Differences in Seed Set and Fill of Cultivars of *Miscanthus* Grown in USDA Cold Hardiness Zone 5 and Their Potential for Invasiveness[1]

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Abstract

Miscanthus sinensis Andersson has become a very popular ornamental grass used in a variety of horticultural settings, yet in many states it now appears on invasive species lists. Many cultivars have been released with a range of different characteristics that likely increase or decrease their invasive potential in different climates. To determine the fecundity, and by extension, the invasive potential of cultivars currently sold in USDA cold hardiness Zone 5, thirty-one cultivars of *M. sinensis* (Maiden grass, Chinese silver grass) along with one *Miscanthus* subspecies cultivar (*M. sinensis* Andersson subsp. *condensatus* (Hack.) T. Koyamama 'Cabaret'), one *Miscanthus* hybrid (*M.* × *giganteus* J.M. Greef & Deuter *ex* Hodk. Renvoize), and one related species (*M. sacchariflorus* (Maxim.) Hack.) were transplanted into a common garden at the Chicago Botanic Garden in Cook County, IL, and evaluated for flowering, growth habit, and seed viability. Over the course of the 5-year trial period, 68.1% of all plants survived. Growth in clump size varied greatly among taxa, as did flowering periods. Most cultivars set filled seed, ranging from 14 to 349,327 seeds per plant; only four produced no seed over the course of the trial. Most cultivars of the species represent a high risk for self-seeding in Zone 5. Because *Miscanthus sinensis* is self-incompatible (8), risk of self-seeding increases when two or more cultivars are grown together. Implications for potential invasiveness are discussed.

Index words: ornamental grass, cultivar, fecundity, invasive potential.

Significance to the Nursery Industry

All taxa of *Miscanthus* tested in our four-year trial flowered, but four failed to set seed — *Miscanthus* × *giganteus*, *M. sinensis* var. *condensatus* 'Cabaret,' *M.s.* 'Silberpfeil,' and *M.s.* 'Hinjo.' However, the cultivar 'Hinjo' did set seed in a similar trial by Meyer and Tchida (17). Based on their lack of seed set in our trial and those of others (17, 32), three taxa of *Miscanthus*, *Miscanthus* × *giganteus*, *M. sinensis* var. *condensatus* 'Cabaret', and *M.s.* 'Silberpfeil' are very unlikely to become invasive in the Chicago region. Two of these, *M.* × *giganteus* and *M.s.* 'Silberpfeil', performed well horticulturally and can be recommended to gardeners who want to use *Miscanthus* in landscapes in the upper Midwest. Our trial demonstrated that cultivars vary considerably in fecundity and that fecundity can increase over time in this long-lived perennial, indicating that invasive assessment trials for cultivars are needed and that they should span several years. In addition, future breeding efforts for cultivars of *Miscanthus* should focus on creating sterile, as well as beautiful, plants.

Introduction

The worldwide total of plant species introduced to new geographical regions by humans is about one-quarter million species (20). Humans have long had a role in plant dispersal; however, the role of humans as agents of plant dispersal has grown with the globalization of trade, making humans the most important vectors for long-distance transport of plants (19). Ornamental horticulture has historically been recognized as one of the primary pathways for plant invasions worldwide resulting in 60–85% of wildland weeds (16, 26). North American seed and nursery catalogues offer over 59,000 plant species and varieties for sale to national and international markets (4). In the United States, a small number (2,500–3,000 species) have become persistent, with approximately 300 of those being truly invasive (15). Evaluation trials and risk assessments to identify this small percentage of invasive species can therefore have significant economic and environmental benefits.

Deleterious effects from the release of invasive species include threats to the environment, national economies, and even human health (21). It is generally agreed that the spread of invasive species is the second greatest threat to biodiversity following habitat destruction (31). Invasive plants can reduce productivity of agricultural crops, pastures, and rangelands; disrupt terrestrial and aquatic ecosystems; choke waterways; and alter fire frequencies (21). The effects of invasive grasses on ecosystem function and resource competition are significant (1). In the United States, economic losses from all invasive species are estimated to be $120 billion annually with invasive plants accounting for at least $35 billion (21).

Gardening is now the most popular active pastime in North America and new products are a major driving force for sales growth. 'New introductions are the lifeblood of this industry,' said one grower at a meeting of the Illinois Invasive Plant Species Council. Annually, 250–300 new cultivars are registered (27). Cultivars often vary significantly in their fecundity and vegetative growth (14), which are both highly related to invasive potential. Strong vegetative growth has been correlated with higher seed production and therefore may be linked with invasive potential (13, 18). Similarly, a

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long flowering and fruiting period can be associated with invasiveness (5). Therefore, to fully assess the invasive status of a species, particularly one with high ornamental value, cultivars should be evaluated (33).

The use of ornamental grass cultivars in a wide variety of horticultural applications has become increasingly popular in recent years, and *Miscanthus sinensis* (Maiden grass, Chinese silver grass) is one of the most popular (32). There are over 100 cultivars of *Miscanthus*, and more than half of them have been introduced in the past 30 years (7, 17). *Miscanthus* has many sought-after horticultural characteristics: it is adaptable to many conditions, able to grow at a prodigious rate, has attractive, often variegated foliage, and also large, attractive panicles. Its high cellulose content also makes it a candidate for biofuel development (11). Another characteristic which makes it desirable from both a horticultural and biofuel perspective is that *Miscanthus* are generally long-lived, with *Miscanthus* × *giganteus* having a life expectancy of at least 15 to 20 years (30). Unfortunately, the broad ecological amplitude of *Miscanthus* helps it naturalize outside cultivation. Horticultural selection for earlier flowering, and as a consequence earlier seed set, may have increased its invasive potential (2).

Native to eastern Asia and South Africa (17), *Miscanthus sinensis* has naturalized in 25 states, the District of Columbia, and in Ontario (29). It is usually found in disturbed areas, such as roadsides and woodland edges, especially in the eastern U.S. (24). *Miscanthus* was noted to escape cultivation as early as 1917 (9). Ornamental varieties of *Miscanthus* have been shown to have a long history of localized escape in the Eastern U.S. (22). *Miscanthus sinensis* is found on numerous state invasive plant lists from Illinois to Alabama, Connecticut, and Georgia (10). To assess potential for invasiveness, Meyer and Tchida (17) tested seed set and germination for 41 taxa of *Miscanthus* grown in four USDA hardiness zones (Zones 4, 5, 6, and 7) over two years. Wilson and Knox (32) performed a similar study in Florida (Zones 8 and 9), focusing on ornamental characteristics and seed viability. However, research on the invasive potential of cultivars of *Miscanthus* at the same site over several years had not previously been tested. The objectives of this study were to investigate differences in potential invasiveness of 34 cultivars of *Miscanthus* in Zone 5 by quantifying differences in fecundity among cultivars over 5 years in a common garden setting.

Materials and Methods

Plant material and field conditions. A total of thirty-four cultivars and subspecies of *Miscanthus* were selected for this study (Table 1). Clonally propagated selections were obtained from a number of sources, both locally and through mail order (Table 2). No single supplier was able to provide all cultivars. To minimize any effects of different production methodologies on phenology and consequently seed set, no measurements were taken until all plants had over-wintered in the common garden. Five plants of each cultivar were planted with the exception of 'Sarabande' (4), 'Kleine Silberspinne' (4), and 'Superstripe' (3), for a total of 166 plants, in a site receiving full sun. Three plants were determined to be mislabeled by the suppliers (each a different one), one each of cultivars 'Autumn Light', 'Huron Sunrise', and 'Gracillimus', and were removed entirely from the analysis. *Miscanthus sinensis* is reported to be self-incompatible (8); planting the cultivars in a single common garden allowed for potentially high cross pollination.

Twenty-seven taxa were installed at the Chicago Botanic Garden, Cook County, IL, Lat./Long 42.143296/–87.785739, (USDA Hardiness Zone 5b) on June 22, 2006; another 7 taxa were installed on July 25, 2006. Cultivars were randomly assigned to rows and plants were placed 5.0 feet on center in a common garden consisting of well-drained clay-loam soil, pH of 7.5. Maintenance practices were kept to a minimum to simulate home garden culture. Overhead sprinklers provided water as needed, and no fertilizer was applied. Mulch consisting of shredded leaves and wood chips was placed on the soil around the plants for water conservation and weed suppression. Although 2006 had a slightly shorter growing season (last spring frost to first autumn frost) than average (143 days vs. 158 days), the remaining years had longer growing seasons than normal (+38 days in 2007, +23 days in 2008, +17 days in 2009, and +17 days in 2010).

Plant growth and fecundity. Weekly assessments of flowering and fruiting were measured during the growing season in 2007, 2008 and 2010. End of season measurements for every individual were taken the same years for vegetative plant height and clump size (two perpendicular diameter measurements were averaged and converted to area covered, then averaged within each taxon). Clump length and width was measured approximately 2 cm (0.75 in) above soil level.

In 2007 and 2008, in late November after a killing frost but prior to seed drop, all inflorescences were removed from each plant and total inflorescence number per plant was recorded. In 2010, inflorescences were harvested from each plant the third week in October, approximately three weeks prior to the first killing frost, which meant we were unable to assess filled seed set in several late flowering cultivars.

In 2007, mature inflorescences were removed from plants and dehulled by hand using a sieve (ASTM E-11 Specification, No. 18, 1 mm, Hogentogler & Co., Inc., Columbia, MD). Seeds were then separated from remaining detritus using a column seed cleaner (Agriculex CB-1 Column Seed Cleaner Guelph, Ontario, Canada). Cleaned seeds were allowed to dry at ambient temperature. A random sample of inflorescences was taken for each cultivar and seeds were collected for each sample. One hundred seeds were counted and weighed. The total volume of seeds for each sample was weighed and the number of seeds was estimated using the 100 seed weight. The total number of seeds for each plant was then projected using the total number of inflorescences per plant divided by the sample number of inflorescences times the projected number of seeds per sampled inflorescence. The formula for each plant is total seeds = (total number of inflorescences / sampled number of inflorescences) × (total weight of seeds per sampled inflorescences / weight of 100 seeds) × 100.

In order to determine seed viability, germination tests were attempted in 2007, but the results were compromised by severe fungal contamination. Therefore, in 2010 we quantified filled seed set via x-ray. X-ray analysis can be a very efficient and non-destructive method of assessing seed quality and quantity (see Fig. 1). A good x-ray image will reveal details of seed fill, insect infestation and also size or absence of the embryo. It may also reveal variation in storage tissue quality. In comparison to traditional viability assessments (cut test or tetrazolium staining), x-ray analysis has the benefit of being non-destructive and much faster (28). However,

Table 1. Cultivar or taxon name, vegetative plant height, clump size area, foliage appearance, number of inflorescences at end of growing season, date when majority of taxon's plants were in flower, projected number of total seeds via mechanical removal (2007), projected number of filled seeds via x-ray analysis (2010), and number of plants dying of those planted. Plant measurements (height, clump size, inflorescence number) were taken at the end of the growing season in 2007, 2008 and 2010 and averaged over all 3 years. Seed set was quantified in 2007 and 2010 and each year's averages are shown separately.

Plant name	Height mean (SE) cm	Clump size area mean (SE) cm^2	Foliage characteristics	No. of inflorescences mean (SE)	Phenology (bloom time)	Total no. of seeds set per plant — 2007 mean (SE)	No. of filled seeds per plant — 2010 mean (SE)	Mortality
'Adagio'	157.8 (2.8)	2,364.7 (256.3)	Narrow green	358.4 (23.7)	Early (8 Aug. ± 3 days)	1,524 (396)	52,632 (12,024)	3/5
'Andante'	218.1 (5.6)	2,317.0 (356.9)	Green w/central stripe	150.3 (19.7)	Mid (6 Sept. ± 5 days)	68,882 (11,725)	53,323 (8,571)	0
'Autumn Light'	213.1 (3.6)	1,828.3 (298.5)	Narrow green w/silver midrib turning yellow	158.7 (28.2)	Mid (6 Sept. ± 5 days)	94,371 (19,061)	221,500 (41,278)	1/5
'Autumn Red'	162.7 (3.9)	1,735.2 (262.1)	Green, turning reddish purple in fall	194.4 (32.8)	Mid (23 Aug. ± 5 days)	902 (149)	24,185 (2,126)	0
'Blutenwunder'	215.5 (2.0)	1,281.0 (169.3)	Green, fine-textured	126.8 (17.3)	Early (13 Aug. ± 17 days)	5,994 (1,576)	177,144 (25,304)	0
'Dixieland'	195.6 (2.5)	1,625.5 (225.2)	Green/white variegated	73.1 (10.6)	Late (25 Sept. ± 6 days)	1,073 (212)	497 (102)	0
'Ferner Osten'	139.7 (6.4)	1,016.7 (123.6)	Dark green w/silver midrib	181.7 (16.6)	Early (31 July ± 8 days)	9,425 (1,708)	8,954 (1,309)	0
'Gold Bar'	70.7 (2.5)	490.6 (79.3)	Green w/creamy yellow bands from base to tips	2.4 (2.4)	Late (20 Sept. ± 0 days)	0	2,061 (2,061)	2/5
'Goliath'	254.9 (4.1)	1,929.5 (334.4)	Green, coarse-textured	116.1 (16.5)	Mid (27 Aug. ± 12 days)	354 (54)	13,920 (1,046)	0
'Gracillimus'	213.4 (5.3)	2,239.8 (350.2)	Light-green w/silver vein	186.4 (23.2)	Late (4 Oct. ± 5 days)	188 (188)	6,103 (2,058)	2/5
'Graziella'	198.6 (8.2)	1,484.1 (186.0)	Thin green turning copper-red in fall	192.4 (8.6)	Early (8 Aug. ± 3 days)	48,845 (10,792)	133,122 (7,656)	0
'Hinjo'	143.3 (11.3)	1,051.6 (403.7)	Green w/vivid horizontal gold banding	51.0 (22.6)	Late (25 Sept. ± 3 days)	0	0	4/5
'Huron Sunrise'	174.6 (4.8)	1,557.0 (212.1)	Green w/silver midrib	170.2 (25.3)	Mid (31 Aug. ± 7 days)	61,237 (9,951)	94,612 (19,603)	1/5
'Kleine Silberspinne'	192.2 (3.4)	2,056.9 (309.1)	Green	569.9 (39.2)	Mid (21 Aug. ± 8 days)	33,076 (2,220)	349,327 (19,395)	1/4
'Little Zebra'	107.5 (28.4)	999.0 (598.8)	Green w/prominent horizontal yellow bands	73.7 (48.8)	Mid (8 Sept. ± 2 days)	14 (NA)	2,704 (NA)	4/5
'Malepartus'	204.0 (3.3)	1,207.1 (191.5)	Green, narrow; golden fall color	90.6 (14.7)	Mid (23 Aug. ± 5 days)	8,675 (1,165)	203,699 (52,611)	0
'Minuett'	187.6 (4.1)	2,077.6 (315.3)	Green	168.5 (13.4)	Mid (14 Sept. ± 6 days)	48,117 (6,502)	91,817 (4,308)	0

Table 1 Continued …

[z]100% mortality by 2010.
[y]Inflorescences were immature at time of analysis; many plants were harvested before their seeds were mature because of the timing of access to the x-ray machine.
[x]Removed from trial in 2008 due to extensive vegetative spread.

Table 1. Continued

Plant name	Height mean (SE) cm	Clump size area mean (SE) cm^2	Foliage characteristics	No. of inflorescences mean (SE)	Phenology (bloom time)	Total no. of seeds set per plant — 2007 mean (SE)	No. of filled seeds per plant — 2010 mean (SE)	Mortality
'Morning Light'	194.9 (3.1)	1,714.1 (330.6)	Green w/narrow bands of white on leaf margins	115.5 (18.3)	Late (2 Oct. ± 3 days)	0	1,936 (763)	2/5
'Nippon'	193.0 (4.6)	821.5 (110.2)	Dark green w/bright silver midrib turning red	342.0 (23.4)	Early (8 Aug. ± 3 days)	11,928 (2,760)	150,120 (NA)	4/5
'Puenktchen'	217.7 (3.7)	2,321.4 (340.7)	Green w/yellow-white irregular horizontal spots	174.5 (14.4)	Mid (7 Sept. ± 6 days)	21,777 (3,185)	16,974 (1,757)	0
'Purpurascens'	177.6 (5.7)	3,790.6 (300.6)	Gray-green w/red tinge; orange/red in fall	274.7 (37.7)	Mid (23 Aug. ± 5 days)	3,022 (331)	24,957 (3,276)	0
'Rotsilber'	183.6 (5.2)	3,439.2 (295.2)	Silvery green turning red	271.8 (26.2)	Mid (24 Aug. ± 2 days)	20,542 (5,894)	339,462 (37,235)	2/5
'Sarabande'	212.1 (6.4)	824.0 (32.3)	Narrow green w/silvery sheen	78.7 (34.3)	Mid (7 Sept. ± 10 days)	3,278 (2,530)	NA[z]	5/5
'Silberfeder'	220.5 (4.9)	1,393.4 (232.0)	Green w/white midrib turns to purple, gold	105.0 (21.3)	Late (27 Sept. ± 5 days)	94,144 (22,718)	3,975 (959)	2/5
'Silberpfeil'	185.4 (9.5)	1,130.0 (517.6)	Variegated green/white striped	71.4 (33.1)	Late (27 Sept. ± 5 days)	0	0	4/5
'Silberturm'	253.3 (9.6)	1,707.3 (226.1)	Green	75.9 (13.5)	Mid (23 Aug. ± 5 days)	9,324 (1,833)	28,941 (5,813)	0
'Strictus'	231.5 (6.0)	1,750.3 (351.4)	Wide green w/gold bands throughout leaf	75.9 (12.2)	Late (18 Sept. ± 6 days)	907 (153)	NA[y]	0
'Superstripe'	202.6 (11.7)	2,212.1 (971.9)	Gold horizontal bands	64.3 (18.4)	Mid (15 Sept. ± 2 days)	1,226 (132)	NA[y]	2/3
'Variegatus'	205.7 (4.0)	1,530.0 (281.6)	Cream and green striped turns to almond	124.3 (26.1)	Late (25 Sept. ± 6 days)	211 (123)	NA[y]	2/5
'Yaku-jima'	149.9 (6.4)	1,406.7 (206.1)	Green, fine-textured	212.6 (53.3)	Early (7 Aug. ± 6 days)	138 (34)	NA[z]	5/5
'Zebrinus'	248.1 (4.3)	2,016.4 (285.4)	Green w/yellow-white horizontal bands	51.8 (5.5)	Late (16 Sept. ± 3 days)	16,621 (3,961)	NA[y]	0
M. sacchariflorus	205.2 (9.3)	23,445.4 (1,307.6)	Olive-green; coarse-textured	126.8 (16.4)	Early (12 Aug. ± 16 days)	746 (190)	NA[x]	0
M. × *giganteus*	360.8 (4.5)	9,339.2 (759.9)	Wide green	61.7 (12.3)	Late (4 Oct. ± 5 days)	0	0	0
M.s. var. *condensatus* 'Cabaret'	195.1 (5.8)	772.5 (68.3)	Dark green margins with white centers	8.2 (3.1)	Late (7 Oct. ± 7 days)	0	NA[a]	5/5

[z]100% mortality by 2010.

[y]Inflorescences were immature at time of analysis; many plants were harvested before their seeds were mature because of the timing of access to the x-ray machine.

[x]Removed from trial in 2008 due to extensive vegetative spread.

Table 2. Plant sources and initial pot sizes for *Miscanthus* in-ground evaluation.

Plant name	Pot size	Source
Miscanthus × *giganteus*	3 gallon	Intrinsic Perennials
Miscanthus sinensis 'Silberturm'	1 gallon	The Natural Garden
Miscanthus sinensis 'Silberfeder'	1 gallon	Hoffie Nursery
Miscanthus sinensis 'Andante'	2 quart	Plant Delights Nursery
Miscanthus sinensis 'Autumn Light'	1 gallon	The Natural Garden
Miscanthus sinensis 'Minuett'	2 quart	Plant Delights Nursery
Miscanthus sinensis 'Huron Sunrise'	1 gallon	Intrinsic Perennials
Miscanthus sinensis 'Gracillimus'	1 gallon	Elite Growers
Miscanthus sinensis 'Graziella'	1 gallon	Hoffie Nursery
Miscanthus sinensis 'Sarabande'	1 gallon	Elite Growers
Miscanthus sinensis 'Rotsilber'	1 gallon	Elite Growers
Miscanthus sinensis 'Kleine Silberspinne'	1 gallon	Intrinsic Perennials
Miscanthus sinensis 'Ferner Osten'	1 gallon	The Natural Garden
Miscanthus sinensis 'Nippon'	1 gallon	The Natural Garden
Miscanthus sinensis var. 'Purpurascens'	1 gallon	Elite Growers
Miscanthus sinensis 'Adagio'	1 gallon	Hoffie Nursery
Miscanthus sinensis 'Zebrinus'	1 gallon	Hoffie Nursery
Miscanthus sinensis 'Strictus'	1 gallon	Elite Growers
Miscanthus sinensis 'Superstripe'	4 inch pot	Blooms of Bressingham
Miscanthus sinensis 'Puenktchen'	1 gallon	The Natural Garden
Miscanthus sinensis 'Hinjo'	2 quart	Plant Delights Nursery
Miscanthus sinensis 'Gold Bar'	1 gallon	Song Sparrow Farm
Miscanthus sinensis 'Little Zebra'	1 gallon	Hoffie Nursery
Miscanthus sinensis 'Morning Light'	1 gallon	Hoffie Nursery
Miscanthus sinensis 'Dixieland'	1 gallon	Intrinsic Perennials
Miscanthus sinensis 'Variegatus'	1 gallon	Hoffie Nursery
Miscanthus sinensis 'Silberpfeil'	6 inch pot	Bluebird Nurseries
Miscanthus sinensis var. *condensatus* 'Cabaret'	1 gallon	Milaeger's, Racine, WI
Miscanthus sinensis 'Yaku-jima'	1 gallon	Home Depot
Miscanthus sinensis 'Autumn Red'	1 gallon	Milaeger's
Miscanthus sinensis 'Malepartus'	1 gallon	Milaeger's
Miscanthus sinensis 'Goliath'	Field grown, but likely dug as 1 gallon size	Bluestem Nursery, British Columbia
Miscanthus sinensis 'Blutenwunder'	Field grown, but likely dug as 1 gallon size	Bluestem Nursery
Miscanthus sacchariflorus	Field grown, but likely dug smaller than 1 gallon size	Bluestem Nursery

although commonly used to infer viability, one cannot be certain that filled seeds are alive without further testing (28). One inflorescence was chosen randomly and harvested from each of three plants per cultivar the third week in October 2010 and taken to Ohio State University for x-ray analysis. Inflorescences were x-rayed using a Faxitron MX-20 digital radiography system. Filled seeds were counted manually from the resulting images by two people independently, the results were averaged, and total seed counts were projected by multiplying average seed set per inflorescence by number of inflorescences.

Reproductive rank (Table 3) was determined by averaging 2007 and 2010 seed sets and ordering them from highest to lowest. For cultivars that failed to set seed in 2010 due to

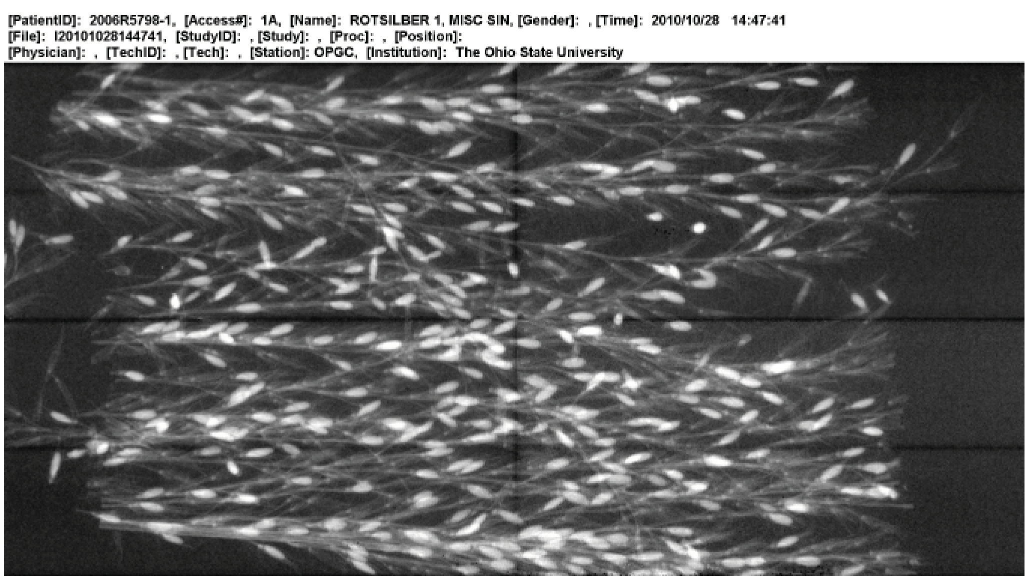

Fig. 1. An x-ray image of *Miscanthus sinensis* cv. 'Rotsilber', showing filled seeds.

Table 3. Reproductive rank (greatest to least fecundity) as determined by the mean seed set (2007 and 2010) and flowering timing (early = before August 15, mid = August 15 to September 15, and late = after September 15). For cultivars that failed to set seed in 2010 due to the early harvest, only 2007 data was used to determine reproductive rank.

Cultivar	Reproductive rank	Mean seed set	Flowering timing
'Kleine Silberspinne'	1	191,202	M
'Rotsilber'	2	179,957	M
'Autumn Light'	3	157,936	M
'Malepartus'	4	106,172	M
'Blutenwunder'	5	91,569	E
'Graziella'	6	90,984	E
'Nippon'	7	81,024	E
'Huron Sunrise'	8	77,925	M
'Minuett'	9	69,997	L
'Andante'	10	61,103	M
'Silberfeder'	11	49,060	L
'Adagio'	12	27,078	E
'Puenktchen'	13	19,376	M
'Silberturm'	14	19,133	M
'Zebrinus'	15	16,621	L
'Purpurascens'	16	13,990	M
'Autumn Red'	17	12,995	M
'Ferner Osten'	18	9,190	E
'Goliath'	19	7,137	M
'Sarabande'	20	3,278	M
'Gracillimus'	21	3,146	L
'Little Zebra'	22	1,359	M
'Superstripe'	23	1,226	L
'Gold Bar'	24	1,031	L
'Morning Light'	25	968	L
'Strictus'	26	907	L
'Dixieland'	27	785	L
M. sacchariflorus	28	746	E
'Variegatus'	29	211	L
'Yaku-jima'	30	138	E
'Hinjo'	31	0	L
'Silberpfeil'	31	0	L
M. × *giganteus*	31	0	L
M.s. var. condensatus 'Cabaret'	31	0	L

the early harvest, only 2007 data was used to determine reproductive rank.

Statistical analysis. Our primary question in this comparative trial was to determine if the taxa of *Miscanthus* we grew are capable of seed set or are sterile or functionally sterile due to their phenology and growing season length in this region. Statistical comparisons of differences between cultivars in size and fecundity would be inappropriate due to differences in initial plant size and are not necessary to address our question. *A posteriori* fecundity comparisons by phenology were determined using Kruskal-Wallis rank sum test using the statistical program R (23).

Results and Discussion

Cultivar growth and size was highly variable. Results ranged from 491 cm^2 to 23,445 cm^2 (Table 1). Depending on the cultivar, clump size remained small or moderate, while others (*M.* × *giganteus*, *M.s.* 'Purpurascens', 'Superstripe', 'Rotsilber', and 'Andante') grew quite large, with the potential for crowding other plants nearby. One closely related species, *M. sacchariflorus*, showed evidence of rapid rhizomatous spread or 'running' and was removed from the plot in 2008. Mortality was minimal in 2006, but increased in 2007 and 2008, with 'Sarabande', 'Yaku-jima', and *M.s.* var. *condensatus* 'Cabaret' dying out completely by the end of the trial (Table 1). All three cultivars appeared to have problems with cold tolerance; cultivars of *M.s.* var. *condensatus* are listed by several plant catalogs to be hardy only to Zone 6.

Flowering phenology and reproductive effort varied by cultivar and year. (H = 57.16, 2 df, $p = 3.8 \times 10^{-13}$). Plants began to flower as early as August 3 and as late as October 12. Beginning flowering date was defined as when the majority of a cultivar's plants had produced inflorescences (Table 1). We followed the definitions of Meyer and Tchida (17) to categorize taxa of *Miscanthus* as early blooming (before August 15; 7 cultivars), mid blooming (August 15 to September 15; 16 cultivars), and late blooming (after September 15; 11 cultivars). Average inflorescence number produced by a taxon within a single season ranged from zero to 822 inflorescences. Seed set differed highly among cultivars in 2007 and 2010. In 2007, total seed set ranged from 0 to 94,371 seeds per plant. In 2010, filled seed set (as determined by x-ray) ranged from 0 to 410,733 seeds per plant. Only 19 cultivars were assessed for filled seed set in 2010 because timing of access to the x-ray facility prevented us from assessing several late flowering cultivars ('Gracillimus', 'Puenktchen', 'Silberfeder', 'Strictus', 'Superstripe', 'Variegatus', and 'Zebrinus').

We found that seed production and fill varied between cultivars, demonstrating the importance of evaluating cultivars for invasive potential. Flowering phenology is also important in this species. Seed set was significantly different among blooming times using 2007 seed set (H = 104.47, df = 29, $p = 1.9 \times 10^{-10}$). We found that many of the less fecund cultivars were late flowering, indicating they may not have had time to complete their life cycle in our zone (Fig. 2). Meyer and Tchida (17) had a similar result, finding that many early-flowering types of *Miscanthus* set viable seed and later-flowering types failed to do so. Unfortunately, many recently developed cultivars have been selected for earlier flowering which may increase their invasive potential (32).

The green industry has specifically bred cultivars of several invasive plants that are less fecund, and thus might have lower invasive potential (25, 3). However, Knight et al. (12) used published matrix population models to simulate

Fig. 2. Mean seeds produced per plant in 2007 for each flowering time category (phenology) with standard error bars. Means with different letters are significantly different at the p < 0.05 level as determined using a Kruskal Wallis multiple comparisons test.

the effect of reducing fecundity on population growth rates of known invasive species. They showed that the population growth rates of long-lived species are relatively insensitive to fecundity reduction, demonstrating that less fecund cultivars will still be invasive if other traits influencing invasiveness (e.g., life span, germination requirements, length of juvenile period, etc.) are equivalent among cultivars. Further, many cultivars are clonal selections, and if crossed with other cultivars or selfed, they produce offspring with traits and fecundities that do not resemble the parent plant. Based on these two lines of evidence, they suggest that only completely sterile cultivars of long-lived invasive species should be considered 'safe' and non-invasive (12).

Although there are some similarities between our results and those in two previous comparative trials of *Miscanthus*, there are also some striking differences (Table 4). Meyer and Tchida (17) assessed 41 taxa grown in USDA hardiness zones 4 through 7. They argue that cultivars that have less than 18% seed viability in at least three of those zones pose the least risk for becoming invasive. We question whether this threshold is stringent enough. Eighteen percent seed viability in cultivars that can set hundreds of thousands of seed may still pose a risk of invasion. Taxa listed as least likely to invade by Meyer and Tchida (17) that were also trialed in this study included *Miscanthus* × *giganteus*, 'Autumn Light', 'Morning Light', 'Silberpfeil', 'Strictus', 'Variegatus', and 'Yaku-Jima'. Although many of these taxa also had relatively low fecundity in our study, 'Autumn Light' was one of our most fecund cultivars, setting more than 220,000 filled seeds per plant in 2010. Wilson and Knox (32) found comparatively high seed viability (all but one cultivar was greater than 40%) in the 15 taxa they tested in Florida but did not quantify seed set.

The only cultivars in this study that did not set seed and thus could be considered non-invasive in the Chicago region are *Miscanthus* × *giganteus*, *M.s.* var. *condensatus* 'Cabaret', 'Hinjo,' and 'Silberpfeil'. These results should be interpreted with caution because seed set could still potentially occur

Table 4. Comparison of mean number of seeds per plant and mean number of inflorescences per taxon from this study (CBG) and two other *Miscanthus* trials (Meyer and Tchida, 1999; Wilson and Knox, 2006). For the Meyer and Tchida study, we present their results from Zone 5 only.

	Mean # seeds/plant				Mean # inflorescences /plant		
	CBG		Meyer and Tchida		CBG		Wilson and Knox
Cultivar	2007	2010	1996	1997	2007	2010	2006
'Adagio'	1,524	52,632	0	0	370	366	481
'Andante'	68,882	53,323	NA	NA	96	212	NA
'Autumn Light'	94,371	221,500	0	3,669	89	250	NA
'Autumn Red'	902	24,185	NA	NA	67	330	NA
'Blutenwunder'	5,994	177,144	4,875	5,340	65	183	NA
'Dixieland'	1,073	497	NA	NA	53	99	NA
'Ferner Osten'	9,425	8,954	—[w]	0	134	218	NA
'Gold Bar'	0	2,061	—	1,077	0	7	NA
'Goliath'	354	13,920	NA	NA	58	186	NA
'Gracillimus'	188	6,103	—	—	202	265	487
'Graziella'	48,845	133,122	—	90	76	220	289
'Hinjo'	0	0	3,288	1,590	8	152	NA
'Huron Sunrise'	61,237	94,612	NA	NA	105	191	NA
'Kleine Silberspinne'	33,076	349,327	NA	NA	435	722	NA
'Little Zebra'	14	2,704	1,836	678	8	169	NA
'Malepartus'	8,675	203,669	NA	NA	63	151	NA
'Minuett'	48,117	91,817	3,249	2,811	119	228	NA
'Morning Light'	0	1,936	NA	NA	105	161	72
'Nippon'	11,928	150,120	0	0	328	417	NA
'Puenktchen'	21,777	16,974	90	54	141	207	131
'Purpurascens'	3,022	24,957	14	270	134	423	NA
'Rotsilber'	20,542	339,462	1,209	2,736	204	350	NA
'Sarabande'	3,278	NA[z]	174	696	59	NA	325
'Silberfeder'	94,144	3,975	4,752	1,962	74	181	439
'Silberpfeil'	0	0	0	0	23	187	NA
'Silberturm'	9,324	28,941	1,044	3,009	38	122	NA
'Strictus'	907	NA[y]	—	—	36	126	NA
'Superstripe'	1,226	NA[y]	NA	NA	35	110	NA
'Variegatus'	211	NA[y]	—	2,571	82	219	312
'Yaku-jima'	138	NA[z]	NA	NA	266	NA	NA
'Zebrinus'	16,621	NA[y]	0	789	42	70	144
M. sacchariflorus	746	NA[x]	0	1,287	81	NA	NA
M. × *giganteus*	0	0	0	0	81	0	NA
M.s. var. condensatus 'Cabaret'	0	NA[z]	0	0	8	NA	103

[z]100% mortality by 2010.

[y]Inflorescences were immature at time of analysis; many plants were harvested before their seeds were mature because of the timing of access to the x-ray machine.

[x]Removed from trial in 2008 due to extensive vegetative spread.

[w]No inflorescences available.

as plants mature or are grown in longer growing seasons; for example, the 'Hinjo' cultivar did set seed in the Meyer and Tchida (1999) trial. *Miscanthus* × *giganteus*, a putative triploid, appears to be completely sterile (6). *M. sinensis* 'Silberpfeil' and 'Cabaret' did not set seed in our study or in Meyer and Tchida's (17) study; however, 'Cabaret' was a poor performer horticulturally and had completely died out by the end our trial, likely due to a lack of winter hardiness.

This trial indicates significant potential for invasiveness due to very high fecundity in many taxa of *Miscanthus*. The possibility of generating large numbers of seedlings due to very large seed quantities produced by most cultivars suggests they should not be used in the Chicago landscape. Although we were not able to successfully germinate seeds in the laboratory due to fungal contamination, both x-ray analysis and the presence of thousands of seedlings in the common garden and neighboring nursery indicate high seed viability (in the third year of the trial no inflorescences were harvested and in the fourth year only one inflorescence per plant was harvested, resulting in heavy seed drop in the common garden). We also have anecdotal evidence that seeds can disperse some distance from the parent plants. We had many seedlings in the Chicago Botanic Garden nursery over 100 m from the common garden, with no other *Miscanthus* growing nearby except those in our study. We also discovered a plant growing in the Garden's restored woodland over 0.5 km from any ornamental or research planting of *Miscanthus*. Quinn et al. have also documented escaped populations up to 3 km from ornamental plantings (22).

Three plants were determined to be mislabeled when sold to us, based on observations after planting by the Chicago Botanic Garden Plant Evaluation staff. From a conservation perspective, this is problematic for implementing restrictions on sales by cultivar as mislabeling could potentially allow plants considered invasive to be sold by mistake. We assume that the average gardener might not notice that they had received an incorrect plant unless its physical characteristics were quite different than what he or she was expecting. Even then, it is doubtful that many would remove the plant and return it to the vendor.

Our study demonstrated that *Miscanthus sinensis* cultivars vary considerably in fecundity and that their fecundity can increase over time. Based on previous modeling (12), and because *M. sinensis* is a known invader and quite long-lived, we recommend that only sterile cultivars be used for landscape or biofuel applications. Lastly, future breeding efforts for cultivars of *Miscanthus* should focus on creating sterile, as well as beautiful, plants.

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