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Planting and Managing Giant Miscanthus as a Biomass Energy Crop

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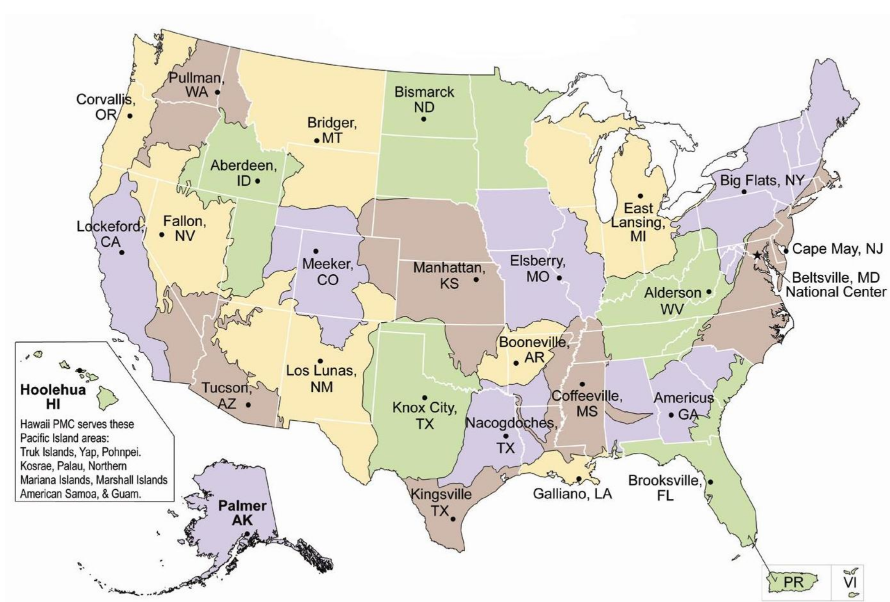
Cover photo: Giant miscanthus growing in research plots at the NRCS Elsberry, Missouri, Plant Materials Center

Preface

The U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Plant Materials Program has been involved in the collection, evaluation, selection, increase, and release of conservation plants for more than 75 years. Recent attention to use plants for energy production has prompted the private sector to look towards high-yielding crops that are economically viable in the emerging bioenergy industry. Giant miscanthus (*Miscanthus* x *giganteus*) is one such perennial grass that holds potential to meet biomass production criteria. Giant miscanthus is a relatively new crop to the United States and has been studied by the USDA NRCS Plant Materials Centers and Agricultural Research Service for the past 4 years. This technical note summarizes much of the available information related to growing giant miscanthus as an energy crop and relies on published data as well as direct experience by USDA researchers and cooperators. For planners and practitioners who are first learning about giant miscanthus, the summary at the end of this document provides basic information about giant miscanthus as well as important criteria for conservation planning purposes.

This publication was prepared to provide information needed by conservationists, producers, or consultants to establish and manage giant miscanthus as a biomass crop for energy production. For additional information on establishment and management of giant miscanthus, see the references section at the back of this publication. For specific information on cultural specifications and soils and climate requirements, consult the NRCS Field Office Technical Guide (FOTG) at http://www.nrcs.usda.gov/technical/eFOTG/, or contact the nearest Plant Materials Center or plant materials specialist (http://plant-materials.nrcs.usda.gov/contact/) and/or the Land Grant Universities that serves the State. Also, see technical resources on the National Plant Materials Program Web site at http://www.plant-materials.nrcs.usda.gov/.

Location and service areas of Plant Materials Centers



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Acknowledgments

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Planting and Managing Giant Miscanthus as a Biomass Energy Crop

Summary and planning considerations

Giant miscanthus is a sterile hybrid, warm-season grass that is native to Asia. It can produce large amounts of biomass, even in more northerly latitudes, due to the ability to grow at cool temperatures. Some of the key characteristics and considerations for using giant miscanthus include:

- Like switchgrass, giant miscanthus is very efficient in the use of soil nutrients because most of the nutrients used to produce stems and leaves are recycled back down to the plant's rhizome system for use in subsequent crops.
- Giant miscanthus sequesters significant amounts of carbon in the rhizome system, and soil organic matter has been shown to increase under giant miscanthus stands.
- Giant miscanthus yields are strongly influenced by water availability. It is best suited to locations receiving at least 30 inches per year of annual rainfall. The high water use of giant miscanthus could potentially reduce groundwater availability if a large number of acres are planted in a single geographic area.
- Yields as high as 15 tons dry matter per acre have been produced, but average yields under natural rainfall are expected to range between 10 and 12 tons dry matter per acre.
- At this time, the NRCS recommends planting only sterile giant miscanthus lines propagated from rhizomes or plugs to reduce the potential of spread. Currently available cultivars and lines do not produce viable seed and, as such, are thought to pose limited potential for becoming invasive. The use of vegetative propagules makes giant miscanthus more expensive to establish than seed-propagated perennials, such as switchgrass.
- Because of a lack of experience with giant miscanthus production in the United States, current recommendations are to establish a setback (buffer area) around giant miscanthus production fields for monitoring spread. A minimum of 25 feet of border is recommended around a giant miscanthus stand to allow for monitoring and management of any giant miscanthus spread. No setback is required when the giant miscanthus planting is adjacent to cropland or actively managed pasture with the same operator.
- Planning for the establishment of giant miscanthus should begin at least 1 year prior to the planting. If there are any concentrated flow areas that are eroding, grassed waterways or similar structures with a 25-year storm event design criteria should be installed before planting the rhizomes. Additionally, if sheet and rill erosion is a concern, practices such as terraces or diversions may be needed to reduce offsite movement of rhizomes. Any earthmoving activity after the planting of the rhizomes creates a strong risk of spreading the rhizomes outside the planned area.
- The plant is very sensitive to competition from weeds during the establishment season, and poor plant survival or stand failure will be likely if weeds are not adequately controlled. Planning for weed control should begin the year before establishment and include burn down, preplant, and postemergence herbicide applications in combination with tillage. Dense stands require little or no weed control after the establishment year.
- Giant miscanthus has been shown to serve as a host plant for corn rootworm and other insect pests of commercial crops. The effects newly planted acres of giant miscanthus will have on pest dynamics are unknown, and plantings should be monitored for pests both within the giant miscanthus and in surrounding cropland.
- Newly planted giant miscanthus stands are considered to have a neutral affect on wildlife, but wildlife and insect diversity in mature stands have been found to be lower than field borders. Concurrent establishment of conservation practices such as field borders and other forms of habitat management around giant miscanthus plantings are recommended to diminish the deleterious effects of mature giant miscanthus stands on wildlife.

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Planting and Managing Giant Miscanthus as a Biomass Energy Crop

Introduction

Important goals of the 2007 Energy Independence and Security Act include:

- reducing carbon dioxide (CO_2) emissions by increasing bioenergy from cofiring 20 percent nationally, and
- producing 36 billion gallons of transportation fuel from renewable sources by 2022 (U.S. Dept. Energy 2010).

To achieve these goals, the projected 130 million dry tons of biomass that will be available in 2012 will need to almost double by 2017, to 250 million dry tons (U.S. Department of Energy 2010). These renewable resources will include wood chips and timber harvest waste, agricultural residues (e.g., corn stalks, cereal straw, etc.), and dedicated energy crops, predominantly perennial grasses (Milliken et al. 2007). Heaton et al. (2004) stated that the ideal dedicated biomass crop is a perennial that efficiently uses available resources, stores carbon in the soil, is an efficient user of water, has low fertilizer requirement, and is not invasive. Giant miscanthus (*Miscanthus* x *giganteus*) possesses many, if not all, of these characteristics.

Giant miscanthus

Plant genetics

The genus miscanthus is comprised of 11 to 12 species of tall, C_4 grasses (Clifton-Brown, Chiang, and Hodkinson 2008) that are native to Southeast Asia, China, Japan, Polynesia, and Africa (Lewandowski et al. 2000; Scally, Hodkinson, and Jones 2001). The genus miscanthus is so closely related to *Saccharum* (sugarcane) that it belongs to the *Saccharum* complex, a group of five genera that can produce fertile F_1 offspring (Mukherjee 1957). Several miscanthus species have been crossed with sugarcane to increase tillering, ratooning ability, disease resistance, and cold tolerance (Tai and Miller 1988). More recent breeding work has focused on *Saccharum* sp. x *Miscanthus* sp. F_1 hybrids for dry matter production for biomass (Burner et al. 2009).

The first plant of what is now known as giant miscanthus was collected in 1935 in Yokahama, Japan, and introduced vegetatively to Denmark for horticultural use (Anderson et al. 2011). This single introduction spread across Europe and into North America (Anderson et al. 2011).

Although at one time considered a separate species, giant miscanthus is now recognized as a naturally occurring hybrid between *M. sinensis* and *M. sacchariflorus* (Lewandowski et al. 2000; Scally, Hodkinson, and Jones 2001; Linde-Laursen 1993). *Miscanthus* x *giganteus* has been placed in its own taxonomic classification due to growth and developmental characteristics not found in other miscanthus species (Scally, Hodkinson, and Jones 2001).

Because *M. sinensis* is a diploid species (2n=2x=38) and *M. sacchariflorus* is a tetraploid species (2n=4x=76), giant miscanthus is a triploid (2n=3x=57) hybrid that produces seed that is sterile (Lewandowski et al. 2000; Scally, Hodkinson, and Jones 2001; Linde-Laursen 1993). Not surprisingly, genetic studies (Hodkinson, Chase, and Renvoize 2002; Greef et al. 1997) have shown that the giant miscanthus lines present in Europe and North America prior to 1983 are genetically very similar. Although natural hybridization is rare in the wild due to different flowering times, ongoing breeding programs in Europe and the United States have developed new lines of giant miscanthus with more cold tolerance and higher dry matter yield (Allen 2008; Clifton-Brown, Chiang, and Hodkinson 2008; Drapala 2010).

C_4 – photosynthetic pathway typical for warm-season grasses

F_1—first cross hybrid

Diploid—having two sets of chromosomes

Triploid—having three sets of chromosomes which causes sterility due to uneven number

Tetraploid—having four sets of chromosome

Growth and development

Unique for many C_4 grasses, giant miscanthus can maintain normal levels of photosynthetic activity down to 57 degrees Fahrenheit (Naidu and Long 2004). In comparison, the photosynthetic activity of corn (*Zea mays*), another C_4 grass, is reduced by 90 percent at the same temperature (Naidu and Long 2004). This accounts for the very high biomass production of giant miscanthus, even as far north as 52 degrees latitude in Europe, where the growing season is too short to produce a mature corn grain crop (Beale and Long 1995). Even in the Midwestern United States, considered a prime corn growing region, giant miscanthus was found to produce 61 percent more biomass than corn (total of stalks, cobs, and grain) (Dohleman and Long 2009). The higher biomass production of giant miscanthus in the Midwest is due, in part, to earlier canopy closure and later fall growth than corn (Dohleman and Long 2009). Midwestern work (Heaton, Dohleman, and Long 2008) also has shown that giant miscanthus is as productive, if not more productive, than the cold-tolerant, native C_4 grass, switchgrass (*Panicum virgatum*). Radiation-use efficiency studies have found that switchgrass is more efficient than giant miscanthus, which means the higher productivity of giant miscanthus compared to switchgrass in the Midwest is also due to longer growing season (Kiniry et al. 2011).

Typical of perennial grasses, giant miscanthus productivity increases as the stand matures, usually until about the third year (Clifton-Brown and Lewandowski 2000b; Clifton-Brown et al. 2001). For established stands (>3 yr old), European experience shows that shoot growth starts when air temperatures exceed 50 degrees Fahrenheit (Bullard and Nixon 1999). In the Midwest, this typically means sprouts start from underground buds on the rhizomes in April (fig. 1) and plants are about 6 feet tall by late May or early June (Pyter et al. 2007). Canopy closure occurs at about the same time (Dohleman and Long 2009; Heaton, Dohleman, and Long 2008), which essentially negates the need for weed control in established stands (Dohleman et al. 2009).

Plants can reach 12 to 13 feet tall (Heaton, Dohleman, and Long 2008); while the roots can extend to a depth of more than 8 feet (Neukirchen et al. 1999). This root depth is comparable to perennial crops such as alfalfa (*Medicago sativa*) and switchgrass, but greater than annual crops such as corn (Russelle 2003). Due to death of part of the root system each year, giant miscanthus root systems begin a regeneration phase each year in the spring and root mass is maximum about 30 days after flowering (Neukirchen et al. 1999). Root dry weight of giant miscanthus is about half that of the aboveground dry matter production (Neukirchen et al. 1999). Since rhizome dry weight (Himken, Lammel, and Neukirchen 1997) is similar to root dry weight, total belowground dry weight of giant miscanthus is about equal to the plant's aboveground dry weight. In the Midwest, maximum aboveground biomass is reached in August, with flowering starting in mid-September (Anderson et al. 2011). Lower leaves start senescing after full light interception is reached around July (Bullard and Nixon 1999), but plants are not fully senescent until after killing frost (September–October in Illinois).

Similar to switchgrass, giant miscanthus translocates most of the nitrogen, phosphorous, potassium, and other minerals in the aboveground biomass to the rhizomes and root system by late fall (Heaton, Long, and Dohleman 2009; Beale and Long 1997), but movement of nitrogen to belowground structures continues even after frost (Lewandowski and Heinz 2003; Long and Beale 2001). Even though substantial amounts of biomass are removed each year at harvest, this movement of nutrients into the rhizomes and root system accounts for the ability of the plant to sustain growth year after year with little supplemental fertilizer input (Beale and Long 1997; Beale, Morrison, and Long 1999). Additionally, lower mineral content in the biomass after the plant senesces improves the quality of the feedstock for cofiring or conversion to biofuel (Heaton and Dohleman 2009; Heaton et al. 2011).

Figure 1 Newly emerging giant miscanthus sprout in the spring

Photo: USDA NRCS, Elsberry, MO

Biomass production and stand longevity

Because using giant miscanthus as a biofuel crop is a relatively new idea in the United States, the majority of the yield reports come from Europe. In those, harvestable yields (yield of harvests made during the winter or after the stand is dormant) of mature stands have ranged from 9,000 pounds per acre in northern Europe to 35,000 pounds per acre in southern Europe (Lewandowski et al. 2000). The oldest giant miscanthus biomass study in the United States was started in 2002 in Illinois (Heaton, Dohleman, and Long 2008). Established stand harvestable yields from that study have been similar to those found in Europe and more than three times higher than switchgrass planted at the same location (table 1). Table 1 also shows first and/or second growing season harvestable yields for giant miscanthus and switchgrass studies in Kansas, Missouri, and Arkansas, as well as second season yield for giant miscanthus from an ongoing Florida study.

The longevity of giant miscanthus stands managed for biomass production is not clearly known. The oldest biomass planting of giant miscanthus in Europe is 25 years (Lewandowski et al. 2003). One European study reported on 14 years of biomass harvests that averaged 11,000 pounds per acre (Christian, Riche, and Yates 2008). The oldest planting in the United States is 7 years old (Heaton, Dohleman, and Long 2008). Based on this information, productive life span in the United States is estimated to be between 15 and 20 years (Heaton et al. 2011).

Environmental issues

Soil organic carbon

To be sustainable, biomass crops should have the ability to sequester carbon in the soil to maintain or improve soil fertility. Aboveground biomass residues, rhizomes, and roots all affect soil organic carbon (SOC) associated with giant miscanthus plantings (Beuch, Boelcke, and Belau 2000). European studies have found that preharvest losses (e.g., senescent leaves and shoot tops) and harvest residues produce about 2,500 pounds carbon per acre annually (Beuch, Boelcke, and Belau 2000), while long-term (between 4–8 yr) carbon storage from the roots and rhizomes accounts for approximately 8,000 pounds carbon per acre (Beuch, Boelcke, and Belau 2000; Clifton-Brown, Breuer, and Jones 2007). Studies have shown that between 75 to 85 percent of the SOC in the upper 12 inches of the soil profile is derived from giant mis-

Table 1 Harvestable yield (yield obtained during the winter or when plants were dormant) for giant miscanthus or giant miscanthus compared to switchgrass at different locations in the United States

	Giant miscanthus	Switchgrass	Giant miscanthus		Switchgrass	
	Harvestable yield (lb dry weight/acre)					
Location	3-yr average	3-yr average	Season 1	Season 2	Season 1	Season 2
Shabbona, IL (41.85 N) 1/	18,000	7,000				
Urbana, IL (40.12 N) 1/	30,000	11,000				
Simpson, IL (37.45 N) 1/	31,000	6,000				
Troy/ Manhattan, KS (39 N) 2/			3,000	11,400	3,600	8,200
Elsberry, MO (39.17 N) 3/				23,000		13,000
Booneville, AR (35.08 N) 4/			2,200	5,300	4,400	10,600
Gainesville, FL (29.67 N) 5/				5,500		
Ona, FL (27.43N) 5/				4,500		
Belle Glade, FL (26.68 N) 5/				9,600		

1/ Heaton, Dohleman, and Long 2008
2/ Propheter et al. 2010
3/ J. Douglas, unpublished data, 2011
4/ Adapted from Burner et al. 2009
5/ Sollenberger et al. 2010

canthus, which is similar to what has been reported for corn (Schneckenberger and Kuzyakov 2007). Also similar to corn, SOC decreased with increasing depth under giant miscanthus stands (Schneckenberger and Kuzyakov 2007). But unlike corn, which had no detectable corn-derived SOC below 24 inches, giant miscanthus-derived SOC was found to a depth of 40 inches (Schneckenberger and Kuzyakov 2007), probably a result of greater rooting depth of giant miscanthus (Neukirchen et al. 1999; Russelle 2003). This makes the SOC profile under giant miscanthus, in both amount and distribution, more similar to naturally occurring perennial grasslands than annual row crops (Schneckenberger and Kuzyakov 2007).

Water quality and use

Studies in England have shown that when grassland was converted to a giant miscanthus planting, nitrate-N in the drainage water from plots, even those receiving no nitrogen fertilizer, exceeded European drinking water limits (11.3 ppm) by almost three times the first year after planting (Christian and Riche 1998). The authors attributed this to high nitrogen mineralization rates and relatively low plant growth the first year (Christian and Riche 1998). This effect was short lived because in subsequent years, nitrate-N levels in drainage water from fertilized and unfertilized treatments were well below drinking water limits (Christian and Riche 1998). Other studies with giant miscanthus planted on previously cultivated ground have shown nitrate-N levels well below the drinking water limit even with 160 pounds nitrogen per acre fertilization (Curley, O'Flynn, and McDonnell 2009). These studies indicate that giant miscanthus production would have a neutral or beneficial impact on groundwater quality (Christian and Riche 1998; Curley, O'Flynn, and McDonnell 2009).

Due to higher biomass production, greater leaf area index, and longer vegetative growing season, giant miscanthus requires more water during the growing season than switchgrass or corn (Lewandowski et al. 2003; McIsacc, David, and Mitchell 2010). Consequently, water availability strongly influences giant miscanthus yields, and the crop is thought to be best suited to locations that receive at least 30 inches per year (Heaton et al. 2011). In a study comparing biomass production and biofuel yield in the Texas Rolling Red Plains (annual rainfall of 25 inches per year), giant miscanthus had marginal persistence and low yields (500 lb/acre) compared to 6,000 pounds per acre for 'Alamo' switchgrass (J. Douglas, unpublished data, 2011).

In contrast to giant miscanthus, switchgrass yields are most strongly influenced by nitrogen availability (Heaton, Voigt, and Long 2004). This means that in areas like the Midwest where rainfall is generally adequate, but water quality (e.g., high nitrates) is an issue, giant miscanthus would be a better choice for producers than switchgrass. In drier areas of the country, where water is limiting, but groundwater quality is not an issue, adequately fertilized (i.e., 50–100 lb nitrogen) switchgrass may produce higher amounts of biomass (Heaton, Voigt, and Long 2004).

Even in the well-watered Midwest, giant miscanthus production could potentially cause long-term changes in the hydrologic cycle. Models suggest that if 100 percent of the current Midwest land cover was converted to giant miscanthus, evapotransporation could increase in excess of 8 inches per year and drainage could decrease between 2 and 10 inches per year (Vanloocke, Bernachii, and Twines 2010). Midwestern field data indicates that wherever giant miscanthus increased evapotranspiration by 5.5 inches, drainage (primarily stream flow) would be reduced by 32 percent (McIsacc, David, and Mitchell 2010). Although 100 percent conversion of current land cover is considered unrealistic, localized 'hot spots' could be an issue if giant miscanthus land cover were to exceed 25 percent in counties surrounding biorefineries or power stations (Vanloocke, Bernachii, and Twines 2010).

Impacts on wildlife

It is well understood that monoculture plantings of any agricultural commodity can cause shifts in the abundance and diversity of wildlife populations compared to native vegetation. Relatively little is known about the comparative conservation cost or benefits of the different biofuel crops (Fargioni 2010; Landis and Werling 2010).

One study in England looked at the numbers and kinds of ground beetles (*Carabidae*), butterflies (*Lepidoptera*), and other flying insects following giant miscanthus rhizome harvest (Semere and Slater 2007b). At that time, ground beetles were as abundant in the giant miscanthus stand as the field margins, but butterfly numbers and other flying insect numbers were less. Another English study looked at insects as a potential food source for birds and found that winter insect communities were similar for young (<5-yr-old) giant miscanthus plantings and winter wheat (*Triticum aestivum)*, but winter wheat had significantly more insects present than giant miscanthus in the spring (Bellamy et al. 2009). These studies suggest that relatively young giant miscanthus stands that have fairly open canopy with a weedy understory would support some, but not all, of the insects in the surrounding landscape.

Work in England also showed that younger age or rhizome donor stands of giant miscanthus had higher bird numbers (both breeding and overwintering species) than reed canarygrass (*Phalaris arundinacea*), a cool-season grass proposed as a biomass candidate (Semere and Slater 2007a). The authors attributed the greater bird numbers in the giant miscanthus planting to more bare ground and more diverse ground vegetation (weeds) in the giant miscanthus than the reed canarygrass. Ground mammal numbers did not differ between the two biomass plants, but both biomass plants had lower numbers of birds and small mammals than their associated field margins.

Greater species diversity and numbers of breeding and wintering birds also were noted in another English study comparing giant miscanthus to wheat. Again, the authors attributed this to more open spaces and weedy understory of the less than 5-year-old giant miscanthus compared to the annual wheat (Bellamy et al. 2009).

A third study in England looking at bird populations compared giant miscanthus to willow (*Salix* sp.) grown as a short-rotation crop for biomass, traditional arable crops, and grassland. Giant miscanthus, the surrounding arable ground, and grasslands were found to have relatively similar species numbers and diversity of birds at the start of the growing season in May, but both numbers and diversity in giant miscanthus declined in July, when the plants were more than 6 feet tall. The short-rotation willow planting always had greater diversity and species numbers than giant miscanthus (Sage et al. 2010).

The general conclusion of all of these studies was that young (<5 yr. old) giant miscanthus stands, due to their more open nature and greater ground cover diversity, would not negatively impact bird or mammal populations (Semere and Slater 2007a; Bellamy et al. 2009; Sage et al. 2010). However, it was also concluded that mature giant miscanthus stands had lower bird and mammal numbers. There also is some concern that mature giant miscanthus stands may actually serve as a breeding trap for ground-nesting birds by providing suitable nesting sites in the spring, only to become rapidly impenetrable and causing nest abandonment (Anderson, Haskins, and Nelson 2004). Proactive management plans, such as wide field borders, unplanted patches in the fields, and targeted plantings for pollinators, will probably need to be developed for giant miscanthus plantations to minimize potential negative effects as the stands mature (Bellamy et al. 2009; Sage et al. 2010).

Diseases, insects, and weeds

In Europe, giant miscanthus plantations have proved to be relatively free of insect pests or diseases (Lewandowski et al. 2000). It is recognized that increased cultivation of any biomass crop is likely to change predator-prey relationships, insect-vectored diseases, etc. (Landis and Werling 2010), and issues will probably develop for giant miscanthus itself and associated crop plants.

For example, several aphids reported in the United States on giant miscanthus are pests themselves of sugarcane and corn (Bradshaw et al. 2010). The aphid, *Sipha flava*, was collected in four States with some populations found to be high enough to cause leaf death in giant miscanthus. Additionally, giant miscanthus and switchgrass are known to be hosts for barley yellow dwarf viruses (BYDV), which are vectored by grass-feeding aphids (Huggett, Leather, and Walters 1999; Bradshaw et al. 2010). Concern has been expressed about grass biomass crops serving as a reservoir for BYDV and what affect increased reservoirs of the disease will have on small grain production (Landis and Werling 2010).

Similar concerns are expressed for western corn rootworm (WCR; *Diabrotica virgifera virgifera*), the most significant pest of corn in the United States. Laboratory studies have shown that WCR can complete its lifecycle on giant miscanthus, and field studies have shown that WCR can lay eggs around the giant miscanthus (Spencer and Raghu 2009). Whether this will be a problem for corn producers is not known at this time. It will depend on whether giant miscanthus acts as a refuge (good) for resistance management or a reservoir (bad) for enhancing pest pressure on the corn crop (Spencer and Raghu 2009).

The only widely recognized pest issue with giant miscanthus is the susceptibility of establishing plants to weed competition (Lewandowski et al. 2000; Christian and Haase 2001). Field trials in Illinois (Anderson, et al. 2010) showed a greater than 40 percent reduction in dry weight and number of shoots per plant for nonweeded check compared to hand-weeded plots 3.5 months after planting.

Invasiveness

Many traits, including highly efficient nutrient and water utilization, quick establishment, and reallocation of nutrients belowground when senesced, that make some perennial grasses good biomass candidates also make them potentially highly invasive species (Raghu et al. 2006). To understand the potential impact of biomass plants, weed risk assessment (WRA) protocols that look at biology, performance of related species, climatic requirements, history, etc., have been used as a preintroduction method of screening of biomass candidates for weediness (Barney and DiTomaso 2008; Fox 2007).

In one study, switchgrass received a WRA score that indicated it should not be introduced as a biofuel candidate into California, a State outside its native range. This was due to high seed production, rapid growth rate, broad environmental tolerance, possible contamination of planting and harvesting equipment, and the strong possibility of seed dispersal during feedstock movement to energy conversion facilities (Barney and DiTomaso 2008).

The authors cautioned that lack of viable seed did not negate the risk associated with a potential biomass crop (Barney and DiTomaso 2008). Giant reed (*Arundo donax*), which does not produce viable seed in North America (Johnson, Dudley, and Burns 2006), was identified in this assessment and others as a potential invasive risk due to difficulty to control once established, known vegetative spread downstream, and weedy character in other regions of the world (Barney and DiTomaso 2008).

Using the same WRA (Barney and DiTomaso 2008), giant miscanthus was rated as not invasive, in spite of the fact that *M. sinensis*, one of its parents, is recognized as an invasive species in 13 States (http://www.invasiveplantatlas.org/subject.html?sub=3052). The authors attribute the noninvasive rating, in part, to three decades of field research in Europe that failed to produce a single report of escape (Lewandowski et al. 2000). For giant miscanthus, slow natural spread in Europe is thought to be due to lack of viable seed production and relatively slow spread by rhizomes (<4 in/yr; Jørgensen 2011). The conventional assumption of slow rate of spread should be viewed with caution since preliminary studies in Illinois have found an average rate of spread of 1.3 feet per year, with occurrences up to 3.9 feet per year (A. Davis, personal communication, 2011).

Although much of the current breeding work to develop new giant miscanthus hybrids is directed to maintaining sterility (Jørgensen 2011), permanent sterility of interspecific hybrids is not given (Ainouche et al. 2009; Ramsey and Schemske 1998). Spontaneous genome duplication of triploid hybrids that result in viable seed producing polyploid plants is not uncommon in nature. For example, Townsend's cordgrass (*Spartina* x *townsendii*) is a sterile hybrid that developed in England after the accidental introduction of smooth cordgrass (*S. alterniflora*) from North America in the late 1800s. Fertile plants were noted in Townsend's cordgrass stands after a couple of decades (Ainouche, et al. 2009). These fertile plants were recognized as a new species in 1968 (Barkworth 2004) and named English cordgrass (*S. anglica*). English cordgrass appears to have arisen by spontaneous doubling of the chromosome number of *Spartina* x *townsendii* (Marchan 1963). English cordgrass is considered to be an invasive species success story with a recognized worldwide range (Ainouche et al. 2009).

If such a spontaneous or deliberate (see Cultivars and lines) doubling of chromosome numbers were to occur with a giant miscanthus line, viable seed and its movement in the environment would be a concern. One study in the United States found that plants of certain lines of *M. sinensis* could produce almost 2,000 seed per plant with as high as 80 percent germination in USDA hardiness zone 4 (Meyer and Tchida 1999). Another study reported that although the majority of *M. sinensis* and *M.* x *giganteus caryopsis* (seed) fell within 150 feet of the parent plant, a small percentage was found 1,000 feet away (Quinn et al. 2011). Combined, these studies suggest should viable giant miscanthus seed be produced, dispersal distances of up to 1,000 feet from existing populations could be produced throughout the Midwestern and North Atlantic States. As with switchgrass, if viable seed becomes a reality, seed movement by harvesting equipment or during transportation to biorefineries also becomes an issue.

Although giant miscanthus is not on any Federal or State legally defined noxious weed list, the potential exists. Management plans (Caslin, Finnan, and McCracken 2010) need to be developed for each biomass planting of giant miscanthus that considers potential for vegetative (and seed) dispersal (see Establishing stands to prevent unintentional spread, and, preventing unintentional spread in established stands). These should include best management practices (BMPs) that ensure containment of rhizome and stem pieces during transport to and from production fields, containment procedures for field margins (e.g., appropriately timed tillage, herbicide, etc.), and minimum required setback or buffer distance from sensitive natural areas and from natural channels for dispersal such as rivers and streams (Quinn, Allen, and Stewart 2010). Any needed earthmoving activities (i.e., activities outside of normal crop tillage such as installation of diversions or terraces) in the field proposed for planting should be completed the year prior to planting the giant miscanthus. To ensure the structures will exceed the life expectancy of the planting, water or erosion control structures need to meet a 25-year storm event design criteria. Earthmoving after planting presents a high risk of the rhizomes moving offsite and creating an invasive situation. Additionally, site restoration responsibilities and procedures need to be clearly delineated for use when a planting is to be decommissioned or abandoned.

Until more experience is gained with giant miscanthus plantings, regional plans need to be developed to specify active monitoring protocols for first generation biomass plantings and include plant identification and eradication procedures. These should be revisited and revised as necessary when new hybrids or cultivars are introduced (Quinn, Allen, and Stewart 2010).

Planting and management

Suitable sites for production

Soils—Giant miscanthus is adapted to a wide range of soils, from sands to those with high organic matter (Caslin, Finnan, and McCracken 2010). Although, the best production can be expected from sites that have well-drained soils with medium to high fertility (Heaton et al. 2011) and pH between 5.5 to 7.5 (Caslin, Finnan, and McCracken 2010). Growth has been poor on soil with pH greater than 8 (Caslin 2010). This means giant miscanthus will produce the highest yields with the lowest inputs on USDA NRCS capability class I to II lands (http://www.nrcs.usda.gov/about/history/articles/landclassification.html). Acceptable yields can be expected from more marginal land as long as crop growth requirements are met and appropriate Conservation Practice Standards (CPS) (e.g., Contour Farming, CPS Code 330; Filter Strip, CPS Code 393; and Terrace, CPS Code 600) to prevent soil erosion are implemented.

Equipment considerations—Crop requirements for field preparation, planting, and harvesting equipment also should be considered when selecting fields for planting. Since in most cases giant miscanthus biomass will be harvested during the winter or early spring, sites with wintertime high water tables should be avoided if harvesting equipment access is questionable (Caslin, Finnan, and McCracken 2010). Refer to section II in the local Field Office Technical Guide (FOTG) (http://www.nrcs.usda.gov/technical/efotg/) for specific information on suitable field agronomic characteristics.

Additional factors to consider—In addition to agronomic considerations for site selection, impacts to wildlife and surrounding natural communities also should be considered when selecting sites.

- Avoid sites without suitable setback or buffer area to minimize potential impact to sensitive natural areas (Caslin, Finnan, and McCracken 2010) (see Establishing stands to prevent unintentional spread).
- Considerations should be given to avoid locating giant miscanthus production fields in floodplains due to the risk of rhizomes or viable stem pieces breaking off during storm events and establishing elsewhere.
- Select sites that will allow for unplanted areas in the field and pollinator plantings on the edges to reduce potential impact to wildlife (see Impacts on wildlife).
- Senesced giant miscanthus poses considerable fire risk (Jørgenson 2011). The energy potential of giant miscanthus is similar to switchgrass on a unit basis (Librenti, Ceotto, and Di Candilo 2010). However, the additional total biomass in a giant miscanthus field may burn more intensely than a field of switchgrass. Adequate field borders will help minimize the risk of accidental fires escaping to adjacent fields or wild land areas. A 30- to 100-foot firebreak is recommended as a defensible space near structures, utilities, etc. The width is dependent on region of the country and local recommendations.

Also, sites need to meet all local, State, or Federal requirements for biomass plantings. For example, Florida law specifies installation of berms, water traps, or minimum fallow areas for biomass plantings (unless the species is deemed noninvasive) adjacent to waterways to prevent spread (Florida Admin. Weekly & Florida Admin. Code 2008). If no such regulations exist locally, see Establishing stands to prevent unintentional spread for minimal procedures and activities recommended to prevent unintentional spread.

Field preparation

As with switchgrass (Douglas et al. 2009), field preparation is important to ensure successful stand establishment. The exact steps required will depend on previous production history of the site.

Establishment fertilization—A soil test should be taken about a year prior to planting to determine the pH and nutrient levels at the site. If necessary, adjust pH to between 6 to 8 (Heaton et al. 2011). If pH needs to be adjusted, liming material needs to be applied and incorporated at least 6 months prior to planting. In contrast, any fertilizer applications should be made shortly before or after the crop is planted.

Whether starter fertilizer is needed at planting has not been determined for all planting situations in the United States. The nutrient requirements of giant miscanthus are lower than for annual row crops due to effective internal cycling of nutrients from aboveground material to the roots and rhizomes as it goes dormant. Nutrient levels in excess of plant requirements will simply promote weed growth. European production guides do not recommend any fertilization the first 2 years. This recommendation is based on field studies that have shown that, for most sites, soil nutrients will be adequate for giant miscanthus growth (Caslin, Finnan, and McCracken 2010).

Since most States lack soil test response curves for giant miscanthus, one option is to follow extension recommendations for low productivity perennial forage grass stands. If the soil test results show nutrient levels are adequate for grass establishment, producers do not need to add additional nutrients at planting. Alternately, producers could follow current Midwestern recommendations (Heaton et al. 2011), which call for adjusting the fertility of the site to within the following ranges:

- nitrogen—5 to 9 lb/ton dry matter removed
- phosphorus—1.5 lb/ton dry matter removed
- potassium—5 to 9 lb/ton dry matter removed

Preparation for previously cropped sites—One usual advantage to planting giant miscanthus on sites with a history of row crop production is that little if any site preparation tillage will be necessary. Another advantage to planting giant miscanthus on cropland is that weed pressure may also be lower. With active cropland sites, however, herbicide residuals from previous cropping systems, which would be expected to impact grasses, should be considered when preparing a site. Until tolerances of giant miscanthus are established, additional fallow time or an additional cropping system that will not result in potentially harmful residuals for grasses may be necessary for these sites. Consult herbicide labeling or contact the local extension service with herbicide questions.

If the field has not been cropped in the previous couple of years, more tillage operations and time (as much as two growing seasons) may need to be allowed for site preparation and weed control. Chemical or mechanical fallowing may be necessary to reduce soil weed seed reserves. Another option is growing a crop of glyphosate-tolerant soybean (*Glycine max*), which will allow a producer to use glyphosate over the top to control weeds. A winter cover crop such as small grains, particularly following soybeans, can help prevent soil erosion and suppress cool-season weeds. The cover crop should be chemically burned down prior to planting to avoid excessive crop residue, which may interfere with planting equipment. If spring weeds develop after the cover crop has been killed, a second chemical burn down with glyphosate or preplant application of registered formulations of acetochlor, acetochlor plus atrazine, or other herbicides that have received labeling for biomass production of giant miscanthus may be necessary. The whole field should be finely tilled to at least a depth of 6 inches prior to planting or, when equipment is available, strip tilling only the planting row will reduce weed competition (Heaton et al. 2011).

Preparation for sites currently in pasture—Although the United States experience has been to plant giant miscanthus on row crop ground, more commonly in Europe, giant miscanthus is planted on land that is planted to perennial grass. In that case, an appropriate broad-spectrum herbicide (e.g., glyphosate) is applied to the site to kill the existing grass (Caslin, Finnan, and McCracken 2010). Consult herbicide label or local extension service for appropriate timing of this herbicide application. For some grasses, especially bermudagrass (*Cynodon dactylon*), a follow-up application of herbicide may be necessary to get complete kill. Types and timing of tillage operation required after the grass cover is killed will vary depending on the site. Application of preemergence herbicides registered for biomass production of giant miscanthus, such as acetochlor or acetochlor plus atrazine, may be necessary. The goal should be to have the site finely tilled to a depth of 6 inches prior to planting.

Cultivars and lines

To minimize the possibility of the planting becoming an invasive liability, the NRCS recommends producers use only vegetatively propagated giant miscanthus that has been verified as a triploid sterile hybrid between *M. sinesis* and *M. sacchariflorous*.

At this time, sourcing quality planting material of known genetic background is a problem in the United States. Only limited quantities of giant miscanthus can be imported from Europe due to quarantine issues (Heaton et al. 2011). Thus, producers are realistically limited to the material currently in the United States. Reportedly sterile, giant miscanthus lines or cultivars available in North America (but not necessarily the United States) include the Illinois line (Pyter et al. 2007; New Energy Farms 2011), Freedom™ (Drapala 2010; Heaton et al. 2010; Repreive Renewables 2009), Amuri (Heaton et al. 2010; New Energy Farms 2011), and Nagara (Heaton et al. 2010; New Energy Farms 2011).

Producers should request third-party verification that the giant miscanthus they are receiving has been certified to not produce fertile seed. The local land grant or agricultural university may be able to assist with verifying that the plant material has a triploid chromosome number.

The Illinois line was developed from the landscaping material obtained from the Chicago Botanical Gardens in the 1980s and used as landscaping at the University of Illinois until incorporated in the University's biomass research in 2002 (Pyter, Heaton, and Voigt, 2009). Amuri and Nagara are new *M. sinesis* and *M. sacchariflorous* hybrids specifically developed for biomass (Allen 2008) that have been shown to be more cold tolerant than the Illinois line in Canada (Armitage, Deen, and Betts 2010). Freedom™ is a giant miscanthus cultivar developed at Mississippi State University (fig. 2) for biomass production in the Deep South (Drapala 2010).

The lines or cultivar listed here do not constitute an endorsement by the NRCS. This does not preclude the use of other giant miscanthus material that can be verified as a sterile, triploid hybrid. More vegetatively and seed propagated giant miscanthus hybrids are in the pipeline, but it may be 5 to 10 years before their advantages are known and planting material is widely available. Any future recommendation of the use of seed to establish giant miscanthus will be dependent on additional studies and analysis of the potential spread of that particular cultivar or line.

Until more standardized cultivar testing programs, like the ones currently being done at six locations in Mississippi (B. Baldwin, personal communication, 2011), are initiated for giant miscanthus around the country, producer's choices may be more limited than even the currently available lines. Often they will be restricted to using the planting material specified in their biomass contracts or required by the biofuel refinery or cofiring station purchasing their product.

Planting material

Types—Since giant miscanthus is a sterile hybrid, new stands are established using vegetative material, either rhizomes, rhizome-derived plugs, or micropropagated (tissue culture) transplants (Anderson et al. 2011). Plugs or transplants have advantages over rhizomes in that they can be planted using modified tobacco or vegetable transplanting equipment, and they are actively growing when transplanted (Anderson 2011). A disadvantage, besides cost, is they need to be watered after transplanting (Heaton et al. 2011). No studies have been published yet that compare rhizome-derived plugs to standard rhizome planting, but micropropagated transplants initially had more shoots, and their rhizome system initially was finer than that from rhizome-derived plants (Lewandowski 1998). These differences were found to disappear as the stand aged (Lewandowski 1998).

Rhizome quality—Age of mother plants affects rhizome quality and rhizome quality affects stand establishment (Pyter et al. 2009; Pryter, Dohleman, and Voigt 2010). In one European study, survival was 88 percent with rhizome pieces from 5-year-old plants compared to only 25 percent for rhizomes from 1-year-old plants and 52 percent for rhizomes from 9-year-old plants (Christian, Yates, and Riche 2009). Preliminary work in Mississippi has shown better rhizome quality from 2-year-old plants than from 4-year-old plants (B. Baldwin, personal communication, 2011). These studies indicate that quality of rhizome increases with mother plant age, but only up to a certain point.

For field planting, harvestable rhizomes should weigh about 1.5 to 2 ounces (50 g) and be about 4 to 5 inches long (Pyter et al. 2009). Rhizomes used for greenhouse propagation of plugs (Pyter et al. 2009) can be as small

Figure 2 Plot of Freedom™ growing at Mississippi State University

Photo by Kat Lawrence, MSU Ag. Comm.

as 1 ounce (25 g). Good quality rhizomes pieces can be branched or unbranched pieces, but should appear scaly and buff colored (Pyter et al. 2009) (fig. 3). If used for field plantings, rhizomes should have minimum of two to three buds per rhizome (Caslin, Finnan, and McCracken 2010); in the greenhouse, pieces need to have a minimum of one bud.

Rhizome yield—Age of mother plant also affects rhizome yield. Hand dug, 1-year-old plants were found to produce 7 to 10 harvestable rhizomes, 2-year-old plants produced 25 to 30 harvestable rhizomes, and 3-year-old plants produced 75 to 80 harvestable rhizomes (Pyter et al. 2009). Yield of mechanically dug rhizomes is not as high. The European rule of thumb is that for each acre of 4-year-old miscanthus mother field, one can expect enough rhizomes to plant 8 to 10 acres (Caslin, Finnan, and McCracken 2010).

Digging considerations—Rhizomes can be harvested using a rotovator with a 6- or 8-inch-blade spacing; the 6-inch spacing produces smaller and less clumpy rhizomes. The rhizome pieces can be lifted using a potato harvester or similar type of equipment (Caslin, Finnan, and McCracken 2010). Specialized harvesting/digging equipment that breaks up the rhizomes and lifts them in one operation has been developed in Europe and the United States (table 2).

Figure 3 Healthy, buff-colored rhizomes

Photo: USDA NRCS, Elsberry, MO

If the nursery area is to be replanted or converted to a production field after the rhizomes have been harvested, the field should be rotovated again to rebury the remaining rhizome pieces and rolled to firm the soil. This operation should be done within an hour or two after the lifting operation to prevent the remaining rhizomes that are left on the soil surface from drying out (Caslin, Finnan, and McCracken 2010).

Although rhizomes can be dug anytime in the fall or winter period after the plants have senesced and biomass removed, the most common time for harvesting for field planting is in the spring prior to shoot emergence (Lewandowski 1998). Rhizomes should be used as soon as possible after digging, but they can be stored temporarily if kept cool and moist. This can be accomplished by covering the rhizome heap with moist soil (Caslin, Finnan, and McCracken 2010), but it is critical that the rhizomes not be allowed to dry out (Anderson et al. 2011) or go through a heat. Additionally, care should be taken to not let rhizomes dry out during transport.

Depending on planting method used, the rhizomes also may need to be cleaned and sized. Sizing is particularly critical to ensure rhizomes pieces will feed through the transplanter openings (Heaton et al. 2011; Caslin, Finnan, and McCracken 2010). Follow planter manufacturer's directions or do some test runs to determine what size rhizome pieces can be used.

Fall or winter digging times are preferable when plugs are being produced in the greenhouse. Planting trays with cells that are approximately 1 inch in diameter and 6 or 7 inches deep are recommended (Anderson et al. 2011). A well-draining commercial potting mix or a pasteurized mixture of native soil combined with sand, perlite, peat moss, and/or vermiculate can be used (Pyter et al. 2009). Rhizome pieces should be planted approximately 2 inches deep and kept moist. Providing

Table 2 Dedicated giant miscanthus digging and planting equipment available for United States/Canadian market in 2011

Available from	Web address
WHL	http://www.miscanthusplanter.com/
Spriggers Choice	http://www.spriggerschoice.com/index_files/miscanthuspropergationmachinery.htm
Cool Fin Partnership	http://bioenergyfeedstocks.igb.uiuc.edu/2010/ppt/maxwell.pdf

supplemental light (12 h/d) and using a complete water-soluble or time-released granular fertilizer will promote active growth (Pyter et al. 2009). The goal is to have well-rooted plants in time for field planting (Anderson et al. 2011).

Regardless of the digging time, care should be taken during rhizome transport/planting operation to ensure pieces do not fall off or out of the transport/planting equipment and becomes sites for unintentional spread. See Establishing stands to prevent unintentional spread.

Field planting

Planting dates—Fields can be planted any time after the last frost date, typically May 1 in the Midwest (Heaton et al. 2011). With transplants, later planting dates, up until early June in the Midwest, can be used if soil moisture is adequate (Pyter et al. 2009). Even later planting dates may be practical for both rhizomes and transplants in other areas of the country, particularly the Deep South, giving careful consideration to rainfall patterns if irrigation is not available and the length of the remaining growing season. The longer the growing season the first year, the better the first-year rhizome development and better chances for first-year winter survival (Caslin, Finnan, and McCracken 2010). Additionally, earlier planting dates are less likely to interfere with ground-nesting birds (DEFRA 2007).

Planting depth—Regardless of the type of planting equipment used, giant miscanthus rhizomes should be planted between 2 and 4 inches deep, or if using transplants or plugs, place the root ball below the soil surface (Heaton et al. 2011; Caslin, Finnan, and McCracken 2010).

Planting rate—Plant populations between 4,000 and 16,000 plants per acre have been evaluated. Higher numbers provide earlier canopy closure and weed control, but are more expensive to establish with relatively little improvements in long-term yield (Danalatos, Archontoulis, and Mitsios 2007). The consensus among researchers is that the desired final population should be between 4,000 and 5,000 plants per acre (Heaton et al. 2010). Since large rhizome (1.5–2 oz) survival usually averages 60 to 70 percent (Caslin, Finnan, and McCracken 2010; Pyter et al. 2009), this means 6,000 to 7,000 rhizomes per acre are needed to get the final recommended stand. The higher rate should be used for less optimum conditions (e.g., soils with lower water holding capacity, higher expected weed competition, late planting, etc.). With irrigation, survival should be higher, and lower rates may be practical. Survival of transplants or smaller mechanically harvested rhizomes could be lower, and planting rates may need to be increased as much as 100 percent to ensure adequate stands (Heaton et al. 2010). Until the interaction of planting material propagation, planting equipment, and environment are better understood in the United States, planting rates should remain on the high end of recommendations to minimize the need to replant thin stands.

Row spacing—The current recommendation in the Midwest is to plant using 30-inch rows with 30-inch spacing between plants (Heaton et al. 2011). This is based on two factors. One is the need to use up to 7,000 rhizomes per acre to get the desired final stand density, and the second is that research has shown that actually leaving equal space around each rhizome or plug gives better first season growth. Given variability in the planting equipment available, slight variations in the 30- by 30-inch spacing would be reasonable as long as plant population is maintained. The number of rhizome pieces or plugs needed for different planting arrangements is shown in table 3.

Planting methods—Most research stands of giant miscanthus have been established by hand planting rhizomes as space plants or by dropping rhizomes into furrows that were subsequently covered up (Pyter et al. 2009). Broadcast planting followed by disking in and packing was the earliest mechanical method of planting rhizome pieces, but issues with consistent planting depth and the need for tillage to control weeds prompted the modification and use of standard row planting equipment (Heaton et al. 2011; Caslin, Finnan, and McCracken 2010).

Modified corn drills and potato planters have been used to plant rhizomes (Caslin, Finnan, and McCracken 2010), and vegetable or tobacco planters have been used for transplants or plugs (Anderson et

Table 3 Effect of planting arrangement on the number rhizomes or plugs per acre

Row spacing	Within row spacing	No. rhizomes or plugs/acre
Inches		
30	24	8,700
30	30	7,000
36	24	7,000
36	30	6,000
36	36	5,000

al. 2011). European and American equipment manufacturers have actively been modifying and/or developing planting equipment to plant both rhizome pieces and transplants. Table 2 lists some of the manufactures advertising specialized giant miscanthus planting equipment for the United States or Canadian market in 2011. Due to the cost of the dedicated equipment, many of the manufacturers have rental/lease options or arrangements with rhizome producers that will allow for an essentially turnkey planting operation.

In the case of rhizomes, the field should be rolled after planting to ensure good soil contact and few air spaces (Caslin, Finnan, and McCracken 2010) unless otherwise directed by the planter manufacturer. Irrigation is recommended after planting if transplants or plugs are used (Heaton et al. 2011), and additional applications may be warranted the first growing season. If available, irrigation also may be warranted to speed the establishment (Lewandowski et al. 2000) and, thus, first-year survival of rhizome-planted field.

Establishing stands to prevent unintentional spread

All local, State, or Federal regulations for containment of biomass plantings will be followed. If no such guidance exists, recommended minimum procedures to prevent unintentional spread of giant miscanthus in production or propagation stands include the following:

- Establish or maintain a minimum 25-foot setback or border around a giant miscanthus stand to allow for monitoring and management of any giant miscanthus spread. No setback is required when the giant miscanthus planting is adjacent to cropland or actively managed pasture with the same operator. Setback areas may be planted to an annual row crop, such as corn or soybeans; may be planted to a site-adapted, perennial cool-season or warm-season forage or turf grass; or kept clear by disking, rotovating, or treating with a nonselective burn-down herbicide at least once a year. The method used to manage the setback may be dependent on slope and the potential for erosion.
- Cover or otherwise contain vegetative planting material (rhizomes) during transportation/planting operations when outside the boundary of the designated biomass production field(s).
- Once planting is complete, inspect and remove any residual vegetative planting material from all equipment used to transport/plant.
- Excess live planting material should **not** be disposed of at edges of fields, in field borders, in farm “trash” piles, or in landfills. Any excess planting material can be hand planted in the designated biomass field or should be killed by allowing it to dry out on an impermeable surface for 48 hours or burning. Air-dried planting material or burn residue should be disposed of at a site that:
  - is not immediately adjacent to sensitive natural areas, artificial or natural water bodies, or areas that are subject to flooding
  - has a minimum of 25-foot setback or buffer area around the planting that is managed as outlined for production or propagation stands
  - is indicated on the conservation plan with GPS coordinates
  - is checked at least once a season for any giant miscanthus sprouts, and if sprouts are observed, herbicide or mechanical methods should be used to kill the volunteer plants

Weed control

Weed control during establishment year is critical to the successful establishment of giant miscanthus (Anderson et al. 2010). Weed control should be based on a combination of avoidance, cultivation, and burn down, preplant, and postemergence herbicides (see Field preparation). Roller wipers for tall weeds or broad spectrum burn-down herbicide, such as glyphosate, applied during the winter (controls winter weeds only) when the giant miscanthus is dormant can also be used (Caslin, Finnan, and McCracken 2010). Various mechanical and cultural methods (Anderson et al. 2011) used for weed control have included:

- rotary hoe cultivation between plant rows during first and second years
- cleaning loose soil from rhizomes prior to planting to minimize weed seed transmission
- timing planting to avoid the most problematic weed competition
- minimize weed seed bank by good weed control in years prior to planting giant miscanthus
- not using fertilizer during planting
- harvesting only once a year

Very few herbicide formulations are currently labeled for giant miscanthus biomass production in the United States, but the general assumption is that any herbicide that is safe for corn will also be safe for giant miscanthus (Anderson et al. 2011). Various herbicides and combinations used in Europe have supported this assumption (Lewandowski et al. 2000; Bullard et al. 1995). Field studies in the United States also have shown the efficacy and safety of various pre- and postemergence herbicides (Anderson et al. 2010). Further studies are needed to determine the safety of sequential applications to give the needed season-long control (Anderson et al. 2010) and provide data necessary for labeling of additional products. Certain formulations of acetochlor and acetochlor plus atrazine have received labeling in the United States for use on giant miscanthus biomass plantings, and producers should contact local university weed specialists or extension offices to find out when additional herbicide options will become available.

Initial survival and replanting decisions

Once established, giant miscanthus is very tolerant of freezing temperatures. Stands have survived winter temperatures in Illinois that regularly drop below 0 degrees Fahrenheit (Pyter et al. 2009). In contrast, survival of newly planted stands of lines not specifically selected for cold tolerance have been as low as 50 percent where soil temperatures drop below 28 degrees Fahrenheit in the upper 2 inches (Clifton-Brown et al. 2001; Clifton-Brown and Lewandowski 2000a). If giant miscanthus is planted in areas of the country where winter temperatures can be expected to be cold enough to affect plant survival, leaving first-year biomass production on the field to provide ground cover has been shown to improve winter survival (Heaton et al. 2011).

All newly planted fields should be scouted the spring following planting to assess stand establishment. If the plant population is less than 4,000 plants per acre, weeds will generally continue to be an issue in the second and even third growing season due to the open canopy (DEFRA 2007). Such stands will also usually take more than 3 years to reach maximum production. Replanting may be the best option (see Site restoration for recommendations on eradicating existing stands).

If the plant population is marginally adequate (3,500 plants /acre) or acceptable but large gaps exist in the stand, spot replanting may be advisable. The European rule of thumb for deciding when gaps need replanting is that gaps greater than the footprint of a small car should be replanted. Spot treatment with glyphosate will usually be necessary prior to replanting gaps to control weeds (Caslin, Finnan, and McCracken 2010).

Managing established stands

Agronomic

Fertility—Nutrient removal with giant miscanthus biomass harvests is low because of the plant's ability to recycle nutrients to the rhizome system in the later part of the growing season. Additionally, most of the leaf material remains in the field, so the only nutrients that must be accounted for are in the stems (DEFRA 2007). In most cases, nutrient requirements of the crop the first two growing seasons will be met by leaf litter decomposition, soil nutrient reserves, rhizome reserves, and atmospheric deposition (Caslin, Finnan, and McCracken 2010; DEFRA 2007). Thus for the second growing season, producers should follow the same guidelines on fertilization as outlined for planting (see Establishment fertilization).

Nutrient removal, particularly nitrogen, is relatively low in spite of the high biomass production. European work (Caslin, Finnan, and McCracken 2010) has shown that given a 10 to 15 tons/acre yield for established stands (>3 yr old), nutrient removal rates per year are:

- nitrogen—50 to 90 lb/acre
- phosphorus—6 to 13 lb/acre
- potassium—45 to 116 lb/acre
- magnesium—3 to 11 lb/acre

In contrast to the European work, higher nitrogen and lower potasium removal rates were found from a February harvest date of 3-year-old stand of Freedom™ giant miscanthus in Elsberry, Missouri, that averaged 12 tons/acre in 2009 to 2010 (J. Douglas, unpublished data, 2011):

- nitrogen—143 to 150 lb/acre
- phosphorus—9 to 18 lb/acre
- potassium—34 to 56 lb/acre
- magnesium—8 to 14 lb/acre
- calcium—24 to 32 lb/acre
- sulfur—2 to 5 lb/acre

Until more experience is gained with the crop, producers should be careful to monitor the nutrient status of their plantings in subsequent years by regular soil testing.

If fertilizer is required, any source (e.g., synthetic, organic, manure, etc.) can be used as long as it satisfies the crop needs and the farm nutrient management plan. Do not use murate of potash (KCl) as the source for potassium without checking with the end product user first. Excessive chlorine can damage some boilers (Caslin, Finnan, and McCracken 2010).

Weeds—From the second year onward, growth of well-established giant miscanthus stands will suppress weed competition and herbicide applications should not be necessary. If weed growth is still a problem, cultivation and herbicide treatments outlined for the establishment year should be followed unless other herbicide options have become available. Until the long-term interactions of giant miscanthus with surrounding vegetation are understood, fields should be monitored on a regular basis to determine if "new" weeds are becoming an issue (Caslin, Finnan, and McCracken 2010).

Insect and disease—Similar to the recommendation for "new" weed scouting, producers should scout their giant miscanthus stands on a regular basis for emerging insect (e.g., corn root worms, aphids, etc.; see Diseases, insects, and weeds) and disease issues. When potential problems are noted, producers should contact the local extension office for assistance with identification and determining appropriate control measures.

Preventing unintentional spread in established stands

Established plantings should be monitored on a regular basis to check for unwanted spread. All local, State, or Federal regulations for containment of biomass plantings should be followed, if applicable. Minimum procedures recommended to prevent unintentional spread of giant miscanthus should include:

- Maintain the established minimum 25-foot setback or border, if required, around a giant miscanthus stand. The setback should be measured every 3 years to make sure it meets this minimum. Monitor the setback to look for unwanted sprouts of giant miscanthus and spot treat according to the guidelines listed under Site restoration.
- If biomass material is harvested prior to killing frost, the materials should be transported in covered equipment to the processing or bioenergy plant. Inspect harvesting equipment and clean off larger stems of plant material prior to leaving the field.

Site restoration

There are no published studies specifically dealing with giant miscanthus eradication. European sources suggest giant miscanthus is relatively easy to eradicate by repeatedly rototilling during the growing season or spraying with glyphosate application followed by tillage (Jørgensen 2011; Caslin, Finnan, and McCracken 2010).

Work in Illinois indicates that eradicating giant miscanthus, at least in their environment, will not be that easy. In that study, 2 years of herbicide application combined with tillage or 2 years of cropping with glyphosate-resistant soybeans or corn and over the top applications of glyphosate did not completely eradicate the giant miscanthus (Anderson 2011). Experience with Freedom™ giant miscanthus has shown that 2 or 3 years of glyphosate application combined with rotovation are necessary to completely eradicate established stands (B. Baldwin, personal communication, 2011). This intensity of eradication effort is similar to that needed to eradicate other well established, C_4 perennial grasses, such as bermudagrass, where 2 years of treatments do not completely eradicate established stands (Harper 2007).

Until people gain more experience with eradicating giant miscanthus, the NRCS recommends that all restoration plans include a minimum of 3 years of active treatment (e.g., herbicide and/or combination of herbicide and cultivation with or without annual crop or cover crop). Application of glyphosate in the fall before a hard frost is preferred to translocate the herbicide into the roots, though that timing may not best coincide with the final harvest.

At the start of the third growing season, the remaining giant miscanthus stand should be accessed for the ability of spot treatments with herbicide to control remaining plants. If the stand is too abundant for spot treatment methods, an additional year of broadcast herbicide and annual cropping is recommended. If the residual giant miscanthus stand can be controlled by spot application of herbicide, the site can be planted to perennial species or continue in annual cropping system based on the landowner's long-term objective. Regardless of the final restoration cover, the site should still be monitored for giant miscanthus sprouts for a minimum of 2 years following restoration planting and follow up herbicide treatments applied.

If giant miscanthus does escape from field production areas and becomes established in natural areas, which may prohibit the use of tillage equipment, other control methods may be necessary. This can be accomplished with a spot treatment of broad-spectrum herbicide coupled with digging and removing plants from the site. This may require repeated applications and the site should be monitored for 2 years following eradication methods.

Biomass harvesting

Harvest timing considerations

Standing biomass losses have been reported to be around 30 percent due to leaf losses in the winter prior to harvesting under European conditions (Himken, Lammel, and Neukirchen 1997). Losses have been higher under midwestern conditions due to more severe winter conditions (Heaton, Dohleman, and Long, 2008). However, losses as low as 1 percent were reported when Freedom™ giant miscanthus harvest was delayed from mid-October to mid-March in a 2-year study in Elsberry, Missouri (J. Douglas, unpublished data. 2011). Delayed harvesting (just before growing season starts) is sometimes recommended in Europe because losses due to delayed harvesting are mitigated by significant moisture declines in standing biomass (Heaton, Dohleman, and Long 2008). But if mistimed, delayed harvesting can result in significant damage to the emerging shoots (fig. 4) and result in lower stem numbers the following year (Caslin, Finnan, and McCracken 2010).

Optimum harvesting time is when the crop is dry enough to store safely (<20% moisture) and at a level that is required by end-use process without requiring supplemental drying (Caslin, Finnan, and McCracken 2010; Caslin 2010). Typical moisture curve for giant miscanthus in Illinois is 50 percent in October to less than 10 percent by February (Heaton et al. 2011). Similar results were reported (J. Douglas, unpublished data, 2011) for moisture concentrations for Freedom™ in eastern Missouri when harvest was delayed from October (50%) to March (18%). Obviously, snow or wet soil conditions that impede harvesting equipment will also affect the decision of when to harvest. Staggering harvest or delaying giant miscanthus harvest as long as possible within the acceptable moisture/yield window also will provide maximum winter cover benefit to wildlife (Caslin, Finnan, and McCracken 2010).

Harvest methods

Giant miscanthus can be harvested with a silage harvester or mowed and baled. Regardless of the method, the goal is to leave a 2- to 4-inch stubble to maximize biomass yield (Heaton et al. 2010), but avoid picking up any of the leaf litter (fig. 5), which will generally increase moisture and ash content of the bales due to contact with the soil (Caslin, Finnan, and McCracken 2010).

Harvest losses are lower when a silage harvester is used (7% vs. 13% for silage harvester and mower, respectively), but chopped material has a very low density and requires more storage space (Caslin, Finnan, and McCracken 2010; Finnan et al. 2011). The size of the chopped pieces needs to meet the intake requirements of the boiler or power station where they are burned. Additionally, if the crop moisture is too high or the pieces too small, the material is more likely to heat up and may catch fire when stored (Caslin, Finnan, and McCracken 2010).

If baled, giant miscanthus should be harvested with a mower-conditioner to break the stems, which acceler-

Figure 4 Giant miscanthus sprouts in early spring

Photo USDA NRCS, Elsberry, MO

Figure 5 Stubble from harvested giant miscanthus

Photo USDA NRCS, Elsberry, MO

ates drying and produces better wind row configuration to facilitate baling. A disk mower/conditioner is not recommended unless test balings have been made to ensure the baler can pick up the material. Additionally, windrows should not be raked together to avoid picking up any leaf litter, which would remove nutrients from the field and decrease biomass quality (Caslin, Finnan, and McCracken 2010).

When producing bales, it is important that bales be packed as tightly as possible to reduce cost (Caslin 2010). Problems associated with not having giant miscanthus bailed correctly include:

- rejection by processing plant
- greater storage area required
- broken and excessively damaged bales from bale handling equipment
- inability to stack correctly to minimize weathering when stored outside
- looser bales means more bales per ton of biomass and higher overall baling cost
- fewer bales on transport trailer means higher transportation cost

Properly baled material should feel hard when kicked and the producer should not be able to get his or her hands under the string for any distance (Caslin, Finnan, and McCracken 2010).

Transportation

If harvested prior to frost, the loss of potentially viable stem pieces (or seed), which could land along the transportation route in suitable location for growth, is the primary concern during transportation. Bales and biomass materials should be covered during transport to prevent this. If harvested after frost, this precaution is not necessary.

Storage considerations for bales

If on-farm storage is required, the goal is to keep the material as dry as possible. This means that bales should be stored under cover as soon as possible. Outside storage is acceptable if stacked on well-drained or impermeable pad, properly stacked, and tarped. Other considerations for outside storage site selection are levelness, accessibility for trucks, distance from power lines, and distance from public access to minimize fire risks.

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