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Natural History Survey of the Ornamental Grass *Miscanthus sinensis* in the Introduced Range

Ryan F. Dougherty, Lauren D. Quinn, A. Bryan Endres, Thomas B. Voigt, and Jacob N. Barney*

Miscanthus sinensis is a perennial grass native to Asia, but since its introduction to the United States in the late 19th century, it has become both a major ornamental crop and invasive species. Previous studies of the ecology of *M. sinensis* in both its introduced and native ranges have suggested that it may be occupying a novel ecological niche in the introduced range. *Miscanthus sinensis* and its daughter species, *Miscanthus* × *giganteus*, are under evaluation as bioenergy crops; therefore, characterization of the ecology and environmental niche of *M. sinensis* is essential to mitigate the risk of fostering future invasion in the United States. In July 2011, we surveyed 18 naturalized *M. sinensis* populations spanning the U.S. distribution, covering a 6° latitudinal gradient from North Carolina to Massachusetts. *Miscanthus sinensis* populations ranged in size from 3 to 181,763 m^2 with densities between 0.0012 and 2.2 individuals m^{-2}, and strongly favored highly disturbed and unmanaged habitats such as roadsides and forest edges. Population size and individual plant morphology (i.e., tiller height, basal diameter, and tiller number) were not affected by soil characteristics and nutrient availability, though increased tree canopy cover was associated with reduced population size ($P < 0.0001$). Plant size and vigor were not significantly affected by low light availability, which supports previous suggestions of shade tolerance of *M. sinensis*. In summary, *M. sinensis* can tolerate a broad range of climatic conditions, light availability, and nutrient availability in the eastern United States, suggesting risk of further invasion beyond its current distribution in the United States.

Nomenclature: Chinese silvergrass; *Eulalia japonica* Trin.; *Miscanthus sinensis* Andersson (Poaceae).

Key words: Biofuel (or bioenergy), invasive, roadside.

Miscanthus sinensis Andersson (Maiden Grass, Chinese Silvergrass, Eulalia) is a C_4 perennial grass native to eastern Asia, but is a wildly popular ornamental grass in the United States. The earliest known introduction of *M. sinensis* to the United States was from Japan to Asheville, NC in 1893 and later to Washington, DC in 1894 (Anon 1984; Quinn et al. 2010). In 1907 the Biltmore Nursery in Asheville, NC had at least four varieties available for sale via mail order catalog (Alexander 2007), and by 1913 *M. sinensis* had naturalized in New York, Florida, and Washington, DC (Britton and Brown 1913). *Miscanthus sinensis* had ‘‘become thoroughly established in many places’’ in West Virginia as early as the 1940s (Core 1941). Despite escapes, the ornamental grass industry has boomed in the last 20 yr, largely because of their pleasing aesthetic and low input costs.

Liberty Hyde Bailey (1909) wrote about *Miscanthus sinensis* (*Eulalia japonica* Trin.) that, ‘‘Although many progressive nurserymen now advertise these favorite grasses as Miscanthus, the name Eulalia will probably remain in the English language as a thoroughly naturalized word, like Geranium or Chrysanthemum.’’ In a search for the origins of *Eulalia japonica* in the United States, it was found that the *Trade List of Plants for the Spring of 1878,* the catalogue of the John Dick, Helendale Nursery, Philadelphia, PA, offered *Eulalia japonica variegata* for 25 to 50 cents each (Dick 1879). The same nursery also offered *Eulalia japonica zebrina* in their Fall 1879 catalogue for 25 to 75 cents each.

As a result of multiple introductions from Asia, traditional breeding programs, and commercialization, there are now over 100 named cultivars of *M. sinensis*

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* First and fifth authors: Graduate Student and Assistant Professor, Department of Plant Pathology, Physiology, and Weed Science, Virginia Tech, Blacksburg, VA 24061; second author: Postdoctoral Research Associate, Energy Biosciences Institute, University of Illinois, Urbana, IL 61801; third author: Associate Professor, Department of Agricultural and Consumer Economics, University of Illinois, Urbana, IL 61801; fourth author: Associate Professor, Department of Crop Sciences, University of Illinois, Urbana, IL 61801. Corresponding author's E-mail: jnbarney@vt.edu

Management Implications

Miscanthus sinensis is an extremely popular ornamental grass, and is currently naturalized across much of the eastern United States. There are > 100 named cultivars commercially available with tremendous phenotypic variation that may facilitate tolerance to a broad range of geographies in the introduced range. In this study, we surveyed 18 naturalized *M. sinensis* populations from North Carolina to Massachusetts to characterize the environmental, climate, and edaphic factors in invaded habitats, as well as describe individual and population-level phenotypic variation. The vast majority of *M. sinensis* populations are found in heavily disturbed habitats such as roadsides, utility rights-of-way, and managed forest edges. Populations ranged in size from 3 m^2 to > 18 ha, and exhibited tolerance to edaphic conditions ranging in pH (4.2 to 7.3) and nutrient availability. The sampled latitudes represent a range of annual precipitation amounts and minimum temperatures—further support that *M. sinensis* has a broad environmental niche. Whether the populations originated from intentional plantings or from escaped ornamental plantings is equivocal. Thus, managers cultivating *M. sinensis* for commercial purposes (e.g., bioenergy, breeding, ornamental nursery stock) should employ best management practices to ensure that the wind-dispersed seeds do not enter sensitive habitat. It appears that *M. sinensis* is tolerant to disturbance common to rights-of-way (e.g., mowing), and prefers high light environments. Land managers should control *M. sinensis* prior to seed development to reduce propagule spread further, and integrate chemical and mechanical management to reduce population size. Because *M. sinensis* is such a popular ornamental grass it is unlikely that future introductions will be prevented; thus, future invasion mitigation would be facilitated by determining if specific cultivars are contributing to escape and prevent their sale.

available on the market (Darke 2007; Quinn et al. 2010). *Miscanthus sinensis* has become one of the most popular and highly recommended ornamental grasses in the United States (Maynard 2012). As recently as 2008, sales of *M. sinensis* totaled nearly $40 million in the state of North Carolina alone (Trueblood 2009). Currently, *M. sinensis* has naturalized in at least 25 states (EDDMaps 2012), and its known distribution continues to expand as more populations are added to public databases. Of the 25 states with naturalized populations, 21 are east of the Mississippi River; however, occurrences have also been recorded in western states such as California and Colorado.

New interest in *M. sinensis* has arisen for use as a potential bioenergy feedstock itself, as well as breeding germplasm for novel lines of high biomass producing crops (e.g., *Miscanthus* × *giganteus*) (Stewart et al. 2009; Zub and Brancourt-Hulmel 2010). Candidate bioenergy crops must possess a litany of agronomic characteristics to fulfill both economic and production requirements, which include perenniality, C4 photosynthesis, few pests, rapid growth, high water-use efficiency, and tolerance of poor growing conditions (Barney and DiTomaso 2010; Raghu et al. 2006). Unfortunately, these traits are shared with many of the most problematic weeds and invasive species (Raghu et al. 2006); thus, bioenergy crops pose a potential invasion risk. *Miscanthus sinensis* is known to express many of these desirable traits, including C4 photosynthesis, rhizome production, rapid growth, and tolerance to cold and frost (Stewart et al. 2009; Zub and Brancourt-Hulmel 2010; Zub et al. 2012). These traits contribute to its immense popularity as an ornamental, as *M. sinensis* cultivation requires relatively few inputs. However, these same traits may have contributed to the success of *M. sinensis* beyond its planted boundaries.

Before large-scale cultivation of any bioenergy crop begins, it is important to understand and assess the potential agricultural, ecological, and economic risks that may come with introducing exotic species to novel ecosystems (Barney and DiTomaso 2010; Yokomizo et al. 2012). Previous comparisons of *M. sinensis* populations from the native (i.e., East Asia) and introduced (i.e., United States) ranges have suggested that it may be shifting into a novel ecological niche in the introduced range because of variation in climate and edaphic factors (Quinn et al. 2012). Invasive species often perform better and grow larger in novel ecosystems for a variety of reasons, including release from pathogens, predators, and competition (Firn et al. 2011; Thébaud and Simberloff 2001). The potential of an ecological niche shift raises the importance of understanding the history, general ecology, and habitat preferences of *M. sinensis* as a precaution to introducing the next major invasive species.

The goal of this study was to investigate the natural history and ecology of *M. sinensis* in the eastern United States. More specifically, our objective was to characterize the ecological niche of *M. sinensis* by identifying habitat, soil, and climate characteristics associated with both individual- and population-level characters of established populations.

Materials and Methods

Study Sites. Eighteen locations were visited in the eastern United States in the summer of 2011 from North Carolina to Massachusetts (35.2690° to 41.5815°N, 70.5256 to 82.5651°W). Sites were chosen from a database we compiled of *M. sinensis* escapes collected from an E-mail survey of Master Gardeners, Master Naturalists, Invasive Plant Councils, Exotic Pest Plant Councils, and Departments of Natural Resources. The 18 sites we visited were chosen based on our ability to travel to and collect samples from as many sites as possible over a 2-wk period (to reduce phenological variation), while representing the latitudinal and geographic range of naturalized *M. sinensis* populations in the eastern United States. Although more sites would have been desirable, nearly the entire latitudinal range of *M. sinensis* in the eastern United States was sampled, and therefore our sample can be considered a reasonable representation of the variation among populations. Populations were always isolated by > 500 m.

At each location we recorded several environmental variables adjacent to *M. sinensis* individuals to broadly characterize the habitat. At each of five randomly placed sampling points within the *M. sinensis* population, we recorded percentage of tree canopy cover with the use of fish-eye lens photography and WinSCANOPY© (Regent Instruments Inc. Nepean, ON, Canada) software or a convex spherical densiometer (Forestry Suppliers Inc., Jackson, MS, USA). We also collected bulk soil samples from the top 15 cm of the soil (including the O horizon when present) with the use of a standard soil probe, the samples were subsequently air dried, homogenized, and analyzed for pH (1 : 1, soil : water), organic matter (%, using loss on ignition at 360 C for 2 h), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), manganese (Mn), copper (Cu), iron (Fe), and boron (B) (in mg/kg) with the use of Mehlich-1 extractant and supernatant analyzed by inductively coupled plasma atomic emission spectrometer (ICP-ES). GPS points were collected around the perimeter of each population, and these were subsequently analyzed in a geographic information system (GIS) to estimate total population spatial extent. GPS data were also used to collect environmental and climate information from WorldClim databases in GIS software (ArcMap 10, ESRI, Golden, CO), including elevation, temperature, and precipitation. To estimate population density, we counted the total number of *M. sinensis* individuals in five, 10 by 1–m belt transects randomly located throughout each population (the same location could not be sampled twice). We estimated plant density over each population by extrapolating the average density per transect (individuals 10 m^{-2}) to the total area of the population.

To characterize the population at each location, we randomly selected several *M. sinensis* individuals for measurement of morphological characters (n = 20 for most sites, except MA-01 [n = 18], CT-01 [n = 13], RI-01 [n = 8], and NJ-02 [n = 2], where only that number of plants were found). For each *M. sinensis* individual we recorded three subsamples of tiller height (soil surface to the uppermost leaf collar) and tiller diameter, the total number of tillers, and basal diameter recorded in two orthogonal directions. Finally, photosynthetically active radiation (PAR) was recorded with the use of an AccuPAR LP-80 PAR/LAI ceptometer (Decagon Devices, Inc., Pullman, WA) above and below the *M. sinensis* canopy. Basal area was calculated as $\pi \times (0.5^*\text{average diameter})^2$, and tiller density as tiller number/basal area.

Finally, we scouted for extant *M. sinensis* individuals or populations (naturalized and ornamental plantings) by driving approximately 1.6 km away from each site in all available directions to scout roadsides. The approximate number of individuals and the GPS location were recorded for each satellite population we located.

Data Analysis. To describe the range and variation of naturalized *M. sinensis* populations in the United States, summary statistics were generated from the morphological characters, demographics, and soil data collected. Soil characteristics, including pH, macronutrients (P, K, Ca, Mg), micronutrients (Mn, Fe, Cu, B, Zn), and organic matter, were ordinated with the use of principal-components analysis (cross-products matrix derived from correlation). Climate and geography characteristics, such as elevation, maximum average temperature of the warmest month, minimum average temperature of the coldest month, precipitation of the driest month, and precipitation of the wettest month, derived from spatial analysis, were also ordinated with the use of principal-components analysis (from correlation). Principal-component analyses enable us to linearize the multivariate soil and climatic data we collected, enabling us to identify which individual characteristics contribute (through loading values to each principal axis) most to our measured population responses (Abella et al. 2012). All soil and climate characteristics were Z-score transformed prior to principal-components analysis. Linear fixed effect regressions (JMP9, SAS Inc., Cary, NC, USA) were performed to determine how *M. sinensis* population size and morphology were correlated with the first and second principal components from the above edaphic and climatic analyses. Further linear fixed effects models compared the same morphological characteristics to canopy cover, with latitude used as a covariate. Plant height, basal area, tiller number, and population size were transformed with the use of the best Box-Cox transformation. The Martinsville, VA site was determined to be a statistical outlier by Grubb's test for outliers ($\alpha = 0.05$), and was subsequently omitted from population size models.

Results and Discussion

Miscanthus sinensis populations are distributed over a large geographic range representing a wide variety of climatic conditions and habitats (Tables 1 and 2). The latitudinal gradient of populations spanned approximately 6°, from 35.55° in North Carolina to 41.58° in Massachusetts. Invaded habitats fell into several categories (Table 1), including forest understories, forest edges, open fields, and road and railroad rights-of-way. Of these categories, forest edges ($n = 10$) and roadsides ($n = 7$) were the most common. Sources of population origin were indeterminable from the surveys of surrounding areas, as it was impossible to estimate which came first. The average estimated population size was 9,437 individuals with an average population density of 86 individuals 100 m^{-2}.

In its native range, *M. sinensis* commonly occurs in mixed grasslands, where it tolerates fire disturbances, grazing, and forage harvesting (Osawa 2011; Stewart et al. 2009). In the introduced range, *M. sinensis* appears to

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Table 1. Locations, *M. sinensis* population information and habitat descriptions for all surveyed sites.

State	City	Site	Latitude	Longitude	Estimated population area	Estimated population density	Habitat description
			N	W	Hectares	plants m^{-2}	
North Carolina	Henderson	NC-01	35.2690	82.4102	0.903	1.4	Roadside, railroad, open field
North Carolina	Asheville	NC-02	35.5505	82.5651	0.911	0.9	Forest understory
North Carolina	Mars Hill	NC-04	35.9410	82.5585	0.419	1.4	Roadside
North Carolina	Mars Hill	NC-03	35.9542	82.5640	0.245	0.8	Forest understory, trail side
Virginia	Martinsville	VA-02	36.7505	79.7340	18.176	1.8	Roadside, open field, forest edge
Virginia	Amherst	VA-01	37.5622	77.0147	1.587	1.6	Forest edge, roadside
Maryland	Cromwell	MD-04	39.4040	76.5623	0.654	1.2	Roadside, forest edge
Maryland	Fallston	MD-03	39.5080	76.3825	0.541	1.1	Open field, forest edge
Maryland	Monkton	MD-02	39.5998	76.6046	1.323	2.2	Forest understory, forest edge
Pennsylvania	Fort Washington	PA-01	40.1197	75.2235	1.107	0.6	Forest edge, trail side
Pennsylvania	Quakertown	PA-02	40.4152	75.3133	1.286	0.9	Railroad, forest edge
New York	Heckscher State Park	NY-02	40.7093	73.1488	4.909	0.8	Trailside, open field, forest edge
New Jersey	Great Swamp	NJ-02	40.7153	74.4875	0.000280	0.7	Forest edge
New York	Seatuck	NY-01	40.7168	73.4083	0.902	0.5	Open field
New Jersey	Bernardsville	NJ-01	40.7329	74.5763	0.196	0.4	Roadside, forest understory
Rhode Island	Charlestown	RI-01	41.3732	71.5938	0.691	0.0012	Forest understory
Connecticut	Quaker Hill	CT-01	41.3974	72.1145	0.146	0.0089	Roadside, forest edge
Massachusetts	Falmouth	MA-01	41.5815	70.5256	0.0302	0.060	Open field

establish in a variety of habitats defining a broad ecological niche, which include highly disturbed, anthropogenic habitats (e.g., rights-of-way), as well as unmanaged forest edges and more rarely forest interiors. This is likely a result of the frequent disturbance along roadsides and the wind-dispersed spikelets of *M. sinensis* (Quinn et al. 2011). One of the key questions regarding invasive species, and especially *M. sinensis*, is the source of the naturalized populations. Are they ornamental hybrids from neighboring houses or commercial properties gone wild? We attempted to identify potential source (or satellite) populations within 1.6 km of the surveyed populations and were generally unsuccessful. Although some ornamental plantings and small cohorts were discovered, it was not possible to attribute them as the propagule source for the sites surveyed, or vice versa. The distance between many of these satellite populations (or plantings) and the original surveyed population often exceeded 800 m (data not shown), which is far beyond the distance *M. sinensis* spikelets have been empirically shown to disperse (Quinn et al. 2011). However, past work has traced the path and distance of *M. sinensis* invasions based on historical records of the original ornamental plantings; this effort has suggested that *M. sinensis* can disperse and establish over a kilometer from ornamental plantings within 20 yr of introduction (Quinn et al. 2010). It is important to note that our survey techniques for these satellite populations were very limited, and we only sampled a few points. Genetic characterization would be needed to link source populations with satellite individuals definitively.

As expected, climate conditions at each site correlated with latitudinal position, with minimum and maximum mean temperatures generally decreasing for northern populations (Table 2). The maximum average annual temperature experienced by any population was 31.4°C (VA-01; Martinsville, VA), while the minimum average annual temperature was −8.3°C (NJ-01; Bernardsville, NJ). In the principal-component analysis of climate conditions, the first principal component accounted for 53% of variance while the second principal component accounted for 32% (85% overall, Figure 1). Characteristics exhibiting the highest loadings included annual precipitation (loading = 0.96), precipitation during the wettest month (0.92), precipitation during the driest month (0.88), and elevation (0.81) in the first principal component. The annual mean temperature (0.93), minimum temperature of the coldest month (0.86), and maximum temperature of the warmest month (0.59) exhibited the highest loadings for the second principal component of climatic conditions.

Edaphic conditions measured from bulk soil samples were highly variable among sites (Table 3). The pH ranged between 4.22 and 7.27 with a mean of 5.29. Macronutrients such as P (3 Mg kg^{-1} to 93 Mg kg^{-1}), K (31.5 Mg kg^{-1} to 167.5 Mg kg^{-1}) and Ca (316.5 Mg kg^{-1} to 1,771 Mg kg^{-1}) had the most variation of any nutrient characteristic, whereas

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Table 2. Elevation and climate data for 18 *Miscanthus sinensis* populations surveyed. All data derived from WorldClim database with the use of ArcMap10. Abbreviations: T_{max}: maximum average temperature of warmest month; T_{mean}: mean temperature across all months; T_{min}: minimum average of coldest month; precip = precipitation. Precipitation of the wettest and driest months (mo) are cumulative across those months. Annual precipitation is cumulative across all months.

Site	Elevation	T_{max}	T_{mean}	T_{min}	Annual precipitation	Precipitation wettest month	Precipitation driest month
	m	C			mm		
NC-01	664	29.0	13.0	−3.6	1,474	148	111
NC-02	664	29.1	12.7	−4.2	1,158	116	83
NC-04	1022	26.1	10.4	−6.3	1,321	130	94
NC-03	1140	25.2	9.8	−6.5	1,390	136	100
VA-02	296	30.4	13.2	−4.0	1,150	115	83
VA-01	137	31.4	14.3	−3.1	1,101	117	76
MD-04	109	30.8	12.6	−5.1	1,151	114	80
MD-03	122	30.2	12.2	−5.6	1,154	113	76
MD-02	179	29.4	11.5	−6.1	1,128	113	76
PA-01	52	29.9	11.9	−5.4	1,130	113	73
PA-02	158	29.1	10.5	−7.0	1,154	112	74
NY-02	3	27.8	11.3	−4.5	1,144	111	84
NJ-02	75	29.3	10.5	−7.6	1,235	123	77
NY-01	0	28.1	11.4	−4.5	1,118	109	81
NJ-01	172	28.5	9.8	−8.3	1,266	124	79
RI-01	15	26.2	10.0	−5.9	1,153	116	77
CT-01	48	27.3	9.9	−7.2	1,224	120	86
MA-01	9	25.7	9.9	−5.7	1,167	118	75

organic matter content ranged from near zero to almost 50% (Table 3). In the principal-component analysis of soil properties, the first principal component accounted for 33% of the variance, and the second principal component accounted for 19% (52% overall, Figure 1). Properties and characteristics exhibiting the highest loadings on the first two components included Ca (loading = 0.94) and pH (0.78) for component 1, and Cu (0.77), Mn (−0.62), and organic matter (0.59) for component 2.

The linear fixed-effects model of the second principal component of climate characteristics was positively correlated with population size (R^2 adjusted = 0.237; P = 0.0273). All other models of principal components and morphological responses were nonsignificant ($P > 0.05$). Finally, we found that tree canopy cover does not significantly affect tiller height (P = 0.1331), basal area (P = 0.4499), tiller number (P = 0.0755), or population size (P = 0.1613).

Surveyed populations were present in both highly disturbed and low disturbance sites with high and low resource availability. Invaded habitats covered a broad latitudinal range, low and high elevations (0 to 1,140 m), acidic soils, and a wide range of macro- and micronutrient availability. Our findings are consistent with previous assertions that *M. sinensis* can tolerate stressful and/or marginal environments in both the native and introduced ranges (Ezaki et al. 2008; Quinn et al. 2012; Stewart et al. 2009).

The large latitudinal range covered in this study exhibits the broad climatic tolerance of *M. sinensis*, which is consistent with climate niche model predictions (Barney and DiTomaso 2011). Several populations occurred in regions with minimum temperatures below freezing (Table 2), supporting previous suggestions of cold tolerance (Stewart et al. 2009; Zub et al. 2012). Populations were significantly smaller in colder areas, but present nonetheless, which is likely caused by the shorter growing season and exposure to lower minimum temperatures. Aside from climatic conditions, this may also be related to population age and time since establishment, combined with limited reproductive output in the shortened growing season. Smaller population sizes may result in limited reproductive output and seed set; however, we found that seed collected from each population along the distribution was viable under lab and greenhouse conditions, regardless of populations size and/or location (Dougherty, unpublished data). The largest populations in this study were found near areas of the earliest introductions of *M. sinensis* (i.e., Asheville, NC and Washington, DC), suggesting that, with time and propagule pressure, there may be population size increases in the northeast in the future. In fact, our multivariate analysis of climatic factors shows that the vast

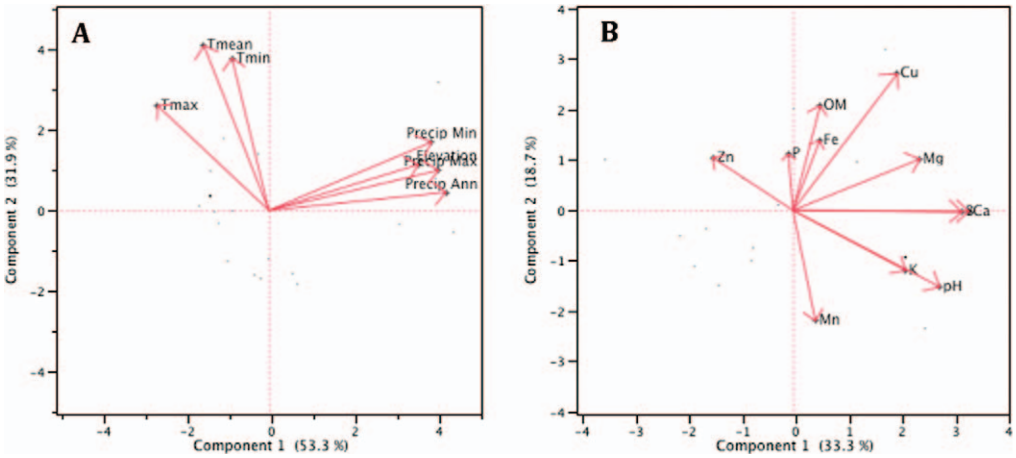

Figure 1. Principal components 1 and 2 (variation accounted for by each component) of (A) climate characteristics and (B) soil characteristics for the 18 naturalized *Miscanthus sinensis* populations. Abbreviations: T_{max}: average maximum temperature of the warmest month. T_{min}: average minimum temperature of the coldest month. T_{mean}: average annual temperature. Precip_Min: average precipitation of the driest month. Precip_Max: average precipitation of the wettest month. Precip_Ann: average annual precipitation. (Color for this figure is available in the online version of this paper.)

majority of populations surveyed cluster together according to temperature variables rather than variables associated with precipitation (Figure 1A). In addition, climate principal component two (loadings: T_{mean}, 0.93; T_{min}, 0.86; T_{max}, 0.59) was positively correlated with population size (R^2 adjusted = 0.237; P = 0.0273). This implies that temperature, much more than precipitation, is a greater driver of the establishment and expansion of *M. sinensis* populations. Previous studies support this notion, often suggesting that *M. sinensis* is a drought tolerant species (Quinn et al. 2010; Stewart et al. 2009); therefore, precipitation would not be expected as a primary limitation to population performance.

In the native range, *M. sinensis* is an early successional species, and is often found as one of the first pioneer plants to establish in extremely acidic (pH < 3.0) volcanic ash–based soils (Stewart et al. 2009). Although such extreme conditions were not found during our survey, populations were established in soils with a wide range of pH (4.22 to 7.27) and equally wide ranges of macro- and micronutrient availability (Table 3). Multivariate analysis of soil characteristics shows most populations do not cluster according to any soil variables, including pH, macronutrients, micronutrients, and organic matter (Figure 1B). Regressions comparing plant morphology and soil principal components were all nonsignificant (P > 0.05). This suggests that soil resources are not a limiting factor in the establishment and success of *M. sinensis* populations.

Because *M. sinensis* is occasionally found in low-light environments, it is increasingly important to understand its shade tolerance. Recent studies have shown that *M. sinensis* can maintain high photosynthetic rates even at extremely low light levels (Horton et al. 2010). However, individuals from native and introduced populations have not shown significant differences in biomass accumulation and total leaf area (Matlaga et al. 2012). In this survey, sites had canopy covers ranging from < 1% to 100% (Table 3), suggesting a broad range of potential tolerance. The majority of surveyed populations established in canopy covers < 50% (n = 10); compared to only 28% of populations under canopy cover > 85% (n = 5). This may suggest enhanced shade tolerance in the introduced range;

Table 3. Summary statistics for soil characteristics and canopy cover across all sites surveyed (n = 18).

	P	K	Ca	Mg	Zn	Mn	Cu	Fe	B	pH	Organic matter	Canopy cover
	mg/kg										%	
Min	3.0	31.5	316.5	17.0	1.50	6.80	0.35	10.7	0.2	4.22	3.9	0.16
Med	6.5	73.5	665.0	124.5	4.00	21.2	0.80	21.4	0.4	5.93	7.65	38.02
Mean	16.0	81.6	835.7	140.0	6.84	26.2	0.96	32.7	.04	5.92	10.4	52.09
Max	93.0	167.5	1,771.0	379.0	37.6	78.7	2.2	137.9	0.8	7.27	49.1	100.0

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however, population size was not significantly correlated with canopy cover. As mentioned previously, the average population size from all sites surveyed was 9,437 individuals ($n = 17$)—average size was $> 27{,}000$ with all sites included ($n = 18$)—compared to 11,844 individuals in a subset of populations with canopy cover $< 50\%$ ($n = 9$), and 2,446 individuals in a subset of populations with canopy cover $>85\%$ ($n = 5$). Even so, canopy cover did not significantly affect *M. sinensis* morphology. It does appear that *M. sinensis* populations can establish in low-light environments; however, more empirical work must be done to determine shade tolerance.

Potential for Future Spread and Conclusions

As mentioned previously, Quinn et al. (2012) found variation in the environmental tolerances between *M. sinensis* populations in the native and introduced ranges, and proposed that it may be occupying a novel ecological niche in the introduced range. Our survey provides evidence in support of this claim. *Miscanthus sinensis* populations in highly disturbed, high-canopy habitats across the eastern United States are quite different from the open grasslands of *M. sinensis* in the native range (i.e., Japan and eastern China). *Miscanthus sinensis* is currently naturalized in 25 states, with population sizes ranging from a handful of individuals to hundreds of thousands, all capable of producing vast amounts of wind-dispersed spikelets. Although not all of these spikelets will be viable, seed collected from each population in this survey was germinable in laboratory conditions (RF Dougherty, unpublished data). A fully mature *M. sinensis* individual can produce > 100 flowering panicles per year (Quinn et al. 2011), with approximately 1,800 spikelets panicle^{-1}. Hypothetically, if we apply these numbers to our average population size (9,437 individuals), assuming each individual produces approximately half of the 100 + potential panicles with 1,800 spikelets panicle^{-1}, the average naturalized *M. sinensis* population is capable of producing over 8.4 billion spikelets year^{-1}. Although these numbers may seem daunting, the amount of actual fertilized and viable spikelets likely varies significantly among individuals and populations, which has yet to be examined.

Currently, it is not uncommon to find populations of *M. sinensis* that span well > 80 km alongside North Carolina interstate highways. This already intense propagule pressure, combined with increasing horticultural demand and potential bioenergy crop status, could result in tremendous spread and propagation well beyond the current distribution. Populations established along roadsides, interstate highways, and railroads could push populations into forest interiors and conservation areas, especially given results that indicate a tolerance for low-light conditions (Horton et al. 2010; Matlaga et al. 2012).

Miscanthus sinensis has broad climatic tolerance and minimal soil requirements for establishment. Although it currently tends to establish in low-value areas such as roadsides and forest edges, horticulturists and bioenergy stakeholders should proceed with caution in order to prevent further spread and naturalization of *M. sinensis* or its derivatives in its introduced range. Further work on *M. sinensis* should explore shade tolerance and soil moisture requirements for establishment in situ to clarify its ecological niche further. There can be significant variation in the reproductive output (i.e., seed set) between *M. sinensis* ornamental cultivars (Meyer and Tchida 1999). Therefore, it would be useful to compare a range of ornamental cultivars and naturalized individuals in order to identify any high or low-risk ornamental varieties.

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