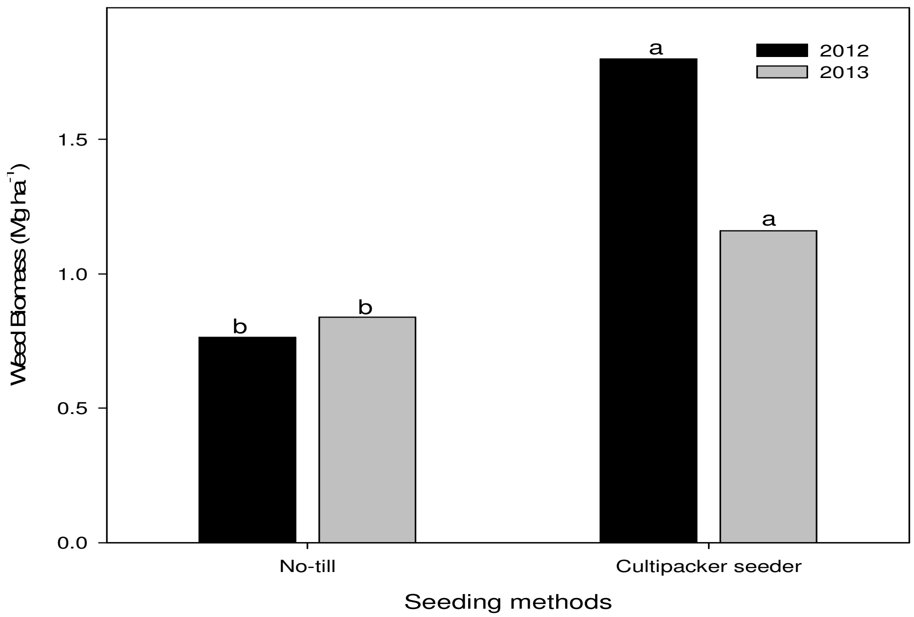
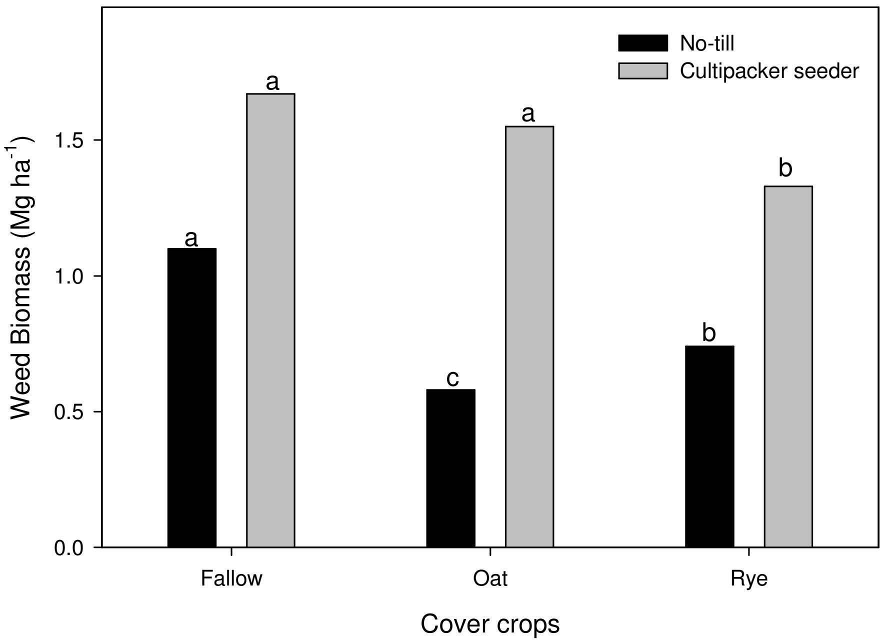


Figure 12: Effect of seeding methods on weed suppression in 2012 and 2013 growing seasons (averaged over cover crop species and herbicide treatments).

Mean values in each column followed by different letters differ significantly at $P<0.05$.



.

Figure 13: Influence of cover crop species and seeding methods on weed suppression (averaged over years and herbicide treatments).

Mean values in each column followed by different letters differ significantly at $P<0.05$.

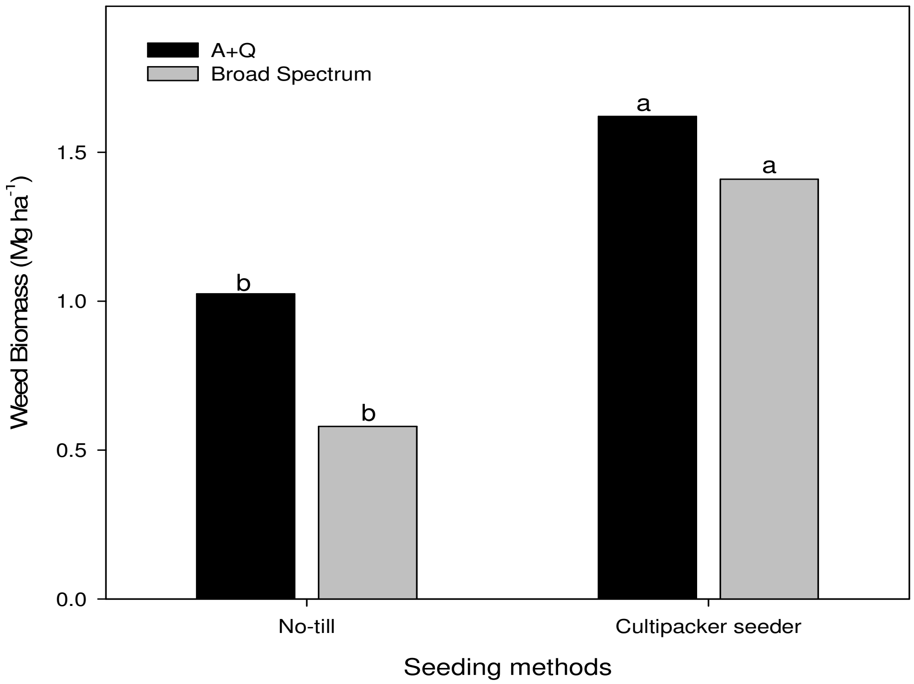


Figure 14: Effect of seeding methods and herbicide treatments on weed biomass (averaged over years and cover crop species).

†A+Q represents for atrazine + quinclorac.

Mean values in each column followed by different letters differ significantly at P<0.05.

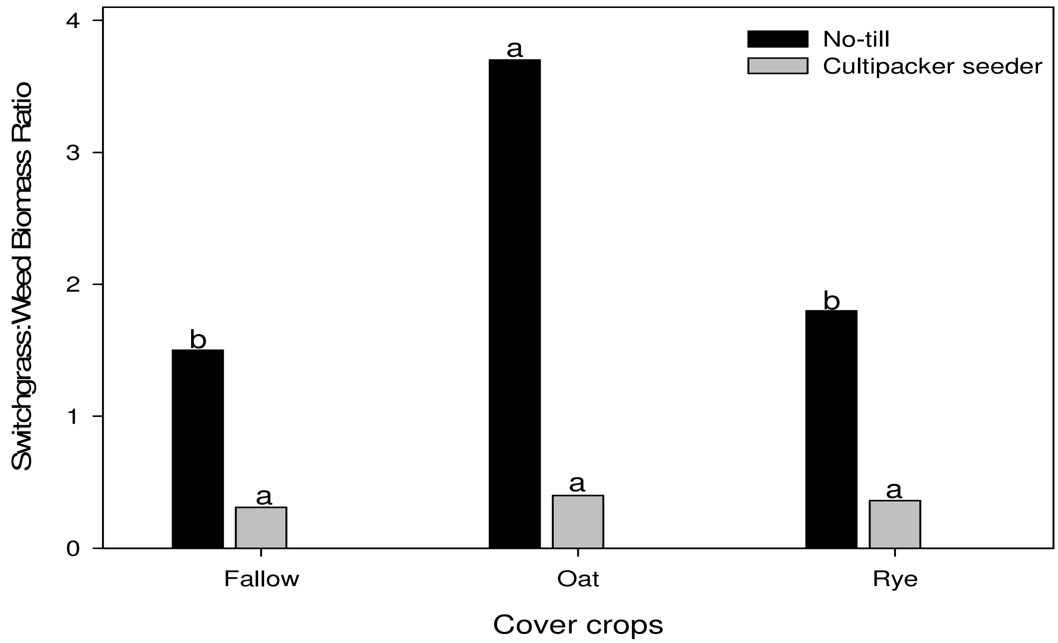


Figure 15: Influence of cover crop species and seeding methods on switchgrass:weed biomass ratio (averaged over years and herbicide treatments).

Mean values in each column followed by different letters differ significantly at *P*<0.05.

CHAPTER 5

SEEDBED FIRMING IMPROVED SWITCHGRASS STAND DENSITY AND PRODUCTION IN THE ESTABLISHMENT YEAR

Abstract

Successful establishment of switchgrass (*Panicum virgatum* L.) remains a challenge. The objective of this study was to improve switchgrass stand establishment with increasing seed-soil contact through compacting the soil with using cultipacker seeder and roller. An experiment was conducted in 2012 and replicated in 2013 growing season at the University of Massachusetts Agricultural Experiment Station in Deerfield. The soil type at the experimental site was Hadley fine sandy loam (nonacid, mesic Typic Udifluvent). Experimental design was a four-replicated randomized complete block design with eight treatments including disking-planting (DP), disking-cultipacker-planting (DCP), disking-cultipacker-planting-cultipacker (DCPC), disking-cultipacker-planting-cultipacker (2 times) (DCPC2), disking-rolling-planting (DRP), disking-rolling-planting-rolling (DRPR), disking- rolling-planting-rolling (2 times) (DRPR2), disking-rolling-planting-rolling (3 times) (DRPR3). Tiller density in rolled/cultipacked soils was significantly higher compared with DP. Disking-Planting with 188 and 110 plants (m^{-2}) had the lowest tiller density in 2012 and 2013 growing seasons, respectively. Tiller density was always higher when soil was firmed once before and at least once after planting. A linear positive correlation was found between tiller density and biomass yield (averaged over two years r^2= 0.90). Similar to tiller density, higher biomass yield was

obtained from soils that were firmed once before and at least once after planting. The highest biomass yield (2.2 Mg ha^{-1}) was recorded from DRPR (3) in 2013 growing season. In general, it could be concluded that at least one time rolling or cultipacking after planting was required to improve switchgrass stand density and biomass production in a sandy-loam soil.

Abbreviations: DP, disking-planting; DCP, disking-cultipacker-planting; DCPC, disking-cultipacker-planting-cultipacker; DCPC (2), disking-cultipacker-planting-cultipacker (2 times); DRP, disking-rolling-planting; DRPR, disking-rolling- planting-rolling; DRPR (2), disking- rolling-planting-rolling (2 times); DRPR (3), disking-rolling-planting-rolling (3 times); GDD, growing degree days; SBF, seedbed firming.

Introduction

Switchgrass (*Panicum virgatum* L.), a warm-season (C_4) grass native to North America, combines several desirable attributes that make it a potential feedstock for ethanol or heat production (Sadeghpour et al., 2014). Switchgrass has a high yield potential in various sites and soils (Sanderson et al., 2012) and can be grown on marginal lands with minimum chemical input after establishment (Parrish and Fike, 2005). It is easy to manage, and can be harvested using conventional hay-making equipments (Herbert et al., 2012).

One of the important challenges in switchgrass production is seedling establishment (Berti and Johnson, 2013). Similar to many warm-season perennial grasses, switchgrass has been known to be difficult or slow to establish (Monti et al., 2001; Mitchell and Vogel, 2012). Poor establishment in the planting year directly relates to reduced stand vigor and yield in succeeding years and limits large scale crop adoption

(Mitchell et al., 2010). It is estimated that a stand failure costs growers over \$300 ha^{-1} (Perrin et al., 2008). This has dissuaded many growers and entrepreneurs from planting switchgrass given the lack of financial return in the first two years; however with proper planning, switchgrass can be profitable endeavor for growers (Foster et al., 2013; Hashemi and Sadeghpour, 2013). Slight compaction could be a practical management practice to improve switchgrass establishment and possibly produce harvestable biomass in the same year (Venturi et al., 1999; Monti et al. 2001; Hashemi and Sadeghpour, 2013). A firm seedbed has been suggested as an effective management practice to increase the establishment of several small grain crops including barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.) and wheat (*Triticum aestivum* L.) (Hakansson et al., 2002). Slightly compacted soil can speed up the rate of seed germination because it promotes good contact between the seed and soil. In addition, moderate compaction may reduce water loss from the soil due to evaporation and, therefore, prevent the soil around the growing seed from drying out (Hashemi and Sadeghpour, 2013). It is reported that rolling is more effective when seed drill left the soil surface most uneven (Hakkanson et al., 2002). This suggested that reshaping the field might reduce the amount of soil which covered the seeds and thus, enhance seed emergence. Crabtree and Henderson (1999) reported that press wheels gave more uniform seeding depth and reduced clods. In a silt-loam soil, Monti et al. (2001) showed that establishment of switchgrass was enhanced when conventionally prepared seedbeds were rolled or compacted before and after seeds were broadcasted. Similarly, Venturi et al. (1999) showed greatest germination in two varieties of switchgrass in well-tilled soil that was compacted before and after planting. They found the lowest germination in tilled treatments without any compaction. In these studies, roller was used to firm the soil while in many regions specifically in USA, cultipacker is a more common tool to increase seed-soil contact (Hashemi and Sadeghpour, 2013). Limited data is available on influence of slight soil compaction on switchgrass establishment and production especially in the Northeast region of United States. Our primary objective of this study was to determine whether switchgrass establishment could be improved with increasing seed-soil contact and if increasing the number of rolling could significantly enhance the stand density and biomass production in the establishment year.

Materials and methods

Experimental site

The experiment was conducted at the Crops and Animal Research and Education Farm of the University of Massachusetts in South Deerfield (42°28′37″N, 72°36′2″W), in 2012 and replicated in 2013. The soil type at the experimental site was a Hadley fine sandy loam (nonacid, mesic Typic Udifluvent) with a pH of 6.2, organic matter content of 1.3%, N, P, K, and Ca content of 3, 11.8, 109, and 616 mg kg^{-1}, respectively. Soil samples in the top 20 cm were taken prior to planting.

Experimental design and cultural practices

The experimental design was a randomized complete block design with four replications. The treatments were disking-planting (DP), disking-cultipacker-planting (DCP), disking-cultipacker-planting-cultipacker (DCPC), disking-cultipacker-planting-cultipacker (2 times) (DCPC2), disking-rolling-planting (DRP), disking-rolling- planting-rolling (DRPR), disking- rolling-planting-rolling (2 times) (DRPR2), disking-rolling-planting-rolling (3 times) (DRPR3). For the check plot (DP) plots were disked and seeds were planted with a cultipacker seeder (Brillion drill) at the depth of approximately 1.5 cm. Cultipacking was performed with a wide cultipacker. Rolling was done with a wide roller. Cave-in-Rock variety which is a common upland variety in temperate regions in USA was used in this study. Seeding rate was 13 kg ha^{-1} pure live seed (PLS) in 2012 and 15 kg ha^{-1} PLS in 2013. The seeding rate differences were due to planting a constant number of seeds into the soil according to standard seed germination test (AOSA, 2010). The plot size for each treatment in a replication was 1.5 × 3.1 m. Weeds were controlled with pre-emergence application of atrazine (2-chloro-4-ethylamino-6-isopropyl-amino-s-triazine) (1.1 kg a.i. ha^{-1}) and quinclorac (3, 7-dichloro-8-quinolinecarboxylic acid) (0.37 kg a.i. ha^{-1}), along with the post-emergence application of 2,4-D ((2,4-dichlorophenoxy) acetic acid) (0.28 kg a.i. ha^{-1}) and dicamba (3,6-dichloro-o-anisic acid) (0.28 kg a.i. ha^{-1}). General management practices are presented in table 8. No irrigation was applied in this experiment, as that is not a common practice in Massachusetts due to adequate precipitation during the growing season (Hashemi et al., 2013). No N fertilizer was applied to avoid weed pressure competition in the establishment year.

Measurements, sampling and data collection

A day after completion of soil compaction, soil resistance was measured using a soil cone penetrometer at two depths (0-10 and 10-20 cm). Ten soil resistance measurements for each depth were recorded in every plot. Stand density was counted approximately 5 weeks after planting each year (Table 8). In each plot, 0.5 m^{-2} area from the center rows was mowed for biomass yield determination using a hand mower (GS model 700, Black and Decker (U.S.) Inc, Towson, MD) at 10-cm stubble height. At the time of harvest the fresh weight was weighed and samples were placed in a forced air oven at 50°C for 72 hr to determine moisture content. At the time of harvest, 0.5 m^{-2} area from the center rows was used to measure the number of established plants, tiller density, and plant height. Also, an average of three people was used to determine the stand rating using the scale of 0 to 5 with 5 showing an excellent weed-free stand and 0 would be a bare soil or a complete stand failure. The timeline for data collection is reported in table 8.

Statistical analysis

Data were analyzed using the ANOVA procedure and proc GLM (SAS Institute, 2009). Main effects were year and seedbed firming (SBF) treatments. All main effects were considered as fixed and only block was treated as a random effect. Where treatment differences were detected, means were compared using Fisher's Protected LSD test at the 5% level of significance. The appropriate error term from the SAS output was used to calculate the LSD value for each variable. Results were not averaged over years when interaction of year by SBF method was significant.

Results and discussion

Weather conditions

Cumulative growing degree days (GDD), observed from the Orange, MA, weather station, for 2012 and 2013 growing seasons (July through Oct) were 1983 and 1874, respectively (Table 9). Cumulative growing season precipitation was 163 mm in

2012, and 352 mm in 2013. Precipitation after the seeding month (August) was much higher (104 mm) in 2013 compared with 2012 (42 mm) which could explain the significant interaction of year by SBF method.

Soil resistance and switchgrass seedling emergence and establishment

Soil resistance was significantly influenced by the SBF methods; however, neither year nor year by SBF interaction had significant effect on soil resistance. Thus, data averaged over two growing seasons was presented (Fig. 16). In the 0-10 cm soil layer, with increasing the number of rolling/cultipacking soil resistance value increased where DP had the lowest soil resistance (0.88 MPa) while the highest value (1.16 MPa) was recorded from DRPR (3) (Fig. 1). Monti et al. (2001) in their study reported that double-rolled plots had higher soil resistance compared with single rolled or tilled unrolled treatments. Similar results to 0-10 soil layer were found at 10-20 cm soil layer (Fig. 16). Soil resistance at 0-10 cm soil layer was significantly correlated with switchgrass emergence (Quadratic R^2=0.66) while no specific correlation was found between soil resistance at 10-20 cm soil layer and switchgrass emergence (data not shown). Monti et al. (2001) reported a highly significant correlation between soil resistance and established seedlings (Quadratic R^2=80) at 0-20 cm soil layer when soil resistance was below 2 MPa. In current study, a significant quadratic response was found between soil resistance at 0-10 cm soil layer and number of established plants (R^2=0.71) (data not shown). In both years, DP and DCP had lower seedling numbers compared with other SBF treatments (Table 10). The lowest seedling number was recorded from DP (98 plant m^{-2}) in 2013 whereas DCPC had the highest seedling number (301 plant m^{-2}) in 2012 (Table 10). Regardless of soil type, Hakansson et al. (2002) reported that rolling after sowing improved final emergence of cereals by 4%. Average seedling loss over two growing seasons from emergence (~end of August) to establishment (~end of October) was significant (60%) regardless of the SBF method which could be due to the sandy-loam soil type of the experimental site. Foster et al. (2013) found lower seedling loss in a silt-loam site compared with a sandy-loam one due to higher water holding capacity of silt-loam soils. Number of established plants was significantly affected by both SBF methods and year by SBF methods interaction. As expected the lowest number of established plants (33 plant m^{-2}) was recorded from DP in 2013 where plant numbers were more than two times lower than that of DRPR (2) in 2012 (Table 10). Overall, the positive effect of firming tended to increase with the level of compaction. Monti et al. (2001) reported that rolling the seedbed prior to sowing, and in case also after sowing improve seedling emergence from 56% to an average 70% in a silt-loam soil.

Tiller density, plant height and stand rating

Tiller density was significantly affected by SBF methods. With increasing the compaction level, the tiller density was increased significantly (Fig. 17). Among SBF treatments, DRDR (3) had the highest tiller density (450 tiller m^{-2}) which had no significant difference with DCPC (2) (436 tiller m^{-2}). Averaged over the two growing seasons, the unrolled treatment (DP) had the lowest tiller density with 146 tillers (m^{-2}) (Fig. 17). Lower tiller density in unrolled plots could be explained by the fact that compacting the soil often results in a more precise seed placement and increase the seed-soil contact whereas an unrolled soil might lead to deeper seed placement which could reduce the uniformity of switchgrass stand (Hashemi and Sadeghpour, 2013). Plant height was significantly influenced by year, SBF method and year by SBF interaction. Year to year variation in switchgrass plant height was attributed to the different precipitation pattern in 2012 and 2013 growing seasons. Cumulative growing season precipitation was two times higher in 2013 (352 mm) compared with 2012 (163 mm) in 2013. Also, precipitation after the seeding month (August) was much higher (104 mm) in 2013 compared with 2012 (42 mm) which could explain the significant differences between plants heights each year. The highest plant height was recorded from compacted soils after planting [DRPR, DRPR (2), DRPR (3)] in 2013 growing season (Table 10). Moles et al. (2009) reported that among all existing environmental factors, plant height was most correlated with precipitation. They also suggested that plant height could be a great indicator of stand longevity and productivity. Similar to plant height, main effects (year and SBF method) and the interaction of year by SBF influenced switchgrass stand rating. Disking-Planting had the least stand rating with 2.5 and 2.7 in 2012 and 2013 growing seasons, respectively (Table 10). On the other hand, DRPR (3) was considered to be an excellent stand in both study years. Averaged over two growing seasons there was a positive linear correlation between tiller density and stand rating (r^2=0.87) (data not shown).

Switchgrass biomass yield and moisture content

Switchgrass biomass yield was influenced by year, SBF method, and year by SBF method interaction. Averaged over SBF treatments, switchgrass biomass yield was 0.8 and 1.3 Mg ha^{-1} in 2012 and 2013 growing seasons, respectively (Table 10). The highest biomass was harvested from DRPR (3) during the 2013 growing season which was 2.2 Mg ha^{-1} (Table 10). Although the tiller densities were slightly higher in 2012 compared with 2013 (Table 10), plants were much more morphologically developed in 2013 due to adequate precipitation which resulted in taller plants (Table 10). Switchgrass total yield positively correlates with plant height (Lemus et al., 2002). Within each year, there was also a significant linear correlation between tiller density and biomass yield (Fig. 18). These findings suggest that tiller size (plant height) was the main factor in biomass yield differences between growing seasons. Our data also suggested a significant positive correlation between soil resistance (MPa) and biomass yield within each year (Fig. 19). Optimal switchgrass emergence and establishment requires a close firm seed-soil contact (Monti et al., 2001). Drilling seeds into a non-compacted soil may not provide such close contact and it produced a non-uniform sparse switchgrass stand leading to stand failure (Sanderson et al., 2012). Recent reports indicated that biomass production of more than 1 Mg ha^{-1} during the establishment year often results in a high crop yield in the succeeding years (Mitchell et al., 2010; Mitchell and Vogel, 2012; Curran et al., 2012; Miesel et al, 2012). The highest biomass production during the establishment year in present study was over 2 Mg ha^{-1} obtained from DRPR (3) which could translate into a completely successful establishment. In general, it could be suggested that SBF treatments with rolling or cultipacking before and two or three times after planting often result in an excellent stand density and therefore biomass yield. One of the important components when considering switchgrass for biomass combustion is moisture content. Moisture reduces available energy content, since higher moisture requires an excess energy input to burn, and ash creates fouling in combustion equipment (McLaughlin et al., 1996; Sokhansanj et al., 2009). In current study moisture content was not influenced by either year or year by SBF method. However, the SBF method significantly influenced the moisture content of the grass. When plots were rolled before and after, moisture content was higher (19-21%) compared with other treatments (12-16%) (Fig. 20).

Conclusion

Switchgrass tiller density was generally lower when seeds were drilled into a non-compacted soil. This also influenced the plant height as well as biomass yield production with DP producing the lowest yield each year. In current study, a significant quadratic response was found between soil resistance at 0-10 cm soil layer and number of established plants (R^2=0.71). Observing much taller plants in 2013 was suggesting that plant size was dependent upon precipitation. Previous findings showed no significant differences in seedling number in silt-loam soils with double rolling (once before and once after planting) compared with a single rolled treatment however, our findings suggested that at least one time rolling or cultipacking after planting was required to improve switchgrass stand density and biomass production in a sandy-loam soil in Massachusetts.

Table 8: Dates of management practices, measurements and harvesting.

Management	Year	
	2012	2013
Seeding	July 17th	July 20th
Soil compaction measurements	July 17th	July 20th
Stand count	August 30th	September 3rd
Preemergence Herbicide	July 18th	July 21st
Postemergence herbicide	August 19th	August 21st
Morphological sampling	Oct 13th	November 8th
Harvest 1st year	Oct 30st	November 8th

Table 9: Monthly and total growing degree days (GDD_{10} °C) and precipitation (mm) during 2012 and 2013 at the University of Massachusetts experimental farm, South Deerfield.

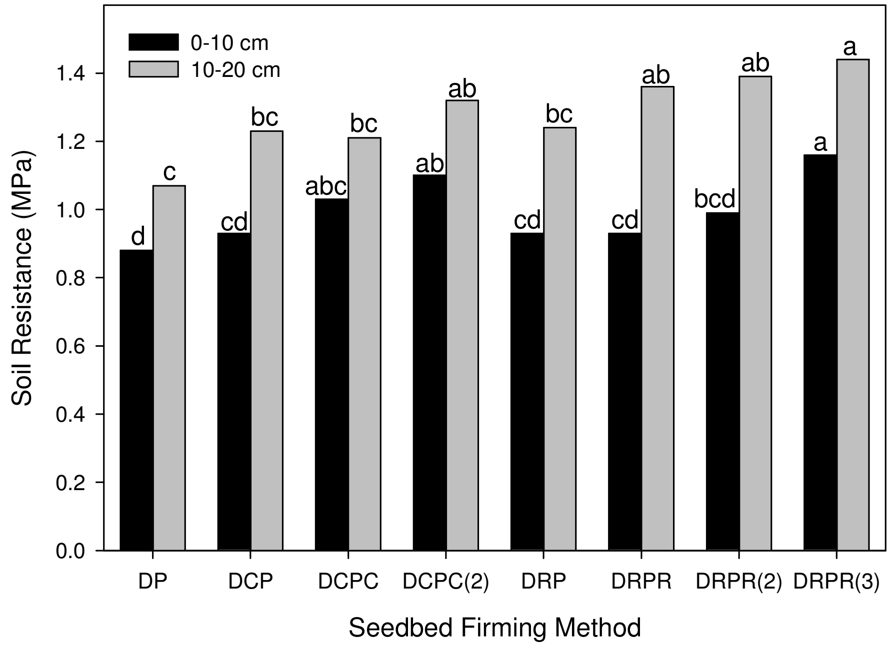
Month	GDD_{10} °C		Precipitation (mm)	
	2012	2013	2012	2013
July	745.7	790.2	14.5	123.7
August	692.7	591.1	42.2	104.1
September	386.7	350.5	37.3	98.5
October	158.7	142.6	69.6	25.9
Total	1,983.8	1,874.4	163.6	352.2

Table 10: Influence of seedbed firming methods on emerged seedlings, established seedlings, plant height, biomass yield, and stand rating of switchgrass in 2012 and 2013 growing seasons.

Treatment†	Year	Emerged seedlings	Established seedlings	Plant height	Biomass yield	Stand rating
		m^{-2}		cm	$Mg\ ha^{-1}$	
DP	2012	174c	67c	25b	0.45d	2.50c
DCP		166c	84a	23c	0.55cd	3.00c
DCPC		301a	83a	39a	1.06a	4.25ab
DCPC(2)		245ab	78ab	37a	1.14a	4.75a
DRP		241b	86a	31ab	0.65bcd	4.00ab
DRPR		237b	83a	31ab	0.82abc	4.00ab
DRPR(2)		281a	89a	33ab	0.89ab	4.50a
DRPR(3)		229b	79ab	34a	1.07a	5.00a
DP	2013	101c	33d	57b	0.64d	2.70c
DCP		178b	68c	58b	0.80d	3.70b
DCPC		206b	71bc	60b	0.88d	3.30b
DCPC(2)		253a	81ab	59b	1.52c	4.50a
DRP		225ab	68c	54c	0.91d	2.60c
DRPR		266a	75abc	66a	1.29c	4.00ab
DRPR(2)		290a	81ab	67a	1.91b	5.00a
DRPR(3)		280a	81a	69a	2.61a	5.00a

† DP, disking-planting; DCP, disking-cultipacker-planting; DCPC, disking-cultipacker-planting-cultipacker; DCPC (2), disking-cultipacker-planting-cultipacker (2 times); DRP, disking-rolling-planting; DRPR, disking-rolling- planting-rolling; DRPR (2), disking- rolling-planting-rolling (2 times); DRPR (3), disking-rolling-planting-rolling (3 times).

Mean values with the same letter are not significantly different at $p<0.05$ according to Duncan Multiple Range Test. Seedbed preparation treatments were tested separately within each year.



.

Figure 16: Soil resistance (MPa) at different seedbed firming methods at two soil depths (0-10 and 10-20 cm).

Each value is the average of 10 measurements within each treatment.
Values in the same column in each depth followed by different letters differ significantly at $P<0.05$.

† DP, disking-planting; DCP, disking-cultipacker-planting; DCPC, disking-cultipacker-planting-cultipacker; DCPC (2), disking-cultipacker-planting-cultipacker (2 times); DRP, disking-rolling-planting; DRPR, disking-rolling- planting-rolling; DRPR (2), disking- rolling-planting-rolling (2 times); DRPR (3), disking-rolling-planting-rolling (3 times).

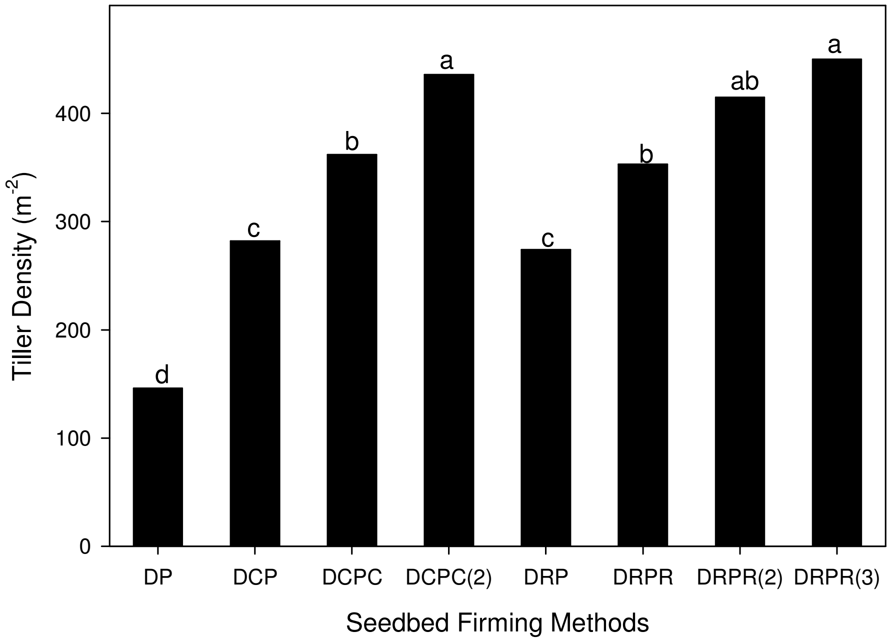


Figure 17: Switchgrass tiller density at different seedbed firming methods (averaged over two growing seasons).

Values in the same column followed by different letters differ significantly at $P<0.05$.

DP, disking-planting; DCP, disking-cultipacker-planting; DCPC, disking-cultipacker-planting-cultipacker; DCPC (2), disking-cultipacker-planting-cultipacker (2 times); DRP, disking-rolling-planting; DRPR, disking-rolling- planting-rolling; DRPR (2), disking- rolling-planting-rolling (2 times); DRPR (3), disking-rolling-planting-rolling (3 times).

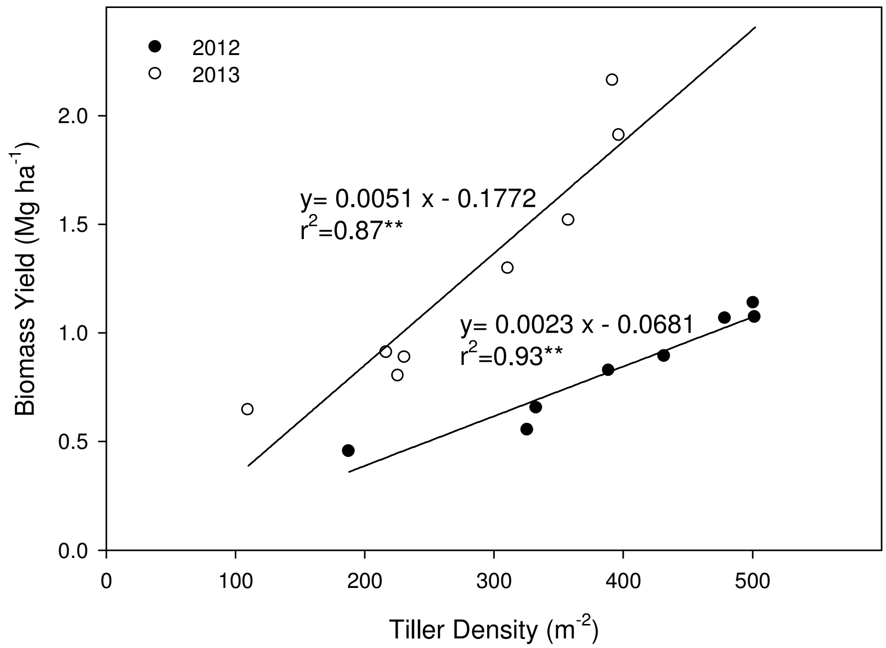


Figure 18: Correlation between switchgrass tiller density with switchgrass biomass yield in 2012 and 2013.

Regression analyses were conducted with mean values for treatments, and therefore, r^2 values were based on means.

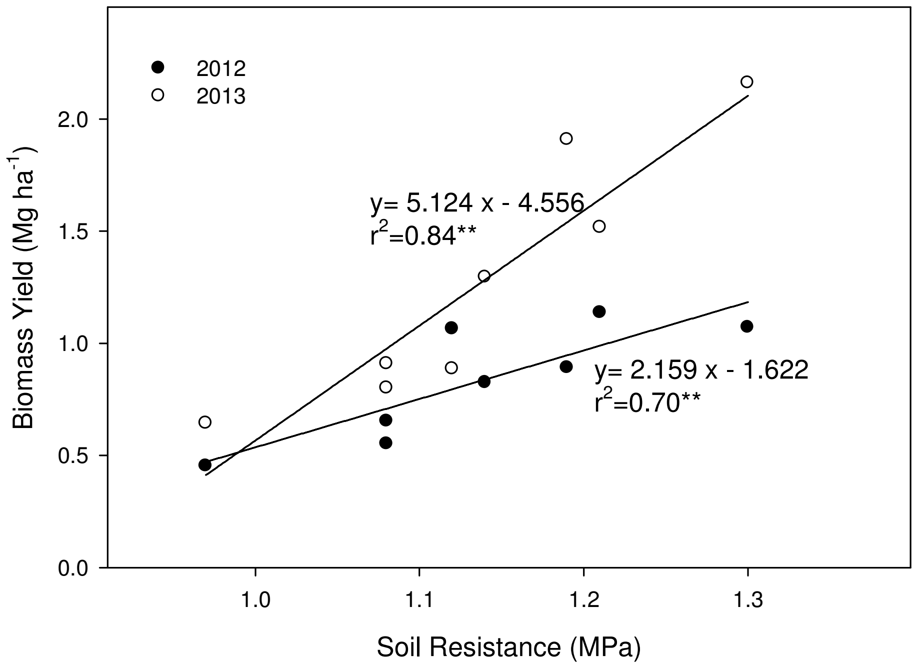


Figure 19: Correlation between soil resistance (MPa) (0-20 cm) with switchgrass biomass yield in 2012 and 2013.

Regression analyses were conducted with mean values for treatments, and therefore, r^2 values were based on means.

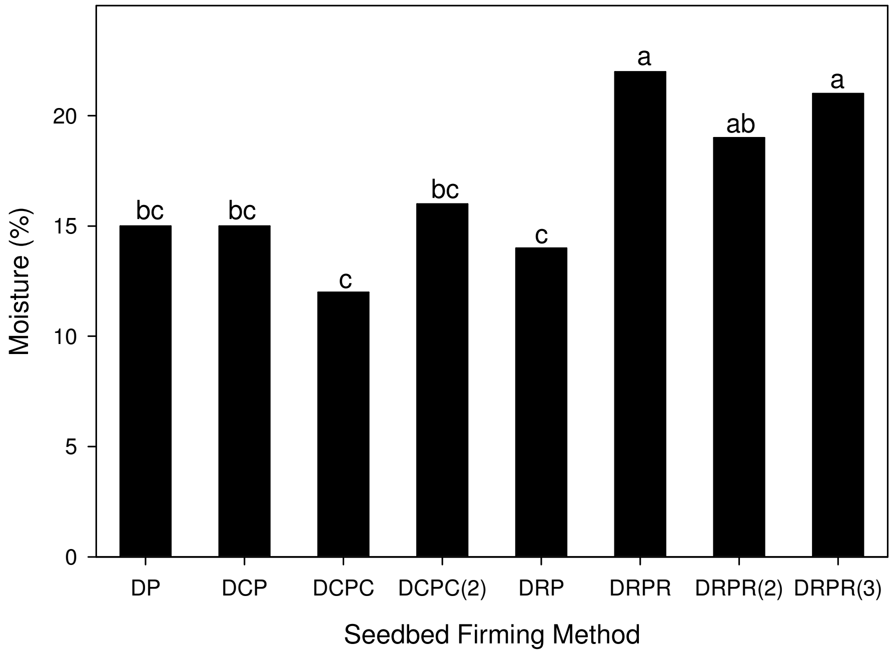


Figure 20: Switchgrass moisture content (%) at different seedbed firming methods (averaged over 2012 and 2013 growing seasons).

Values in the same column followed by different letters differ significantly at P<0.05.
DP, disking-planting; DCP, disking-cultipacker-planting; DCPC, disking-cultipacker-planting-cultipacker; DCPC (2), disking-cultipacker-planting-cultipacker (2 times); DRP, disking-rolling-planting; DRPR, disking-rolling- planting-rolling; DRPR (2), disking- rolling-planting-rolling (2 times); DRPR (3), disking-rolling-planting-rolling (3 times).

CHAPTER 6

EVALUATING SWITCHGRASS VARIETIES FOR BIOMASS YIELD AND QUALITY IN MASSACHUSETTS

Abstract

Currently there is little or no published data on switchgrass (*Panicum virgatum* L.) yield potential for Massachusetts. Our objective was to determine how cultivars perform in this northeastern United States climate and how time of harvest affected yield and quality of switchgrass. Five upland varieties (Blackwell, Carthage, Cave-in-Rock-, Shawnee, and Shelter) were harvested at senescence (fall), kill frost (winter), and spring between 2009-2011. Measurements were taken for yield, ash, total nitrogen, and mineral content in the feedstock and non-structural carbohydrates in roots at each time of harvest. In the first year Carthage was the highest yielding variety, and harvesting at senescence in the fall consistently produced higher yields for all varieties than harvesting in winter or spring. Harvesting Blackwell, Cave-in-Rock, Shawnee, and Shelter as the plant went into senescence in the first year caused a reduction in yield the following year, such that winter harvests were equivalent to or better than fall and spring harvests. Nutrients such as nitrogen, phosphorus, potassium, magnesium and ash all decreased in the feedstock when the harvest was delayed from fall to winter or spring. Soluble nonstructural carbohydrate concentrations in the roots were three times higher in the winter than in the fall. These levels decreased again in the spring. Biomass yields ranged from 6.8 Mg ha-1 to 12.6 Mg ha-1 across upland varieties in all years.

Results of this study recommend a winter harvest after a killing frost rather than a fall post-anthesis harvest.

Keywords: Ash, Nonstructural carbohydrates, Nutrient concentrations, Time of harvest.

Introduction

An important aim of contemporary switchgrass research is to determine which cultivars grow best under local growing conditions. Switchgrass biomass production has been reported to have high variation among cultivars depending on the location (Fike et al., 2006). Hopkins et al., (1995) reported significant variation among switchgrass cultivars in date of heading and yield at heading. They also noted that early heading was associated with lower yields. Successive researchers (Casler et al., 2004; Fike et al., 2006) have shown the dramatic effects of the latitude of origin of a cultivar on its production in different geographic locations.

Switchgrass' survival during winter months and re-growth in spring to early summer depends on the extent of its root structure (Ma et al., 2001). To maintain a healthy root structure for continual crop production while applying only minimal amounts of fertilizer, it is important to determine the appropriate harvest time to allow movement of carbohydrates and nutrients from the stalk to the root system (Thomason et al., 2004). It is thought that the ideal time for harvest is after the primary nutrients have translocated from the stalk to the plant's root structure (Casler and Boe, 2003; Adler et al., 2006). Some have suggested early fall harvests may be preferable to late fall or winter harvests because weather conditions are generally more favorable requiring less time and labor to cure the crop (Samson and Mehdi, 1998; Adler et al., 2006).

Harvest time not only influences switchgrass biomass production, it also affects the biofuel quality (Adler et al., 2006). As switchgrass matures during the growing season, its ash content decreases (Sanderson and Wolf, 1995; Adler et al., 2006), which leads to an increase in biofuel quality. In addition, less nitrogen is required by the plant because of the translocation of nutrients into the roots (Vogel et al., 2002). Delaying harvest until spring has been shown to reduce the biomass production of some biofuel crops such as reed canarygrass (*Phalaris arundinacea* L.), Miscanthus sp. and switchgrass. However because mineral concentrations continue to decrease as well, it is as-yet unclear whether the increase in fuel quality offsets the decrease in total production (Burvall, 1997; Lewandowski et al., 2003; Adler et al., 2006).

The objectives of this study were (i) to determine high-yielding cultivars with the ability to survive winter in Massachusetts and (ii) to study how different harvest times influence switchgrass biomass yield, re-growth and the quality for energy production.

Materials and methods

Variety trials were established in 2006 at the University of Massachusetts Agricultural Experiment Station Farm in Deerfield in the Connecticut River valley (42°N, 73°W). The soil type was a Hadley fine sandy loam (nonacid, mesic Typic Udifluvent). Twelve varieties of switchgrass (Alamo, Blackwell, Carthage, Cave-in-Rock, Dacotah, Ecotype-WI, Forestburg, NE28, Pathfinder, Shawnee, Shelter, Sunburst) were obtained for an evaluation of their productive potential and adaptability to Western Massachusetts. Each variety was grown in pure cultures similar to forage grasses for permanent pastures.,After establishment trials were completed, in 2009, five highest yielding varieties (Blackwell, Carthage, Cave-In-Rock, Shawnee, and Shelter) were selected for further study. The plot size for each variety in a replication was 3 m x 6 m, allowing for a harvested sample and adequate borders. No irrigation was applied in this experiment, as that is not a common practice in Massachusetts due to adequate rainfall during the growing season. In early June of 2009, each plot was fertilized with calcium ammonium nitrate (27% N) at a rate of 136 kg N ha^{-1}.

A randomized complete block design with a split plot arrangement was conducted using the selected varieties as main plots and three harvest times (post-anthesis, killing frost, and early spring) as sub plots from 2009 to 2011. Spring harvest for each year took place the following April, such that in the 2009 trial, the spring harvest took place in April 2010. In order to keep descriptions simple the spring harvest will be referred to as in the year of 2009, since the harvested vegetation actually grew during 2009. Each plot was divided into three sections for each harvest time.

A 2.8 m^2 area of the plot was mowed using a BCS sickle mower at 10-cm stubble height and either side of the sectioned plot was discarded. Harvested switchgrass were hand gathered, and weighed in the field with a tarp and digital balance. A representative subsample was collected from each plot. The subsamples were weighed and placed in a forced air oven at 50°C for 48 hours to determine moisture content at harvest. Harvested fresh weights were then adjusted by moisture content. After drying, tissue samples were ground to pass a 1-mm screen of a Wiley mill for determination of ash and mineral content. A cup cutter was used to remove a cylinder of roots 15 cm in diameter and 15 cm deep at time of harvest to determine non-structural carbohydrates. Nitrogen content of plant tissue was determined using the Total Kjeldahl procedures. Plant tissue samples were ashed in a Furnatoral Type 53600 Controller at 500°C for 5 hours. The ash was analyzed for mineral content using an Inductively Coupled Plasma Spectro Cirsos CCD. Harvested roots along with the below-ground portion of the crown were washed and dried and then ground twice, once using a large grinder and then a second time using a 40-mesh Wiley mill. Carbohydrate analysis for the nonstructural carbohydrates of the roots was performed using High Pressure Liquid Chromatography for sucrose, glucose, and fructose. The method was developed and described in Hagidimitriou and Roper (1994).

Biomass yield, mineral content, and non-structural carbohydrate data were analyzed using the ANOVA and GLM proc (SAS institute, 2005). Means were compared using least significant differences (LSD). Results were not averaged over years when interactions of year by main effects were found significant.

Results

Switchgrass dry matter yield was influenced by year. In 2009 biomass yields averaged 11.2 Mg ha^{-1} but were reduced by 18 percent in the 2010 and then another 6.6 percent in the 2011 (Table 11). Among varieties, Carthage produced the highest biomass (12.6 Mg ha^{-1} in 2009 and 9.5 Mg ha^{-1} in 2011), whereas Blackwell was the superior variety in 2010 (10.5 Mg ha^{-1}). Shelter consistently produced lower yield compared with other varieties (Table 11). Harvest time significantly affected the dry matter yield with highest yields in the harvest that occurred during the fall of the first year (14 Mg ha^{-1}) (Table 2). Yields steadily declined as much as 43 percent in the second (9.6 Mg ha^{-1}) and third (8.0 Mg ha^{-1}) years (Table 12). Although harvest time had a significant impact on yield in 2009 and 2010, it had no effect on yield in 2011 and yields were on average at 8.5 Mg ha^{-1} for all three harvest times.

The effect of year and variety on ash content was not significant. Total ash in the switchgrass depended on the time of harvest. Early harvest had almost twice the ash content compared with later harvests (Table 13). There were fluctuations in the ash content by year but this is likely due to the effect of variable weather.

The mineral content of biomass was significantly changed for all years. The only mineral that was not affected by year was Fe. Nitrogen showed a similar trend to ash, with the highest residues occurring in the fall harvest, whereas no significant differences were observed between the concentrations in the winter and following spring harvests (Table 14). Phosphorous, K, and Mg all showed a steady decrease from the fall harvest to the spring harvest, with K showing the most pronounced difference between harvest times (Table 14). Calcium concentration remained nearly constant across all harvest times, with the largest differences in Ca concentration occurring in the winter. Iron and Al concentrations were at their lowest in the winter harvest, and there was some rise in the spring harvest (Table 14).

Soluble non-structural carbohydrate levels in the roots and below ground tissue of the crown were affected significantly by year, variety and harvest time. Fluctuation of sugars in various years is expected to reflect changes in weather. The levels of glucose and fructose in all five varieties were similar while sucrose which was the most abundant non-structural carbohydrate differed among varieties (data not shown). Cave-in-Rock and Shelter had the lowest levels of sucrose, while Blackwell, Carthage, and Shawnee had similar levels of sucrose. The effect of time of harvest on the sugar levels was highly significant. Sucrose level was highest when switchgrass was harvested in November and was lower in August and April harvests (Fig. 21). Glucose and fructose levels were lower and less affected.

Discussion

Our experiments indicated that all varieties preformed similarly and changes depended on weather conditions. For Massachusetts conditions it appeared that Carthage and Cave-in-Rock on average were better adapted to the harsh winters and short summers found in this area. Blackwell preformed the best in 2010 but yields were the second lowest in 2011. Upland varieties; throughout the United States produce yields on average between 5-11 Mg ha^{-1} (Sanderson and Adler, 2008; Schmer et al., 2008). The trials at the University of Massachusetts across upland ecotypes ranged from 6.7-14 Mg ha^{-1}, which are similar yields to other areas in the United States. Dry matter yields were more susceptible to harvest time in the first and second year of the experiment but did not have an effect in the third year. Carthage and Cave-in-Rock produced yields at 17.0 $Mg.ha^{-1}$ and 16.2 $Mg.ha^{-1}$ in the fall of the first year and were then reduced by 28 and 51 percent, respectively, in the second year but remained more constant from the second to third year.

Many researchers claim that optimal harvest time is at senescence and that delaying the harvest until a killing frost will result in a significant decrease in yield and that harvesting prior to maturation in midsummer also negatively affects yield (Sanderson et al., 1996; Vogel at al., 2002; Sanderson and Adler, 2008). Moore et al., (1991) stated that for Cave-in-Rock optimal harvest is in the third week of August for the Midwest when switchgrass plants have just completed the senescence stage of development. In our experiment this appeared to be true for Carthage, but not for Cave-in-Rock. Cave-in-Rock yields were similar among fall and winter harvest times; so that it appears that delaying the harvest had no effect on yield in 2010 and 2011. With Blackwell, Shawnee, and Shelter delaying the harvest resulted in higher yields. In 2011 the spring harvest produced on average the highest yields at 9.2 Mg ha^{-1}, but this was still significantly less when comparing overall yield for all three years.

Switchgrass stand density declines over time, producing fewer tillers as the crop ages. This is more apparent in upland varieties than it is in low land varieties. The crop compensates for the thinning of the stand by increasing the size of the plant (Cassida et al., 2005). In the current experiment, there was a consistent decrease in dry matter yield from year to year that was more apparent when fields were harvested in fall than in the winter or spring. This might be attributed to the decrease in the number of tillers as the plants aged. More years of data are needed to determine the overall expected yield for the crop over its life span and if the decrease in fall yield is significant enough that over a ten-year period it would recommend harvesting in the winter or spring when yields are more stable.

Ash concentrations decreased with a later time of harvest as the plants matured resulting from changes in mineral content. This result confirmed prior findings reported by Sanderson and Wolf (1995). Ash content is an important factor when considering grass for combustion. Across all years and all varieties, nitrogen and ash content showed similar trends, with the highest residues occurring in the fall harvest and no significant difference between concentrations in the winter and following spring harvest. Harvesting after kill frost decreased nitrogen in plant tissue compared to the higher level at the beginning of senescence. With respect to nutrients such as P, K, and Mg which had initial concentrations greater than 1000 ppm, a delay in the harvest until at least the winter period, lowered the nutrient levels and improved the feedstock quality for combustion. Calcium concentrations were not reduced as the plant matured over the season. One of the appeals of using switchgrass as a biofuel is that it efficiently recycles its nutrients. It was a consistent finding that harvesting in fall removed vital nutrients in the harvested biomass, such that N, P, and K removal over successive years would likely cause depletion in nutrients and require more fertilizer to be used. Harvesting later in the winter period would lessen this removal. Casler and Boe (2003) stated that switchgrass had the ability to mobilize nutrients to the root system before a killing frost. Changes in levels of Fe and Al would have less effect on ash levels because of their low concentrations.

Parrish and Wolf (1993) claimed that the reduction in yield from September to November was due to the remobilizing of carbohydrate reserves and nitrogen from the stem to the roots and that remaining loss in yield was due to leaf loss. Anderson et al. (1989) showed that peak concentration in total nonstructural carbohydrates (TNC) were present in the above ground tissue in September. Figure 21 is consistent with this finding. There was three times more sucrose in the winter harvest than in the fall, which might be expected as the plant prepares for dormancy due to cold acclimation. By spring the carbohydrate levels were again low, due to the plants presumably having consumed some of their reserves to survive the winter. An analysis of the nonstructural carbohydrates in the roots sampled at each harvest date showed sucrose to be the primary sugar, with much lower quantities of fructose and glucose which is consistent with finding by White (1973), that warm season grasses store reserves in the form of sucrose and starch.

Conclusion

Given that i. yields in the fall fell dramatically enough that a winter harvest was equivalent to a fall harvest and sometimes better, ii. ash content and nutrients decreased when the harvest was delayed, and iii. soluble nonstructural carbohydrate concentrations in the roots were three time higher in the winter than in the fall we recommend a winter harvest after a killing frost rather than a fall post-anthesis harvest.

Table 11: Switchgrass dry matter yield (Mg ha^{-1}) for varieties in 2009-2011.

Variety (V)	Year (Y)			
	2009	2010	2011	Mean
Blackwell	9.9bc	10.5a	8.2ab	9.5
Cave-in-Rock	12.3ab	8.0a	9.0ab	9.7
Carthage	12.6a	9.5a	9.5a	10.6
Shawnee	11.8abc	8.4a	8.7ab	9.6
Shelter	9.6c	9.0a	7.1b	8.6
$LSD_{(0.05)}$ V×Y	2.6	2.6	2.1	

Values with the same letters are not significantly different.

Table 12: Effect of time of harvest on dry matter yield (Mg ha^{-1}) in 2009-2011.

Harvest (H)*	Year (Y)			
	2009	2010	2011	Mean
Late summer	14.0a	9.6a	8.0a	7.4
Late fall	10.1b	10.9a	8.2a	6.3
Spring	9.5b	6.7b	9.2a	6.0
Mean	11.2	9.1	8.5	
LSD $_{(0.05)}$ H×Y	2.0	2.0	1.5	

Values with the same letters are not significantly different.
*Harvest time: Late summer (Senescence), Late fall (Kill frost), Spring (Snow melt).

Table 13: Ash content (%) in feedstock as affected by harvest time 2009-2011.

Harvest (H)*	Year (Y)			
	2009	2010	2011	Mean
Late summer	4.7a	5.5a	4.7a	5.0
Late fall	1.9b	2.9b	2.6b	2.5
Spring	2.6b	2.1c	2.0b	2.2
Mean	3.1	3.5	3.3	

Values with the same letters are not significantly different.
*Harvest time: Late summer (Senescence), Late fall (Kill frost), Spring (Snow melt).

Table 14: Harvest time influence on chemical constituents in dry matter in 2009-2011.

Harvest (H)*	Nutrients (ppm)						
	N	P	K	Mg	Ca	Fe	Al
Late summer	0.58a	1414a	10305a	1408a	2028b	42b	66a
Late fall	0.30b	743b	5338b	1085b	2362a	40b	37b
Spring	0.33b	312c	538c	652c	2215ab	58a	59a

Values with the same letters are not significantly different.
*Harvest time: Late summer (Senescence), Late fall (Kill frost), Spring (Snow melt).

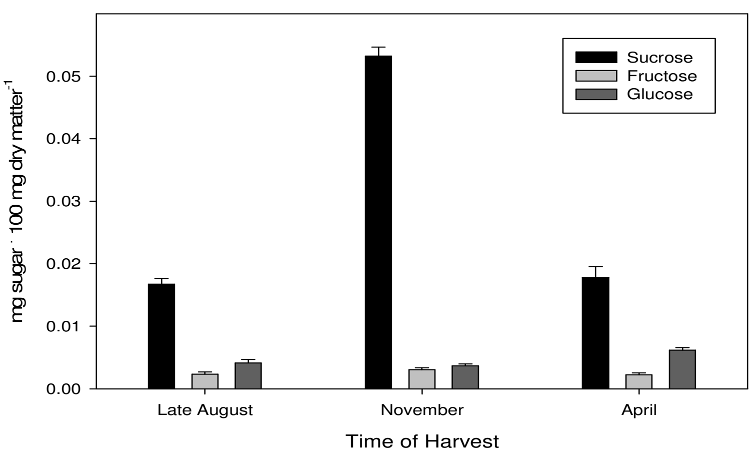


Figure 21: Soluble nonstructural carbohydrates at time of harvest for roots and crown (averaged over variety and year).

CHAPTER 7

RESPONSE OF SWITCHGRASS YIELD AND QUALITY TO HARVEST SEASON AND NITROGEN FERTILIZER

Abstract

Attaining high switchgrass (*Panicum virgatum* L.) yields with optimum quality for combustion while also maintaining crop health is challenging. A three-year study was conducted at the Crops and Animal Research and Education Farm of the University of Massachusetts in South Deerfield, MA, from 2009-2012 to assess the influence of harvesting season and N application rates on biomass yield, mineral content of the grass, non-structural carbohydrate (NSC) reserves in the roots, as well as nitrogen use efficiency (NUE) of switchgrass (cv. Cave-in-Rock) grown for combustion. Delaying harvest from summer until spring reduced the biomass yield by 27%. The highest biomass production (7.82 Mg ha^{-1}) was obtained from summer harvest in the first growing season. Averaged over three years, increasing N application rate up to 134 kg ha^{-1} resulted in the highest biomass production in the summer harvest with 7.41 Mg ha^{-1}. Nutrient concentrations in the grass were dependent on the season of harvest. In general, delaying the harvest reduced N, P, K, and Mg content in the feedstock. Lower N application rate resulted in higher agronomic efficiency (AE) and NUE. Peak NSC concentrations in belowground tissues were measured in fall and were two times higher than those in summer and spring. These data suggest that not more than 67 kg N ha^{-1}

combined with fall harvest maintain switchgrass yield and quality for combustion processes.

Abbreviations: AE, agronomic efficiency; GDD, growing degree days; NSC, non-structural carbohydrate; NUE, nitrogen use efficiency.

Introduction

Switchgrass is a C_4-grass indigenous to North America being considered as the "model" energy crop for many years due to its numerous desirable characteristics (Guretzky et al., 2011). Switchgrass is highly productive in diverse settings (Sanderson et al., 2012) and has the ability to grow on marginal lands with low fertilizer and pesticide requirement after establishment (Parrish and Fike, 2005). It is easy to manage, and can be harvested using conventional hay-making equipment (Teel et al., 2003). Switchgrass is also known to be a cold, drought, and heat tolerant grass (Hashemi and Sadeghpour, 2013).

Maximum biomass production with acceptable biofuel quality is the ultimate goal of bio-energy feedstock growers (Mitchell and Schmer, 2012). Primary components when considering switchgrass for biomass combustion include energy content of grass, moisture, and ash. Moisture and ash both reduce available energy content, since higher moisture requires an excess energy input to burn, and ash creates fouling in combustion equipment (McLaughlin et al., 1996). The presence of alkali metals and silicates in ash are major contributors to the production of slag, a thick black liquid material that forms when feedstock is burned at high temperatures. Slag coats surfaces of machinery (furnaces, boilers, fluidized beds, etc.), causes fouling and prevents heat from being recovered (McLaughlin et al., 1996; Cassida et al., 2005), possibly making the burning process cost prohibitive. Part of the appeal of switchgrass is that is can be used with existing technologies to supplement current energy systems. It is imperative that the end product be used without causing high external costs to existing systems. Appropriate harvesting management of switchgrass such as season of harvest may change the quantity of unwanted nutrients present in the grass and therefore impact feedstock quality for combustion systems.

Season of harvest has been reported to influence switchgrass biomass production (Adler et al., 2006; Guretzky et al., 2011). A mid-September harvest is reported by Sanderson et al. (1999) to produce the maximum biomass yield in south-central USA. Adler et al. (2006) found 40% reduction in switchgrass biomass production when harvest was delayed until spring. Generally, biomass yield is reduced when harvest is delayed until after killing frost (Herbert et al., 2012; Mitchell and Schmer, 2012). However, later harvest may ensure stand productivity and persistence of switchgrass. Casler and Boe (2003) found that a mid-August harvest in north central USA reduced switchgrass stand density over time. As switchgrass matures during the growing season, its ash content decreases (Sanderson and Wolf, 1995; Adler et al., 2006), which leads to an increase in biofuel quality. It is reported that every 1% increase in ash concentration decreases the heating value by 0.2 MJ kg ha^{-1} (Cassida et al., 2005). In addition, less nitrogen would be required by the plant because of the translocation of nutrients into the roots (Vogel et al., 2002). Delaying harvest until spring has been shown to reduce the biomass production of some biofuel crops such as reed canarygrass (*Phalaris arundinacea* L.), miscanthus (*Miscanthus* sp.), and switchgrass. However, because mineral concentrations continue to decrease as well (Burvall, 1997; Lewandowski et al., 2003; Adler et al., 2006), it is as-yet unclear whether the increase in fuel quality offsets the decrease in total biomass production.

Nitrogen is a critical nutrient for production of biomass and typically the most limiting factor to plants productivity (Lemus et al., 2008a). Managing N fertilizer application is important not only for optimum biomass production but also to maximize the NUE as well as feedstock quality. Excess N concentration in harvested switchgrass can be a liability by increasing the release of NO_x compounds into the atmosphere when co-firing (Parrish and Fike, 2005; Lemus et al., 2008a). Most of the studies on nitrogen management have been conducted on lowland switchgrass varieties in the Midwest, South, and upper southeastern U.S.A. In a multi-location study throughout the upper southeastern USA, Lemus et al. (2009) found that a single-cut system without adding any N would be a more sustainable management practice compared with a split application of N (100 kg N ha^{-1}) in a 2-cut system. Muir et al. (2001) reported Alamo switchgrass yielded highest at N rates up to 224 kg ha^{-1}. In a season of higher-than-normal rainfall, production was maximized at 168 kg N ha^{-1}. Vogel et al. (2002) tested N application rates up to 300 kg ha^{-1} for the Cave-in-Rock (a southern upland cultivar). They reported maximum yields at 120 kg N ha^{-1}. Guertsky et al. (2011) tested N up to 225 kg ha^{-1} at three harvest seasons (July, October, and December) and reported positive response of switchgrass biomass production to N fertilization. They found a 2-cut (July plus post-frost) harvest system the most productive however; higher N input was needed for this harvest system. Harvesting switchgrass once a year after frost (December) has been suggested by several researchers (Sanderson et al., 1999; Muir et al., 2001; Vogel et al., 2002).

Maintenance of a perennial root system, such as fibrous structure of switchgrass, is essential in developing healthy, high-yielding plants which persist for several years (McLaughlin et al., 1999). A single-cut system in which harvest is delayed until after senescence may allow nutrients to translocate from shoots to roots. Nonstructural carbohydrates are the primary source of energy reserve in perennial grasses (Herbert et al., 2012). These reserves are essential for winter survival of the crop and re-growth in the spring. Cutting or grazing at elongation stage will weaken the plant as compared with cutting after flowering (Smith, 1975). Understanding how the roots store carbohydrates is vital for maintaining a healthy crop year after year.

Our objectives were (i) to determine the most suitable harvest season for biomass production (ii) to assess the impact of season of harvest and N application rate on grass quality for combustion (iii) to examine the influence of harvest season and N application rate on carbohydrate reserves and (iv) to evaluate NUE of switchgrass harvested at various seasons and N application rates.

Materials and methods

Experimental site

The experiment was conducted at the Crops and Animal Research and Education Farm of the University of Massachusetts in South Deerfield (42°28′37″N, 72°36′2″W), from 2009-2012. The soil type was a Hadley fine sandy loam (nonacid, mesic Typic Udifluvent) with pH of 6.7, organic matter content of 1.2%, N, P, K, and Ca content of 3, 9, 73, and 868 mg kg^{-1}, respectively. Soil samples in the top 20 cm were taken prior to N fertilizer application in June 2009.

Experimental design and cultural practices

A three-replicated randomized complete block design with a split plot arrangement was conducted on a 2-yr old, well-established switchgrass (cv. Cave-in-Rock) field using N fertilizer rates (0, 67, and 134 kg N ha^{-1}) from calcium ammonium nitrate [$CaNH_4(NO_3)_3$] (27% N) as main plots and three harvest seasons [late summer (mid-July), late fall (early Nov), and early spring (mid-April)] as sub plots. To facilitate the presentation, harvest seasons were reported as summer, fall and spring harvests. The plot size for each N rate in a replication was 3 × 6 m, allowing for a harvested sample and adequate borders. No irrigation was applied in this experiment, as that is not a common practice in Massachusetts due to adequate rainfall during the growing season. Nitrogen fertilizer was applied in a single application in mid-June each year was applied at early jointing stage.

Sampling and data collection

Each plot was divided into three sections, each allocated to a harvesting season. In each plot, 2.8 m^2 area (~0.7 m wide and 4 m long) was mowed for biomass yield determination using a Sickle bar mower (BCS model 710, BCS America, Portland, OR) at 15-cm stubble height. Both sides of the harvested area were mowed and discarded. At each season of harvest the fresh weight was measured and a representative subsample was collected from each plot. The subsamples were weighed and placed in a forced air oven at 50°C for 72 hr to determine moisture content at each harvest. Biomass fresh weight was then adjusted by moisture content to determine the dry weight. After drying, tissue samples were ground to pass a 1-mm screen in a Wiley mill then dried again before determining ash and mineral content.

A cup cutter was used to remove a cylinder of roots 15 cm in diameter and 15 cm deep at each season of harvest to determine NSC in roots. Belowground samples were immediately put in ice to prevent NSC loss and later after washing were frozen. Nitrogen content of plant tissue was determined using the Total Kjeldahl procedures (Bremner, 1996). Plant tissue samples were ashed in furnace (Furnatrol model 53600 Controller Thermolyne Corporation, Dubuque IA) at 500°C for 5 hr. The ash was analyzed for mineral content using a plasma spectrophotometer (Inductively Coupled Plasma Spectro Ciros CCD, Spectro Analytical Instruments, Inc, Mahwah NJ). Harvested roots, along with the belowground portion of the crown were washed and dried and then ground twice, once using a large grinder and then a second time using a 40-mm mesh Wiley mill. Carbohydrate analysis for the NSC of the roots was performed using high pressure liquid chromatography (Prominence, UFLC, XR, Shimadzu, Tokyo) for sucrose, glucose, and fructose. The method was developed and described in Hagidimitriou and Roper (1994).

Nitrogen use efficiencies

To calculate agronomic and nitrogen-use efficiencies (AE and NUE) the following equations adopted from Ball-Coelho et al. (2006) and Lemus et al. (2008a) were used:

Agronomic efficiency = kg biomass ha^{-1}/kg total applied N fertilizer ha^{-1}.

Nitrogen use efficiency = (kg biomass at N_x – kg biomass at N_0)/ kg of applied N

where N_x = N rate > 0, and N_0 = no N application

Statistical analysis

Biomass yield, mineral content, NSC, AE, and NUE data were analyzed using the ANOVA procedure and Proc GLM (SAS Institute, 2009). Main effects were year, harvest season, and N fertilization rate. Main plots were harvesting season and subplots were N fertilization rate. All main effects were considered as fixed and only block was treated as a random effect. Data for N application rates were analyzed using Proc REG. Duncan multiple range tests were used for mean separations at $P<0.05$ significance level. Results were not averaged over years when interactions of year by main effects were significant.

Results

Weather

Cumulative growth degree days (GDD), observed from the Orange, MA, weather station, for 2009, 2010 and 2011 (April through Nov) were 2383, 3023, and 2909, respectively which were lower than the norm (3278) for this location (Table 15). Cumulative growing season precipitation was 829 mm in 2009, 634 mm in 2010, and 957 mm in 2011. Precipitation was only higher than the norm (863 mm) in the 2011 growing season. Weather data for 2012 (spring harvest) are not presented due to lack of growth (Nov through April).

Biomass yield

Switchgrass dry matter yield was influenced by year and harvesting season, but not by N application rate. The highest biomass was harvested during the first growing season (2009) which was 6.46 Mg ha^{-1} (Table 16). Averaged over harvesting seasons, switchgrass biomass yield was reduced up to 33% in 2011 growing season (Table 16).

The highest switchgrass biomass yield was obtained from summer (6.28 Mg ha^{-1}) and fall harvest (6.09 Mg ha^{-1}) (Table 16). Delaying the harvest until fall did not reduce switchgrass yield however, yield declined as much as 27% when switchgrass was harvested in spring compared with the summer harvest (Table 16). Overall, the greatest biomass production (7.82 Mg ha^{-1}) was recorded from summer harvest in the first growing season (Table 16). Switchgrass dry matter yield averaged over N fertilizer application rates (across all years and harvest seasons) was 5.72 Mg ha^{-1}. Response of biomass yield to N application rate within each harvest season was different. Increasing N application rate resulted in a quadratic increase in biomass production when switchgrass was harvested in summer whereas no significant response to N application was found in fall and spring harvests (Table 17).

Moisture content of switchgrass was influenced only by season of harvest and year by season of harvest. However, interaction was reflected relatively small differences in the magnitude of the moisture response to year and harvest season. Switchgrass moisture content was at its peak when switchgrass was harvested in the summer (62%) and was steadily decreased with delaying the harvest until fall (40%) and spring (13.6%) (Table 18).

Ash and mineral content

Neither year nor N fertilizer rate influenced ash content of switchgrass. Total ash in the switchgrass was dependent on the season of harvest. Biomass harvested in the summer had the highest ash concentration (47 g kg^{-1}) compared with fall (33 g kg^{-1}) and spring (29 g kg^{-1}) harvests. The mineral composition of harvested switchgrass was significantly influenced by harvesting season. Aluminum concentration did not vary as a function of harvesting season. However, the effect of harvesting time on Ca, and Fe was inconclusive (Table 19). Overall it seems that harvesting season had no or little effect on concentration of these two elements in harvested grass. Delaying harvest until spring resulted in significant decrease in switchgrass mineral content (Table 19). Nitrogen concentration of switchgrass, averaged over growing seasons, were 6.0, 2.6, and 2.4 g kg^{-1} for summer, fall and spring harvests, respectively (Table 19). This indicated that there were no significant differences between fall and spring harvests with respect to switchgrass N content. Phosphorous, K, and Mg all consistently decreased from summer to the spring harvest, with K having the most pronounced change between the harvest seasons (Table 19). Calcium concentration remained nearly constant across all harvest seasons. Nitrogen, P, K, and Fe were all influenced by N application (Table 20). Switchgrass biomass in the highest N rate (134 kg ha^{-1}) had 30% higher N content compared with no N application. Nitrogen yield, averaged over three harvest seasons and years was 17, 19, and 30 kg ha^{-1} from plots receiving 0, 67, and 134 kg ha^{-1} N, respectively. Highest P concentration (5.1 g kg^{-1}) was recorded from switchgrass plots receiving 0 N fertility; in contrast, maximum K concentration (1.2 g kg^{-1}) was obtained from the highest N fertilizer rate (Table 6).Concentration of Fe in switchgrass plants was increased when 134 kg N ha^{-1} was applied to the switchgrass plots compared with 0 and 67 kg N ha^{-1}.

Carbohydrate reserves

Soluble non-structural carbohydrate levels in belowground tissue (roots and crown) were affected significantly by year, harvest season and year by harvest season interaction. Nitrogen application rate did not affect NSC level in belowground tissues.

Levels of glucose and fructose were similar in all treatments, but sucrose, which normally is the most abundant NSC, was significantly influenced by year and harvest season. Sucrose levels were higher when switchgrass was harvested in fall, compared with both summer and spring harvests (Fig. 22). Significant interaction between harvesting season and year largely reflected the lower sucrose levels observed in fall 2010 following a sever drought.

Nitrogen Use Efficiency

Agronomic efficiency (AE) varied across years and N application rates, but was not influenced by harvesting seasons. Wet conditions in 2011, reduced AE compared with the 2009 and 2010 growing seasons (Table 21). Agronomic efficiency was reduced dramatically (by 45% averaged over three years) as nitrogen application rate increased from 67 kg N ha^{-1} to 134 kg N ha^{-1} (Table 21). Nitrogen use efficiency was only influenced by harvest season with highest values recorded in the summer harvests.

Discussion

Biomass yield

Several researchers have reported that optimal harvest season was at senescence and that delaying the harvest until a killing frost will result in a significant decrease in yield and that harvesting prior to maturation in mid-summer also negatively affects yield (Sanderson et al., 1996; Vogel at al., 2002; Sanderson and Adler, 2008). In most rainfed environments of the Great Plains and Midwest USA, maximum first-cut yields could be achieved when panicles are fully emerged to the post-anthesis stage (Mitchell and Schmer, 2012). In our study switchgrass yields were similar among summer and fall harvests only during 2011 growing season; delaying harvest until spring however, resulted in lower biomass yield (Table 16). A 27% yield reduction from summer to spring harvest was similar to those reported in the literature where switchgrass biomass losses ranged from 11 to 40% (Adler et al., 2006; Mitchell et al., 2012; Wilson et al., 2013). In general, overwinter losses are specifically common in temperate climates where snowfall can impact tiller lodging and make the stand difficult to harvest with conventional equipment (Herbert et al., 2012). Switchgrass stand density declines over time, presumably producing fewer tillers as the crop ages. This is more apparent in upland than in lowland varieties (Herbert et al., 2012). The crop compensates for the thinning of the stand by increasing the size of tiller diameter and height of the plant (Cassida et al., 2005). In the current experiment, there was a consistent decrease in dry matter yield from year to year that was more apparent when fields were harvested in summer than those harvested in the fall or spring. This might be attributed to the decrease in the number of tillers as the plants aged, but in this study there was too much initial variation in stand density and this aspect was not pursued. More years of data collection are needed to determine the overall expected yield for the crop over its life span and if the decrease in late summer yield is significant enough that over a ten-year period it would be recommendable to harvest in the fall when yields were more stable.

Moisture content could directly influence the energy content of the grass for combustion (Adler et al., 2006). As the season progress, the moisture content of the plant decreases (Sokhansanj et al., 2009). In the current study (Table 18), delaying the harvest until spring resulted in significant reduction in moisture content of the switchgrass. Previous reports (Sanderson et al., 1997; Adler et al., 2006; Mitchell and Schmer, 2012) have suggested that moisture content of the grass ranges from 70% in summer, 40% in late fall and less than 20% in spring. Our findings are in accordance with their results, which showed the possibility of direct baling with spring harvests (Mitchell and Schmer, 2012).

Ash and mineral content

Ash content is an important factor when considering grass for combustion purposes. Ash concentrations decreased with delay in harvest. Average ash concentration in our study (3.6%) was significantly lower than 4.5% reported by McKendry (2002) and Wilson et al. (2013). Across all years and N application rates, N and ash content showed similar trends, with the highest concentrations measured in the summer harvest and no significant difference between fall and following spring harvest. Plants harvested after killing frost (fall) had decreased N in plant tissue compared with plants harvested at the beginning of senescence. This could be because of higher yields in earlier harvest as well as higher N in the biomass (Lemus et al., 2008a). This also could be explained by switchgrass perenniality which means that the plant has evolved to go dormant at the onset of the winter; translocates nutrients, including N, from aboveground tissues to belowground storage organs to be used for regrowth in succeeding season. As expected, higher N fertilizer application increased N content in the biomass. This finding was in line with results reported by Lemus et al. (2008b) where greater N application yielded higher N concentration in switchgrass biomass. With respect to other nutrients such as P, K, and Mg which had initial concentrations greater than 1 g kg^{-1}, a delay in the harvest until at least the fall period, lowered the nutrient levels and improved the feedstock quality for combustion. Calcium concentrations were not reduced as plant senesced over the season. Regardless of harvest season, lower mineral concentration was observed in grass tissues during the 2011 growing season which could be partially explained by the wet conditions. Wilson et al. (2013) reported that high precipitation could lower the mineral concentration. Casler and Boe (2003) stated that switchgrass had the ability to mobilize nutrients to the root system before a killing frost. One of the appeals of using switchgrass as a biofuel is that the plant can efficiently recycle its nutrients. Harvesting in summer consistently removed more nutrients in the harvested biomass, which then, would as soils were depleted, require more fertilizer to replace removed nutrients.

Carbohydrate reserves

The peak concentration of total NSC in the belowground tissue was measured in fall harvest (Fig. 22). There was almost three times more sucrose in the fall harvest than in the summer, since the plants prepared for dormancy due to cold acclimation. By spring the carbohydrate levels were lowered, presumably due to the plants' consumption to survive the winter. Parrish and Wolf (1993) similarly reported that the reduction in yield from September to November was due to the remobilizing of carbohydrate reserves and N from stem to roots and leaf loss. Our findings are also in line with Adler et al. (2006) who reported lower carbohydrate reserves in spring compared with fall harvest. Analysis of the NSC in the roots sampled at each harvest date indicated that sucrose was the primary sugar, with minor quantities of fructose and glucose. Our results confirmed earlier reports by White (1973) and Adler et al. (2006), that warm-season grasses store carbohydrates in the form of sucrose.

Nitrogen Use Efficiency

Variation in AE across three years of study could be attributed to lower biomass production in the 2011 growing season as a result of the age of the stand. Wet conditions resulted in lower N biomass content; which lowered AE. Although switchgrass biomass was maximized at the highest N application rate, the response was not high enough to improve AE. Bransby et al. (1998) suggested that biomass yield should be account for differences in nutrient use efficiencies. In our study, NUE ranged from 14 up to 33% which is obviously lower than the 30 to 70% reported by Bransby et al. (1998). Nitrogen use efficiency can also be soil/site specific (Parrish and Fike, 2005). Lemus et al. (2008a) calculated different NUE for two different locations in Virginia. They reported that increasing the N rate resulted in decreasing NUE at one site with no significant response at the other site. In a five-year experiment, Lemus et al. (2008b) in Iowa found 56 kg ha^{-1} an ideal N rate in terms of NUE. Our results are in line with their findings with less than 67 kg ha^{-1} as the optimum N rate to achieve highest NUE. Comparisons of NUE between various experiments may not be appropriate since NUE metrics may change with soil/site, harvest management strategies, crop age, as well as source of N.

Conclusion

Switchgrass yield generally decreased when delaying the harvest from fall to spring. Delaying harvest also reduced ash content of the biomass which could be translated into increasing the energy content of the biomass for combustion. The reduced concentration of minerals such as N, P, K, and Mg in fall and spring harvest would reduce the potential for formation of fusible ash, thereby reducing slagging and fouling of boilers used for direct combustion. Nitrogen application rate up to 134 kg ha^{-1} only gave a slight increase in biomass yield but elevated biomass N content of the grass biomass. The highest biofuel quality appeared to be obtained when switchgrass harvest was delayed over winter until spring.

Overall, considering switchgrass biomass yield, quality and NUE, harvesting in winter with not more than 67 kg ha^{-1} could be the more sustainable management practice in Massachusetts.

Table 15: Monthly and total growth degree days (GDD_{10}°C) and precipitation (mm) from 2009-2011 at the University of Massachusetts experimental farm, South Deerfield.

Month	GDD				precipitation (mm)			
	2009	2010	2011	30-year Average	2009	2010	2011	30-year Average
April	99	107	87	80	72	21	208	115
May	245	380	326	375	98	50	218	103
June	455	546	483	639	129	81	77	107
July	566	755	742	785	200	79	97	109
Aug	643	670	630	745	110	51	204	101
Sept	298	463	472	488	38	106	57	107
Oct	55	106	131	146	116	137	29	118
Nov	13	2	38	20	65	109	67	103
Total	2383	3023	2909	3278	829	634	957	863

Table 16: Effect of season of harvest on dry matter yield in 2009-2011 (averaged over three N fertilization rates and replications).

Harvest season	Year			Mean
	2009	2010	2011	
		Mg ha^{-1}		
Summer	7.82a	5.53b	5.49a	6.28A
Fall	6.28b	6.74a	5.26a	6.09A
Spring	5.28c	5.93ab	3.86b	5.02B
Mean	6.46A	6.06A	4.87B	-

Values with the same letters are not significantly different at $P<0.05$.
Capital letters represent mean separation for year and harvest season.
Lower case letters represent mean separation for harvest season within each year.

Table 17: Effect of harvest season and N fertilization rates on switchgrass dry matter yield (averaged over three growing seasons and replications).

Harvest season	N fertilization rate (kg ha^{-1})			
	0	67	134	
		Mg ha^{-1}		Trend
Summer	4.61a	6.72a	7.41a	Q**
Fall	5.28a	6.48a	6.33b	ns
Spring	5.07a	4.84b	5.05c	ns
Mean	4.99B	6.01A	6.26A	-

Values with the same letters are not significantly different at *P*<0.05.
Capital letters represent mean separation for harvest season and N fertilization rate.
Lower case letters represent mean separation for N fertilization rates among harvesting seasons.
Q, quadratic, ns, non-significance; **, significant at *P*<0.001.

Table 18: Influence of season of harvest on moisture content of switchgrass in 2009-2011 (averaged over three N fertilization rates and replications).

Harvest season	Year			
	2009	2010	2011	Mean
		(%)		
Summer	63.0a	58.0a	65.0a	62.0A
Fall	40.0b	42.0b	38.0b	40.0B
Spring	15.0c	15.0c	11.0c	13.6C
Mean	39.3A	38.3A	38.0A	-

Values with the same letters are not significantly different at *P*<0.05.
Capital letters represent mean separation for year and harvest season.
Lower case letters represent mean separation for harvest season within each year.

Table 19: Harvest season influence on chemical constituents in dry matter in 2009-2011 (averaged over three N fertilization rates and replications).

Harvest season		Nutrients						
		N	P	K	Ca	Mg	Fe	Al
		$g\ kg^{-1}$						
Summer		5.90a	1.60a	2.60a	1.9a	1.50a	0.16a	0.10a
Fall	2009	2.80b	1.00ab	0.90b	2.4a	1.20a	0.07b	0.05a
Spring		2.90b	0.30c	0.10c	2.3a	0.90b	0.18a	0.05a
Summer		7.20a	1.80a	1.20a	3.0a	1.90a	0.15b	0.04a
Fall	2010	2.90b	0.90b	1.40a	2.9a	1.40a	0.11b	0.07a
Spring		2.30b	0.20b	0.07b	2.2b	0.60b	0.57a	0.08a
Summer		5.00a	1.70a	1.10a	2.0a	1.30a	0.11b	0.02a
Fall	2011	2.10b	0.80b	1.20a	2.0a	1.00a	0.25a	0.02a
Spring		2.00b	0.40b	0.30b	1.6a	0.70b	0.09b	0.03a

Values with the same letters are not significantly different at *P*<0.05.
Letters represent mean separation for harvest time within each year

Table 20: Effect of N fertilization rates on N, P, K, and Fe content in aboveground tissues of switchgrass (averaged over three growing seasons, harvest seasons and replications).

N application rate ($kg\ ha^{-1}$)	N	P	K	Fe
		$g\ kg^{-1}$		
0	0.34	1.20	4.40	0.01
67	0.32	0.87	4.00	0.01
134	0.45	0.81	5.10	0.03
Trend	†Q**	†Q**	†Q**	†Q**

**, significant at *P*<0.001.
†Q, quadratic.

Table 21: Nitrogen-use estimators as influenced by N fertilization rates in 2009-2011 (averaged over three seasons of harvests and replications).

N rate (kg ha^{-1})		N-use metrics	
		AE	NUE
		(kg biomass/ kg N)	
67	2009	94a	28a
134		50b	33a
67	2010	99a	20a
134		58b	14a
67	2011	64b	29a
134		35b	15b

Values within each year with the same letters are not significantly different at $P<0.05$.
AE, agronomic efficiency; NUE, nitrogen-use efficiency.
Letters represent mean separation for N fertilization rate within each year.

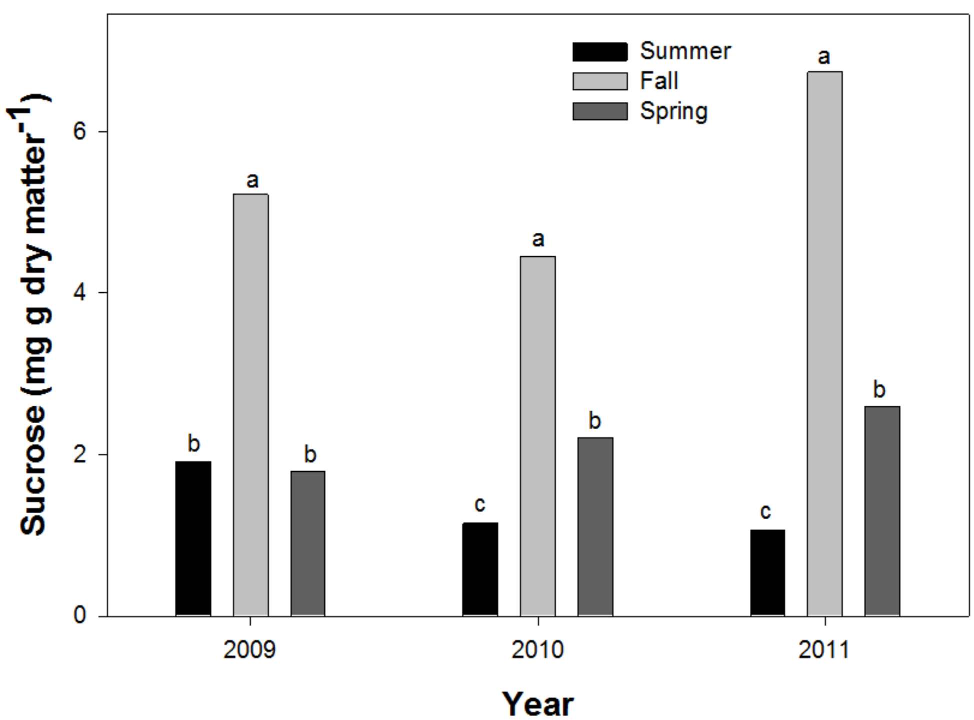


Figure 22: Sucrose concentration in roots and crowns of switchgrass as affected by harvest season from 2009-2011.

Values with the same letter in each column are not significantly different at $P<0.05$.

CHAPTER 8

SUMMARY AND CONCLUSION

In the last 30 years, significant progress through dedicated research efforts has been made in developing switchgrass as a bioenergy crop. Although there is an improved understanding of the biology and agronomy of switchgrass, a few aspects of switchgrass establishment and production need further investigation. Reliable establishment methods and effective weed management practices to produce a harvestable biomass in the establishment year, appropriate nutrient management to enhance fertilizer efficiency, and biomass conversion methods are yet not fully determined. Thus, we conducted researches to address these issues and increase the knowledge of switchgrass establishment and production. These studies ranged from finding the most promising switchgrass variety to adjusting switchgrass seeding rate, find the most appropriate seeding date, seeding methods, weed management, nitrogen application, and harvest management.

Six experiments were conducted to investigate the following topics:

1) A simple vigor test for adjusting switchgrass seeding rate in marginal and fertile soils

2) Cover crops, seeding methods, and herbicide application influence on switchgrass establishment and weed control

3) Switchgrass establishment and biomass yield response to seeding date and herbicide application

4) Seedbed firming improved switchgrass establishment and production in the establishment year

5) Evaluating switchgrass varieties for biomass yield and quality in Massachusetts

6) Response of switchgrass biomass yield and quality to harvest season and nitrogen fertilizer

These experiments were designed to address major issues in establishment and production of switchgrass mainly grown for combustion. Calculating switchgrass seeding rate is misleading and often causes stand failure. Switchgrass seeds are expensive thus, finding the most appropriate seeding rate for successful switchgrass establishment could significantly increase the economic viability of growing switchgrass. We developed a simple vigor test to calculate a proper seeding rate for successful switchgrass establishment. The media and depth of planting for greenhouse experiment was adopted from a previous study conducted by Daniel Forberg; however, that study used 400 fast established seedlings m^{-2} as a base of seeding rate calculation. In this study, we used 200 fast established seedlings m^{-2} and added marginal land to the experiment to determine how different the calculations would be from one soil type to another. Our results suggested that soil type can change the calculations and seeding rates recommended for a fertile soil might not be sufficient for obtaining a well-established switchgrass stand in a marginal soil. In this study we could not reach the target of 200 established seedlings m^{-2}. In general, however, one established seedling often produces between 3–4 tillers providing 300–400 tiller m^{-2} which suffices for producing more than 1 Mg ha^{-1} in the establishment year. Based on our findings in fertile soils a 50% adjusted seeding rate (averaged over varieties, 6.2 kg ha^{-1}) could produce enough seedlings to provide acceptable stand and therefore first-year harvestable biomass. In marginal soils, however, 100% adjusted seeding rate (average over varieties, 15.2 kg ha^{-1}) was required to provide sufficient stand density for harvestable biomass in the establishment year.

Weed pressure is a major limiting factor in switchgrass establishment. However, with an integrated approach using appropriate seeding date, cover crops, tillage systems and herbicide application, switchgrass establishment could be improved. Our findings suggested that delaying the seeding date could increase switchgrass stand density and control weeds however, morphologically limited plants might produce with late plantings (July) compared with November and May. Overall, when rainfall is adequate, earlier planting of switchgrass could help plants to establish better and sufficient biomass in the establishment year and significantly higher biomass in the production year (second year). To establish switchgrass broadcast seeding method could not be recommended to growers, especially in regions with intermittent rainfall or a predicable dry climate. No-till drill seeding resulted in most efficient weed control and therefore highest switchgrass establishment. Although rye and oat cover crops controlled weeds to a greater extent than no cover crop when used as mulch, rye reduced switchgrass stand density whereas oat mulch provided weed suppression as well as satisfactory switchgrass establishment. Seedbed firming is another method of improving switchgrass establishment. In an study we suggested that increasing the contact between soil and soil could improve switchgrass establishment. We compared roller with cultipacker which is more common among growers to firm the soil. Switchgrass tiller density was generally lower when seeds were drilled into a non-compacted soil. This also influenced the plant height as well as biomass yield production with disk-planting producing the lowest yield each year. In current study, a significant quadratic response was found between soil resistance at 0-10 cm soil layer and number of established plants (R^2=0.71). Observing much taller plants in 2013 was suggesting that plant size was dependent upon precipitation. Previous findings showed no significant differences in seedling number in silt-loam soils with double rolling (once before and once after planting) compared with a single rolled treatment however, our findings suggested that at least one time rolling or cultipacking after planting was required to improve switchgrass stand density and biomass production in a sandy-loam soil in Massachusetts.

Our results indicated that Application of herbicide is highly recommended for successful switchgrass establishment, as non-treated plots resulted in many weeds and poor switchgrass establishment. A mixed pre-emergence application of atrazine and quinclorac plus a post-emergence application of 2,4-D and dicamba promoted switchgrass establishment and resulted in the most effective weed control than just the atrazine and quinclorac treatment. Overall, highest weed suppression, switchgrass tiller density, and switchgrass biomass yield was achieved with the no-till drill seeding of switchgrass into a winter killed oat mulch with the application of the broad spectrum herbicide combination of atrazine, quinclorac, 2,4-D, and dicamba.

Variety selection is an important aspect of improving switchgrass production. We evaluated twelve switchgrass varieties to determine the most promising varieties for Massachusetts. Among top five selected switchgrass varieties (Blackwell, Carthage, Cave-in-Rock, Shawnee, and Shelter), Carthage, an upland variety, consistently produced the highest biomass yield each year. However, Cave-in-Rock and Shawnee both also produced comparable biomass yield as well. This was an interesting finding because currently, Cave-in-Rock was mostly suggested as a desirable upland variety. Attaining high switchgrass yields with optimum quality for combustion while also maintaining crop health is challenging. Harvest season and nitrogen management could impact switchgrass yield and quality. Our findings suggested that switchgrass yield generally decreased when harvest was delayed from fall to spring. Delaying harvest also reduced ash content of the biomass which could be translated into increasing the energy content of the biomass for combustion. The reduced concentration of minerals such as N, P, K, and Mg in fall and spring harvest would reduce the potential for formation of fusible ash, thereby reducing slagging and fouling of boilers used for direct combustion. Nitrogen application rate up to 134 kg ha^{-1} only gave a slight increase in biomass yield but elevated biomass N content of the grass biomass. The highest biofuel quality appeared to be obtained when switchgrass harvest was delayed over winter until spring. Overall, considering switchgrass biomass yield, quality, and NUE, harvesting in winter with no more than 67 kg ha^{-1} could be the more sustainable management practice in Massachusetts.

BIBLIOGRAPHY

Adler PR, Sanderson MA, Boateng AA, Weimer PJ, Jung HG. 2006. Biomass yield and biofuel quality of switchgrass harvested in fall or spring. Agron. J. 98: 1518-1525.

Aiken GE, Springer TL. 1995. Seed size distribution, germination, and emergence of 6 switchgrass cultivars. J. Range Manage. 48: 455-458.

Anderson WP. 1996. Weed Science: Principles and Applications.3rd ed., Long Grove, IL: Waveland Press Inc.

Anderson EK, Parrish AS, Voigt TB, Owens VN, Hong CH, Lee DK. 2013. Nitrogen fertility and harvest management of switchgrass for sustainable bioenergy feedstock production in Illinois. Ind. Crops Prod. 48: 19-27.

AOSA. 1993. Rules for testing seed. J. Seed Tech. 16: 1-113.

AOSA. 2010. Rules for testing seed. J. Seed Tech. 16: 1-113.

Aravindhakshan SC, Epplin FM, Taliaferro CM. 2011. Switchgrass, bermudagrass, flaccidgrass, and lovegrass biomass yield response to nitrogen for single and double harvest. biomass and bioenerg. 35: 308-319.

Ateh CM, Doll JD. 1996. Spring planted winter rye (*Secale cereale*) as a living mulch to control weeds in soybean (*Glycine max*). Weed Technol. 10:347–353.

Bahler CC, Vogel KP, Moser LE. 1984. Atrazine tolerance in warm-season grass seedlings. Agron. J. 76: 891-895.

Balan V, Kumar S, Bals B, Chundawat S, Jin M, Dale B. 2012. Biochemical and thermochemical conversion of switchgrass to biofuels. In: Switchgrass. London: Springer. pp. 153-185.

Ball-Coelho BR, Roy RC, Bruin AJ. 2006. Nitrogen recovery and partitioning with different rates and methods of sidedressed manure. Soil Sci. Soc. Am. J. 70:464–473.

Becker, R. L. and D. W. Miller. 1998. Warm season grass establishment systems. Proc. West. Soc. Weed Sci. 51:127–128.

Berti MT, Johnson BL. 2013. Switchgrass establishment as affected by seeding depth and soil type. Ind. Crops Prod. 41: 289-293.

Blanco-Canqui H. 2010. Energy crops and their implications on soil and environment. Agron. J. 102: 403-419.

Boydston RA, Collins HP, Fransen SC. 2010. Response of three switchgrass (*Panicum virgatum*) cultivars to mesotrione, quinclorac, and pendimethalin. Weed Technol. 24: 336-341.

Bransby DI, McLaughlin SB, Parrish DJ. 1998. A review of carbon and nitrogen balances in switchgrass grown for energy. Biomass Bioenerg. 14: 379-384.

Brejda JJ, Moser LE, Vogel KP. 1998. Evaluation of switchgrass rhizosphere microflora for enhancing seedling yield and nutrient uptake. Agron. J. 90: 753-758.

Brejda JJ. Fertilization of native warm-season grasses. In: Anderson BE, Moore KJ, editors. Native warm-season grasses: Research trends and issues. Wisconsin: Madison. 2000; 30: 177-200.

Bremner JM. Nitrogen—Total. In D.L. Sparks (ed.) Methods of soil analysis. Part 3. Chemical methods. 1996; p. 1085–1121. SSSA Book Ser. 5. SSSA, Madison, WI.

Bona L, Belesky DP. 1992. Evaluation of switchgrass entries for acid soil tolerance. Commun. Soil Sci. Plant Anal. 123: 1827-1841.

Buhler DD, Netzer DA, Riemenschneider DE, Hartzler RG. 1998. Weed management in short rotation poplar and herbaceous perennial crops grown for biofuel production. Biomass and Bioenerg. 14: 385-394.

Burgos NR, Talbert RE. 1996. Weed control by spring cover crops and imazethapyr in no-till southern pea (*Vigna unguiculata*). Weed Technol. 10:893–899.

Burvall J. 1997. Influence of harvest time and soil type on fuel quality in reed canary grass (*Phalaris arundinacea* L.). Biomass and Bioenerg. 12:149-154.

Butler TJ, Kering MK, Huo C, Guretsky JA. 2012. Effect of safener, activated charcoal coated seed, and charcoal banding on establishment of switchgrass receiving pre-emergent herbicides. Forage Grazinglands. doi:10.1094/FG-2012-1214-01-RS.

Campiglia E, Radicetti E, Mancinelli R. 2012. Weed control strategies and yield response in a pepper crop (*Capsicum annuum* L.) mulched with hairy vetch (*Vicia villosa* Roth.) and oat (*Avena sativa* L.) residues. Crop Prot. 33:65–73.

Casler MD, Boe AR. 2003. Cultivar x environment interactions in switchgrass. Crop Sci. 43: 2226-2233.

Casler MD, Vogel KP, Taliaferro CM, Wynia RL. 2004. Latitudinal adaptation of switchgrass populations. Crop Sci. 44: 293-303.

Casler MD. 2005. Ecotypic variation among switchgrass populations from the northern USA. Crop Sci. 45: 388-398.

Cassida KA, Muir JP, Hussey MA, Read JC, Venuto BC, Ocumpaugh WR. 2005. Biofuel component concentration and yield of switchgrass in south central USA environments. Crop Sci. 45: 682-692.

Christian DG, Elbersen HW. Switchgrass (*P. virgatum* L.). Energy plant species. Their use and impact on environment and development, Vol. I., London: James and James. 1988; 257-263.

Clark RB, Zobel RW, Zeto SK. 1999. Effects of mycorrhizal fungus isolates on mineral acquisition by *Panicum virgatum* in acidic soil. Mycorrhiza. 9: 167-176.

Clark RB. 2002. Differences among mycorrhizal fungi for mineral uptake per root length of switchgrass grown in acidic soil. J. Plant Nutr. 25: 1753-1772.

Colbran, N, Eide A. 2008. Biofuel, the environment, and food security: A global problem explored through a case study of Indonesia. Sustain Dev Law Pol. 9: 4-11.

Crabtree WL, Henderson CWL. 1999. Furrows, press wheels and wetting agents improve crop emergence and yield on water repellent soils. Plant Soil. 214:1–8.

Curran WS, Lingenfelter DD, Calvin DD, Tooker JF, Dillon JM. Forages pest management. In: Kirsten A, editor. Agronomy Guide. University Park, PA: Penn State University, College of Agricultural Sciences. 2008; 323-346

Curran WS, Ryan MR, Myers MW, Adler PR. 2011. Effectiveness of sulfosulfuron and quinclorac for weed control during switchgrass establishment. Weed Technol. 25: 598-603.

Curran WS, Ryan MR, Myers MW, Adler PR. 2012. Effect of seeding date and weed control on switchgrass establishment. Weed Technol. 26: 248-255.

Dawson JH, Rincker CM. 1982. Weeds in new seedlings of alfalfa (*Medicago sativa*) for seed production: Competition and control. Weed Sci. 30: 20-25.

Elbersen HW, Ocumpaugh WR, Hussey MA, Sanderson MA, Tischler CR. 1998. Crown node elevation of switchgrass and kleingrass under low light. Crop Sci. 38: 712-716.

Elbersen HW, Christian DG, El-Bassem N, Bacher W, Sauerbeck G, Alexopoulou E, Sharma N, Piscioneri I, Visser PD, Berg DVD. 2001. Switchgrass variety choice in Europe. Aspects of Appl. Biol. 65: 21-28.

Evers GW, Butler TJ. Switchgrass establishment on Coastal Plain soil. Proc. American Forage and Grassland Council; 2000; 150-154.

Evers GW, Parsons MJ. 2003. Soil type and moisture level influence on Alamo switchgrass emergence and seedling growth. Crop Sci. 43: 288-294.

Farsad A, Herbert SJ, Hashemi M, Sadeghpour A. 2012. An automated suction lysimeter for improved soil water sampling. Vadose Zone J. 11: -. doi:10.2136/vzj2012.0003.

Fike JH, Parrish DJ, Wolf DD, Balasko JA, Green Jr JT, Rasnake M, Reynolds JH. 2006. Long-term yield potential of switchgrass-for-biofuel systems. Biomass and Bioenerg. 30: 198 206.

Forberg DB. Evaluation of seed vigor test for the establishment of switchgrass. Amherst (MA): University of Massachusetts, 2009.

Forberg DB, Herbert SJ, Prostack R, Hashemi M. Seed vigor test for the establishment of switchgrass. ASA, CSSA, and SSSA Annual meetings; 2009 Nov 1-5; Pittsburgh, PA.

Foster JL, Guretzky JA, Huo C, Kering MK, Butler TJ. 2013. Effects of row spacing, seeding rate, and planting date on establishment of switchgrass. Crop Sci. 53: 309–314.

Friedrich JW, Smith D, Schrader LE. 1977. Herbage yield and chemical composition of switchgrass as affected by N, S and K fertilization. Agron. J. 69: 30-33.

Gorlitsky LE. Management of switchgrass for the production of biofuel. Amherst (MA): University of Massachusetts, 2012.

Gorlitsky LE, Sadeghpour A, Hashemi M, Weis SA, Herbert SJ. Optimal fall harvest time for production of high-quality switchgrass grown for combustion. ASA, CSSA, SSSA Annual meetings; 2013 Nov 3-6; Tampa, FL.

Guretzky JA, Biermacher JT, Cook BJ, Kering MK, Mosali J. 2011. Switchgrass for forage and bioenergy: Harvest and nitrogen rate effects on biomass yields and nutrient composition. Plant Soil. 339: 69-81.

Gutormson TJ, Patin AL. 2002. Sources of laboratory test result variation in warm-season grasses. Seed Tech. 24: 52-61.

Hajidimitriou M, Roper TR. 1994. Seasonal changes in nonstructural carbohydrates in cranberry. J. Am. Soc. Hortic. Sci. 119:1029–1033.

Hakansson I, Myrbeck A, Etana A. 2002. A review of research on seedbed preparation for small grains in Sweden. Soil Tillage Res. 64:23–40.

Hall KE, George JR, Riedl RR. 1982. Herbage dry matter yields of switchgrass, big bluestem and indiangrass with N fertilization. Agron. J. 74: 47-51.

Haque M, Biermacher JT, Kering MK, Guretzky JA. 2013. Economics of alternative fertilizer supply systems for switchgrass produced in phosphorus-deficient soils for bioenergy feedstock. BioEnergy Res. 6: 351-357.

Harper J, Spooner AE. Establishment of selected herbaceous species on acid bauxite mine soils. Proceedings Symp. on Surface mining, hydrology, sedimentology and reclamation. Aluminum Company of America. Bauxite, AR: 1983; 413-422.

Harper CA, Morgan GD, Dixon CE. Establishing native warm-season grasses using conventional and no-till technology with various applications of Plateau herbicide. Proceedings of the 3rd Eastern Native Grass Symposium. Randall J, Burns JC, editors, Chapel Hill, NC: 2004; 63-70.

Hashemi M., Sadeghpour A. 2013. Establishment and production of switchgrass grown for combustion: A review. Int J Plant Biol Res. 1(1): 1002, available from URL: http://www.jscimedcentral.com/PlantBiology/Articles/ plantbiology-1-1002.pdf [cited 27 November 2013).

Hashemi M, Farsad A, Sadeghpour A, Weis SA, Herbert SJ. 2013. Cover crop seeding date influence on fall nitrogen recovery. J. Plant Nutr. Soil Sci. 176: 69-75.

Henry DS, Everett HW, Evans JK. Clipping effect on stand, yield and quality of three warm-season grasses. Proceedings of the Hill Lands Symposium Morgantown, WV: West Virginia University. 1976; 701-704.

Herbert SJ, Gorlitsky L, Hashemi M, Sadeghpour A. Evaluating switchgrass varieties for biomass yield and quality in Massachusetts. In: Proceedings from Sun Grant National Conference: Science for Biomass Feedstock Production and Utilization, 2–5 Oct 2012, New Orleans, LA, available from URL: http://sungrant.tennessee.edu/NR/rdonlyres/3880A277-C502-4EC9-9DEB-C385186A5C85/3701/29Herbert.pdf [cited 27 November 2013].

Hintz RL, Harmoney KR, Moore KJ, George KR, Brummer EC. 1988. Establishment of switchgrass and big bluestem in corn with atrazine. Agron. J. 90:591–596.

Hopkins AA, Taliaferro CM. 1997. Genetic variation within switchgrass populations for acid soil tolerance. Crop sci. 37: 1719-1722.

Hosseinirad A, Chaichi MR, Sadeghpour A. 2013. Response of alfalfa seed yield and yield components to phosphorus fertilizing systems and seeding rate at semi-saline soil conditions. J. Plant Nutr. 36: 491-502.

Hultquist SJ, Vogel KP, Lee DJ, Arumuganathan K, Kaeppler S. 2013. Chloroplast DNA and nuclear DNA content variations among cultivars of switchgrass, Panicum virgatum L. Crop Sci. 36: 1049-1052.

Hsu FH, Nelson CJ. Relationships between germination tests and field emergence of perennial warm-season forage grasses. In: Proceedings of XV Int. Grassl. Cong. Kyoto, Japan, 1985; 380-381.

Hsu FH, Nelson CJ. 1986a. Planting date effects on seedling development of perennial warm-season forage grasses. I. Field emergence. Agron. J. 78: 33-38.

Hsu FH, Nelson CJ. 1986b. Planting date effects on seedling development of perennial warm-season forage grasses. II. Seedling growth. Agron. J. 78: 38-42.

Jannasch R., Quan Y, Samson R. A process and energy analysis of pelletizing switchgrass. Final report. Natural Resources Canada. 2001.

Jefferson PJ, McCaughey, WP. 2012. Switchgrass (*Panicum virgatum* L.) cultivar adaptation, biomass production, and cellulose concentration as affected by latitude of origin. ISRN Agron. doi:10.5402/2012/763046.

Johnson GA, Defelice MA, Helsel ZR. 1993. Cover crop management and weed control in corn. Weed Technol. 7: 425–430.

Jung GA, Shaffer JA, Stout WL. 1988. Switchgrass and big bluestem responses to amendments on strongly acid soil. Agron. J. 80: 669-676.

Kelly, AF. Principles of Seed Growing. In Seed Production of Agricultural Crops. New York: Wiley. 1988; 36-56.

Kering MK, Huo C, Interrante SM, Hancock DW, Butler TJ. 2013. Effect of various herbicides on warm-season grass weeds and switchgrass establishment. Crop Sci. 53: 666-673.

King MA, Waller SS, Moser LE, Stubbendieck JL. 1989. Seedbed effects on grass establishment on abandoned Nebraska Sandhills cropland. J. Range Manage. 42:183-187.

Kiss Z, Fieldsend AF, Wolf DD. 2007. Yield of switchgrass (*Panicum virgatum* L.) as influenced by cutting management. Acta Agronomica Hung. 55: 227-233.

Knapp AD. An overview of seed dormancy in native warm-season grasses. In: Anderson BE, Moore KJ., editors. Native warm-season grasses: Research trends and issues., 2000; 107-122.

Lemus R, Parrish DJ, Abaye O. 2008a. Nitrogen-use dynamics in switchgrass grown for biomass. Bioenergy Res. 1: 153-162.

Lemus R, Brummer EC, Burras CL, Moore KJ, Barker MF, Molstad NE. 2008b. Effects of nitrogen fertilization on biomass yield and quality in large fields of established switchgrass in southern Iowa, USA. Biomass Bioenerg. 32: 1187-1194.

Lemus R, Parrish DJ, Wolf DD. 2009. Nutrient uptake by "Alamo" switchgrass used as an energy crop. Bioenergy Res. 2: 37-50.

Lewandowski I, Scurlock J, Lindvall E, Christoud M. 2003. The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass and Bioenerg. 25: 335-361.

Liebl R, Simmons FW, Wax LM, Stoller EW. 1992. Effect of rye (*Secale cereale*) mulch on weed control and soil moisture in soybean (*Glycine max*). Weed Technol. 6: 838 – 846.

Ma Z, Wood CW, Bransby DI. 2000. Soil management impacts on soil carbon sequestration by switchgrass. Biomass and Bioenerg. 18: 469-477.

Madakadze IC, Coulman BE, McElroy AR, Stewart KA, Smith DL. 1998. Evaluation of selected warm-season grasses for biomass production in areas with a short growing season. Bioresour. Technol. 65: 1-12.

Madakadze IC, Stewart KA, Peterson PR, Coulman BE, Smith DL. 1999. Cutting frequency and nitrogen fertilization effects on yield and nitrogen concentration of switchgrass in a short season area. Crop Sci. 39: 552-557.

Martin AR, Moomaw RS, Vogel KP. 1982. Warm-season grass establishment with atrazine. Agron. J. 74: 916-920.

Masters RA. 1995. Establishment of big bluestem and sand bluestem cultivars with metochlor and atrazine. Agron J. 87: 592-596.

McKendry P. 2002. Energy production from biomass (part 1): overview of biomass. Bioresour Technol. 88: 37-46.

McKenna JR, Wolf DD, Lentner M. 1991. No-till warm-season grass establishment as affected by atrazine and carbofuran. Agron. J. 83: 311-316.

McLaughlin S, Bouton J, Bransby D, Conger B, Ocumpaugh W, Parrish D, Taliaferro C, Vogel K, Wullschleger S. Developing switchgrass as a bioenergy crop. Pespectives on new crops and new uses. Alexandria, VA: ASHS Press,. 1996; 282-299.

McLaughlin SB, Kszos LA. 2005. Development of switchgrass (*Panicum virgatum*) as a bioenergy feedstock in the United States. Biomass Bioenerg. 28: 515-535.

Miesel JR, Renz MJ, Doll JE, Jackson RD. 2012. Effectiveness of weed management methods in establishment of switchgrass and a native species mixture for biofuels in Wisconsin. Biomass Bioenerg. 36: 121-131.

Miller DA. 1996. Allelopathy in forage crop systems. Agron. J. 88:854–859.

Mitchell RB, Vogel KP, Sarath G. 2008. Managing and enhancing switchgrass as a bioenergy feedstock. Biofuels, Bioprod. Biorefin. 2: 530-539.

Mitchell RB, Vogel KP, Berdahl J, Masters RA. 2010. Herbicides for establishing switchgrass in the central and northern Great Plains. Bioenergy Res. 3: 321-327.

Mitchell R, Schmer M. Switchgrass harvest and storage. In: Monti A, editor. Switchgrass a valuable crop for energy. Springer-Verlag: London. 2012; 113-127.

Mitchell RB, Vogel KP. 2012. Germination and emergence tests for predicting switchgrass field establishment. Agron. J. 104: 458-465.

Moles AT, Warton DI, Warman L, Swenson NG, Laffan SW, Zanne AE, Pitman A, Hemmings AE, Leishman MR. 2009. Global patterns in plant height. J. Ecol. 97:923–932.

Monti A, Venturi P, Elbersen HW. 2001. Evaluation of the establishment of lowland and upland switchgrass (*Panicum virgatum* L.) varieties under different tillage and seedbed conditions in northern Italy. Soil Tillage Res. 63: 75-83.

Moore MJ, Gillespie TJ, Swanton CJ. 1994. Effect of cover crop mulches on weed emergence, weed biomass, and soybean (*Glycine max*) development. Weed Technol. 8: 512–518.

Moser LE, Vogel KP. Switchgrass, Big Bluestem, and Indiangrass. In: Barnes RF, Miller DA, Nelson JC, editors. Forages Vol. 1, An Introduction to Grassland Agriculture, 5th edition. Ames, IA: Iowa State Univ. Press, 1995: 409-420.

Muir JP, Sanderson MA, Ocumpaugh WR, Jones RM, Reed RL. 2001. Biomass production of “Alamo” switchgrass in response to nitrogen, phosphorus, and row spacing. Agron. J. 93: 896-901.

Mulkey VR, Owens VN, Lee DK. 2006. Management of switchgrass-dominated Conservation Reserve Program lands for biomass production in South Dakota. Crop Sci. 46: 712-720.

Mullen RE, Kassel PC, Bailey TB, Knapp AD. 1985. Seed dormancy and germination of switchgrass from different row spacings and nitrogen levels. J. Applied Seed Prod. 3: 28-33.

Naik SN, Goud VV, Rout PK, Dalai AK. 2010. Production of first and second generation biofuels: a comprehensive review. Renew Sust. Energ. Rev. 14: 578-597.

Newman PR, Moser LE. 1988. Seedling root development and morphology of cool-season and warm-season forage grasses. Crop Sci. 28: 148-151.

Oldfather S, Stubbendieck J, Waller SS. 1989. Evaluating revegetation practices for sandy cropland in the Nebraska sandhills. J. Range Manage. 42: 257-259.

Parrish DJ, Fike JH. 2005. The biology and agronomy of switchgrass for biofuels. Crit Rev Plant Sci. 24: 423-459.

Parrish DJ, Fike JH. Selecting, establishing, and managing switchgrass (*Panicum virgatum*) for biofuels. Methods Mol Biol. 2009; 581: 27-40.

Parrish DJ, Casler DM, Monti A. The evolution of switchgrass as an energy crop. In: Monti A, editor. Switchgrass a valuable biomass crop for energy. Springer-Verlag: London. 2012; 1-28.

Pedroso GM, Hutmacher RB, Putnam D, Wright SD, Six J, van Kessel C, Linquist BA. 2013. Yield and nitrogen management of irrigated switchgrass systems in diverse ecoregions. Agron. J. 105: 311-320.

Perrin R, Vogel K, Schmer M, Mitchell R. 2008. Farm-scale production cost of switchgrass for biomass. Bioenergy Res. 1: 91-97.

Peters EJ, Linscott DL. Weeds and weed control. In: Hanson AA, Barns DK, Hill, RR, editors. Alfalfa and alfalfa improvement. ASA. Madison, WI, 1988; 705-735.

Porter Jr, CL. An anlaysis of variation between upland and lowland switchgrass *Panicum virgatum* L. in central Oklahoma. Ecology. 1966; 47: 980-992.

Potvin MA. 1993. Establishment of native grass seedlings along a topographic moisture gradient in the Nebraska sandhills. Amer. Midland Naturalist. 130: 248-261.

Pullaro TC, Marino PC, Jackson MD, Harrison HF, Keinath AP. 2006. Effects of killed cover crop mulch on weeds, weed seeds, and herbivores. Agric. Ecosyst. Environ. 115: 97–104.

Putnam AR. Allelopathy: Problems and opportunities in Weed Management. In: Altieri MA, Liebman M, editors. Weed Managment in Agroecosystems: Ecological Approaches. Boca Raton, FL: CRC Press. 1988; 77-88.

Rehm GW. 1990. Importance of nitrogen and phosphorus for production of grasses established with no-till and conventional planting systems. J. Prod. Agric. 3: 333-336.

Reynolds JH, Walker CL, Kirchner MJ. 2000. Nitrogen removal in switchgrass biomass under two harvest systems. Biomass Bioenerg. 19: 281-286.

Rushing JB, Baldwin BS, Taylor AG, Owens VN, Fike JH, Moore KJ. 2013. Seed safening from herbicidal injury in switchgrass (Panicum virgatum L.) establishment. Crop Sci. 53: 1650-1657.

Samson R, Mehdi B. Strategies to reduce ash content of perennial grasses. Expanding Bioenergy Partnership, Bioenergy 98, Great Lakes Regional Biomass Energy Program, Chicago, Illinois, 1998; pp. 1124-1131.

Sadeghpour A, Jahanzad E, Esmaeili A, Hosseini MB, Hashemi M. 2013. Forage yield, quality and economic benefit of intercropped barley and annual medic in semi-arid conditions: Additive series. Field Crops Res. 148: 43-48.

Sadeghpour A, Hashemi M, DaCosta M, Weis SA, Jahanzad E, Herbert SJ. Cover crops, seeding methods and weed control for improving switchgrass establishment. ASA Northeastern regional meeting, Delaware, June 23-26; 2013.

Sadeghpour A, Hashemi M, Jahanzad E, Gorlitsky LE, Weis SA, Herbert SJ. Assessing various seedbed preparations on switchgrass establishment and production. ASA, CSSA, SSSA meetings, Tampa, FL, Nov 3-6; 2013.

Sadeghpour A, Gorlitsky LE, Hashemi M, Weis SA, Herbert SJ. Harvest management and nitrogen application rate influence on biomass yield, quality and nitrogen-use efficiency of switchgrass grown for combustion. ASA, CSSA, SSSA meetings, Tampa, FL, Nov 3-6; 2013.

Sadeghpour A, Gorlitsky LE, Hashemi M, Weis SA, Herbert SJ. 2014. Response of switchgrass yield and quality to harvest season and nitrogen fertilizer. Agron. J. 106: 290–296.

Sanderson MA, Reed RL, McLaughlin SB, Wullschleger SD, Conger BV, Parrish DJ, Wolf DD, Taliaferro CM, Hopkins AA, Ocumpaugh WR, Hussey MA, Read JC, Tischler CR. 1996. Switchgrass as a sustainable bioenergy crop. Bioresour. Technol. 56: 83-93.

Sanderson MA, Read JC, Reed RL. 1999. Harvest management of switchgrass for biomass feedstock and forage production. Agron. J. 91: 5-10.

Sanderson MA, Reed RL. 2000. Switchgrass growth and development: Water, nitrogen, and plant density effects. J. Range Manage. 53: 221-227.

Sanderson MA, Adler PR, Skinner RH, Dell CJ, Curran B. Establishment, production, and management needs of switchgrass for biomass feedstock in the north-eastern U.S.A. In: Proc. Third Eastern Native Grass Symposium., 2004; pp. 92–97. Randall, J., Burns, J.C., Eds. Omnipress, Chapel Hill, NC.

Sanderson MA, Adler PR, Boateng AA, Casler MD, Sarath G. 2006. Switchgrass as a biofuels feedstock in the USA. Can J Plant Sci. 86, 1315-1325.

Sanderson MA, Schmer M, Owens V, Keyser P, Elbersen W. Crop management of switchgrass. In: Monti A, editor. Switchgrass a valuable biomass crop for energy. Springer-Verlag: London. 2012; 87-112.

Sautter EH. 1962. Germination of switchgrass. J. Range Manage. 15: 108-110.

Schmer MR, Vogel KP, Mitchell RB, Moser LE, Eskridge KM, Perrin RK. 2006. Establishment stand thresholds for switchgrass grown as a bioenergy crop. Crop Sci. 46: 157-161.

Shastri YN, Hansen AC, Rodríguez LF, Ting KC. 2012. Switchgrass practical issues in developing a fuel crop. CAB Reviews 7: 1-14.

Shen ZX, Welbaum GE, Parrish DJ, Wolf DD. 1999. After-ripening and aging as influenced by anoxia in switchgrass (*Panicum virgatum* L.) seeds stored at 60 deg C. Acta Hort. 504: 191-197.

Shen ZX, Parrish DJ, Wolf DD, Welbaum GE. 2001. Stratification in switchgrass seeds is reversed and hastened by drying. Crop Sci. 41: 1546-1551.

Smart AJ, Moser LE. 1997. Morphological development of switchgrass as affected by planting date. Agron. J. 89: 958-962.

Smart AJ, Moser LE. 1999. Switchgrass seedling development as affected by seed size. Agron. J. 91: 335-338.

Smart, AJ, Moser, LE, Vogel, KP. 2004. Morphological characteristics of big bluestem and switchgrass plants divergently selected for seedling tiller number. Crop Sci. 44: 607-613.

Smith D. 1975. Trends of nonstructural carbohydrates in stem bases of switchgrass. J. Range Manage. 28: 389–391.

Sokhansanj S, Mani S, Turhollow A, Kumar A, Bransby D, Lynd L, Laser M. 2009. Large-scale production, harvest and logistics of switchgrass (*Panicum virgatum* L.) –

current technology and envisioning a mature technology. Biofuels, Bioprod. Bioref. 3: 124-141.

Teasdale JR, Beste CE, Potts WE. 1991. Response of weeds to tillage and cover crop residue. Weed Sci. 39:195–199.

Teel A, Barnhart S, Miller G. Management guide for the production of switchgrass for biomass fuel in southern Iowa. Ames, IA: Iowa State University Extension. 2003.

Thomason WE, Raun WR, Johnson GV, Taliaferro CM, Freeman KW, Wynn KJ, Mulle RW. 2005. Switchgrass response to harvest frequency and time and rate of applied nitrogen. J. Plant Nutr. 27: 1119-1226.

Trócsányi ZK, Fieldsend AF, Wolf DD. 2009. Yield and canopy characteristics of switchgrass (*Panicum virgatum* L.) as influenced by cutting management. Biomass and Bioenerg. 33: 442-448.

Uwatoko N, Tanaka M, Saito A, Gau M. 2011. Establishment of plant regeneration system in *Erianthus arundinaceus* (Retz.) Jesweit, a potential biomass crop. Grassland Sci. 57: 231–237.

Van Esbroeck GA, Hussey MA, Sanderson MA. 2003. Variation between Alamo and Cave-In-Rock switchgrass in response to photoperiod extension. Crop Sci. 43: 639-643.

Venturi P, Monti A, Elbersen HW. Soil tillage and switchgrass (*P. virgatum* L.) establishment. In: Proceedings of the Conference on Energy and Agriculture Towards the Third Millennium, Athens, June 2–5, 1999; 76-84.

Vogel, KP. Improving warm-season forage grasses using selection, breeding, and biotechnology. In: Anderson BE, Moore KJ, editors. Native Warm-Season Grasses: Research Trends and Issues, Madison, WI: CSSA. 2000; 83-106.

Vogel KP, Masters RA. 2001. Frequency grid–a simple tool for measuring grassland establishment. J. Range Manage. 54: 653-655.

Vogel KP, Brejda JJ, Walters DT, Buxton DR. 2002. Switchgrass biomass production in the Midwest USA. Agron. J. 94: 413-420.

Waramit N, Moore KJ, Heggenstaller AH. 2011. Composition of native warm-season grasses for bioenergy production in response to nitrogen fertilization rate and harvest date. Agron. J. 103: 655-662.

West DR, Kincer DR. 2011. Yield of switchgrass as affected by seeding rates and dates. Biomass Bioenerg. 35:4057–4059.

Weston, LA. 1990. Cover crop and herbicide influence on row crop seedling establishment in no-tillage culture. Weed Sci. 38:166–171.

White, L. 1973. Carbohydrate reserves of grasses: A review. J. Range Manag 26:13-18.

Wilson DM, Dalluge LD, Rover M, Heaton EA, Brown RC. 2013. Crop management impacts biofuel quality: influence of switchgrass harvest time on yield, nitrogen and ash of fast pyrolysis products. Bioresour Technol. 6: 103-113.

Wolf DD, Parrish DJ, Daniels WL, McKenna JR. 1989. Notill establishment of perennial, warm season grasses for biomass production. Biomass. 20: 209-217.

Wullschleger SD, Davis EB, Borsuk ME, Gunderson CA, Lynd LR. 2010. Biomass production in switchgrass across the United States: database description and determinants of yield. Agron. J. 102: 1158-1168.

Yang J, Worley E, Wang M, Lahner B, Salt DE, Saha M, Udvardi M. 2009. Natural variation for nutrient use and remobilization efficiencies in switchgrass. Bioenergy Res. 2: 257-266.

Yenish JP, Worsham AD, York AC. 1996. Cover crops for herbicide replacement in no-tillage corn (*Zea mays*). Weed Technol. 10:815–821.

Zarnstorff ME, Keys RD, Chamblee DS. 1994. Growth regulator and seed storage effects on switchgrass germination. Agron. J. 86: 667-672.

Zegada-Lizarazu W, Wullschleger SD, Nair SS, Monti A. Crop physiology. Monti A, editor. Switchgrass a valuable biomass crop for energy. Springer-Verlag: London. 2012; 55-86.

Zhang JH, Maun MA. 1991. Effects of partial removal of seed reserves on some aspects of seedling ecology of 7 dune species. Can. J. Botany. 69: 1457-1462.