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The role of lake effect snow cover in reducing the susceptibility of
***Miscanthus × giganteus* to extreme cold soil temperatures in**
Michigan

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Abstract

Miscanthus × giganteus (hereafter “*M. × giganteus*”) is a low-input, highly productive perennial grass increasingly grown in the US Midwest for conversion into cellulosic ethanol. *M. × giganteus* must be propagated rhizomatously because it is a sterile hybrid, and because it is a perennial crop, mass die-offs may take two to three years to recover fully. This leads to economic loss and interruption of bioenergy supply. Several experimental *M. × giganteus* crops in Illinois and Wisconsin experienced mass mortality due to extreme cold soil temperatures in the winter of 2008–2009. During this same winter, experimental *M. × giganteus* crops in Michigan experienced little to no mortality. It is hypothesized that the insulating effect of increased snow depth and duration due to lake effect snowfall is sufficient to reduce the risk of cold-induced *M. × giganteus* mortality in the Lower Peninsula of Michigan, where the opportunity cost of farmland is also lower than in other parts of the US Midwest. Observations of air and soil temperatures from experimental *M. × giganteus* plots in Illinois, Wisconsin, and Michigan are analyzed during periods of snow cover and no snow cover in two anomalously cold winters, and a synoptic analysis is also presented. It is found that the absolute difference between the shallow soil temperature and air temperature was 3–7°C greater when there was at least 2.5 cm of snow on the ground at these sites. However, shallow soil temperatures were observed to drop below laboratory mortality temperature thresholds of *M. × giganteus* (–3°C and –6.5°C) despite snow cover, demonstrating that snowfall alone should not be relied upon to sufficiently insulate *M. × giganteus* rhizomes during their winter dormancy. Additionally, seven winters of shallow soil

47 temperature observations at 12 sites in Michigan are compared with satellite-
48 derived estimates of snow cover and it is shown that increased snow cover depth
49 may not lead to decreased likelihood of soil temperatures below -3°C .

50

51 **Keywords**

52 Bioenergy, *M.× giganteus*, rhizome establishment, mortality, snow cover, soil
53 temperature, Michigan

1. Introduction

1.1 *M. × giganteus* as a viable biofuel

As use of the world's fossil fuel reserves becomes increasingly more contentious, innovative alternatives continue to be sought to satisfy the world's increasing energy demands. In the United States transportation sector, an alternative method of focus has been the use of biofuels, including the conversion of dry plant matter into liquid ethanol as well as thermal-chemical conversion. This focus is largely motivated by the fact that biofuels are the only type of renewable energy that can be produced in a liquid form and are scale-compatible with existing transportation infrastructure (Heaton et al., 2010). The Energy Independence and Security Act (EISA) of 2007 (US House, 2007) calls for the domestic production of 36 billion gallons (bga) of ethanol by 2022 (up from 4.7 bga in 2007). EISA also specifies that 21 of the 36 bga ethanol must be derived from biomass sources other than corn since it would be impossible to meet the 36 bga goal using domestic corn alone (e.g. Heaton et al., 2008). A prime candidate crop for this role is asserted to be *Miscanthus × giganteus* (hereafter "*M. × giganteus*").

M. × giganteus is a dense, tall grass (3–5 meters) native to eastern Asia that is a favorable source of cellulosic ethanol due to its productivity (260% more harvestable biomass per unit surface area than corn and 280% more than switchgrass, another proposed cellulosic ethanol crop [Heaton et al., 2008]) and its low agrochemical requirements (Kucharik et al., 2013). *M. × giganteus* is a natural sterile hybrid of *Miscanthus sinensis* and *Miscanthus sacchariflorus*, propagating by rhizome instead of by seed (Beale and Long, 1997; Dohleman and Long, 2009). It has

77 been used in Europe as a feedstock for ethanol production for over 30 years and has
78 shown no evidence of being an invasive species (Heaton et al., 2010).

79 **1.2 Strategic propagation methods of *M. × giganteus***

80 To avoid mass *M. × giganteus* die-off and the agro-economic consequences of
81 a disruption of several years, there are two ways in which it has been proposed to
82 strategically propagate *M. × giganteus*: first, by initiating crops exclusively in areas
83 where the climatological range of temperature and moisture make a year of
84 unsustainability extremely unlikely (i.e. an area of stable productivity; Jain et al.,
85 2010), and second, by the adoption of strategic in situ planting and management
86 methods.

87 **1.2.1 Bounds of *M. × giganteus* sustainability in the US Midwest**

88 Many studies have focused on the water-limited sustainability of *M. ×*
89 *giganteus* (e.g. McIsaac et al., 2010; VanLoocke et al., 2012; Zeri et al., 2013). Such
90 research has contributed insight into the location of the western boundary of *M. ×*
91 *giganteus* sustainability in the US Midwest given water limitations. Research on the
92 southern US bounds of *M. × giganteus* sustainability has focused on the quantity of
93 damaging overly-hot growing season days (Kiniry et al., 2013; Song et al., 2014) and
94 the annual lack of a killing frost, necessary as an impulse for *M. × giganteus* to
95 senesce or “brown down” in the winter, thereby returning vital nutrients to the
96 rhizomes for growth the following year (Christian et al., 2009). From these
97 hypothetical bounds have arisen several propositions of the geographical boundary
98 of *M. × giganteus* sustainability in the Midwest, the results of which are shown in
99 Figure 1.

100 In contrast to these efforts to characterize and prevent the mortality of *M. ×*
101 *giganteus* due to water limitations and heat stress, a considerably smaller amount of
102 research has focused on the mortality of *M. × giganteus* due to extreme cold soil
103 temperatures, which can kill rhizomes during winter dormancy. Extreme post-
104 harvest cold has several times been a principal cause of death during the
105 establishment of *M. × giganteus* experimental field sites, including the almost
106 complete mortality of the University of Illinois Urbana-Champaign (UIUC) Energy
107 Farm site in the winter of 2008–09 (Heaton et al., 2010; Zeri et al., 2011) that
108 disrupted a number of planned bioenergy crop comparison studies. Other mass die-
109 offs have occurred in northern Michigan (Song et al., 2014; D. Pennington, personal
110 communication, 2015) and in central Wisconsin during the winter of 2008–09
111 (Heaton et al., 2010; G. Sanford, personal communication, 2015). In Europe, where
112 *M. × giganteus* has been an experimental biofuel crop since at least 1992 (Heaton et
113 al., 2008), a mass winter die-off occurred in Sweden (56°N; 93% loss) and Denmark
114 (56.5°N; 100% loss) following a June 1997 planting; during this time the minimum
115 5cm soil temperature reached –5.4°C and –4.5°C, respectively (Clifton-Brown and
116 Lewandowski, 2000). Nearby *M. × giganteus* stands in the United Kingdom (51.8°N)
117 and Germany (48.7°N) experienced complete survival during the same winter, with
118 5cm minimum soil temperatures reaching –1.2°C and –2.8°C respectively. In a
119 laboratory test, Clifton-Brown and Lewandowski (2000) found that freezing *M. ×*
120 *giganteus* rhizomes to a temperature of –3°C began to induce mortality and that at –
121 3.5°C, half of the rhizomes had died. Peixoto et al. (2015) found that *M. × giganteus*
122 rhizomes tolerated temperatures as low as –6.5°C when lowered 1°C per hour in a

laboratory freezing experiment, and several specific strains tolerated temperatures as low as -14°C when the temperature was lowered more slowly (1°C per day). Rosser (2012) notes that rarely did stands suffering 10% or greater mortality have yields in the following year that were sufficient to compensate for the loss.

1.2.2 Strategic in situ management methods of *M. × giganteus*

A set of *M. × giganteus* propagation strategies calls for the adoption of different planting techniques in areas with a greater likelihood of extreme cold winter temperatures in order to better insulate the rhizomes and prevent mortality. While Clifton-Brown and Lewandowski (2000) report a standard rhizome planting depth of 5cm in early European *M. × giganteus* stands, the standard practice in the US is now a planting depth of 10cm. This depth was first employed in Illinois in 2002 (Heaton et al., 2008) and was confirmed by Pyter et al. (2010) in a separate trial to be the planting depth which produced the greatest quantity of biomass after a single year's growth.

Pennington (2011) suggests that propagating *M. × giganteus* via plugs (i.e. with a small, viable existing shoot and root structure established in a greenhouse and micro-propagated within a block of soil), instead of via rhizomes, significantly reduces mortality and increases yield during the first two years of growth. Plazek et al. (2011) likewise observed decreased mortality in *M. × giganteus* plugs versus rhizomes, although only during the first year of growth, emphasizing the importance of mitigating winter temperature stress during the establishment year. However, Boersma and Heaton (2014) asserts that during *M. × giganteus* establishment in Iowa from 2009 to 2011, no significant difference in yield or winter mortality was

observed between the two propagation methods; moreover, *M. × giganteus* losses from failure to survive initial establishment outweighed *M. × giganteus* losses due to winter die-off by a factor of 20 during this time.

Kucharik et al. (2013) used a dynamic ecosystem model to show that as little as 2.5cm (1in) of post-harvest field residue was enough to raise the annual minimum 10cm soil temperatures by 1–3°C compared to bare soil across Iowa, Wisconsin, and Illinois, and 5cm of residue (enough to raise 10cm temperatures 2–5°C) virtually eliminated the risk of 10cm soil temperature reaching –3°C in Iowa, Illinois, Michigan, Kansas, and all states farther south. It is mentioned that leftover residue/stubble not only insulates the surface soil layer from radiative cooling but also preferentially traps snow, which insulates the soil even further; this is supported by Benoit et al. (1986).

1.3 Michigan as a favorable region for *M. × giganteus* propagation

1.3.1 Opportunity cost of land

Several studies analyzing the economic requirements and viability of a *M. × giganteus* regime in the US have been undertaken (e.g. Khanna et al., 2008; Jain et al., 2010; Xie et al., 2013). Notably, Jain et al (2010) developed a county-level budget of and switchgrass production costs in the Midwest. Michigan was found to be the state with the lowest opportunity cost of land for a corn-soybean rotation. It is asserted that in regards to the opportunity cost of land for *M. × giganteus*, Michigan is second to Missouri. The hypothetical *M. × giganteus* yield in Michigan was found to have a breakeven price for profitability of \$79–128 per ton of dry matter,

comparable to Iowa but slightly higher than that of Illinois, Indiana, Ohio, and Missouri due to the modeled risk of cold mortality in Michigan.

1.3.2 Snowpack insulation

Just as it takes little crop residue to decrease soil heat loss in the winter per Kucharik et al. (2013), the insulating effects of snowpack are also significant. The thermal conductivity of snow is one-third to one-fifth that of mineral soil; therefore, less heat is transferred by conduction to a colder atmosphere when the ground is snow-covered (Figure 2). Specifically, Geiger (1965) found that it takes 7.5cm of snow to dampen the daily range of surface soil temperature by fifty percent, and Sharatt et al. (1992) and Isard and Schaeztl (1995) analyzed empirical data to conclude that 15cm of snow is sufficient to achieve a steady state soil temperature. In Finland, the lowest observed 10cm soil temperature under a non-vegetated surface and at least 30cm of snow during several weeks of temperatures below – 20°C was –1.5°C (Sutinen et al., 2008).

It is hypothesized that regions that are characterized not only by relatively high annual snowfall but also by continuous snowpack coverage are less likely to experience threateningly low shallow soil temperatures for *M. x giganteus* (i.e. less than –3°C). Areas that experience regular lake effect snowfall fit these criteria, and one such area in particular is the west coast of Michigan’s Lower Peninsula due to the impact of lake effect snow from the Great Lakes of North America. When cold air aloft behind a cold front travels over the relatively warmer water of the Great Lakes, vigorous convection can occur that results in bands of heavy snowfall downwind (Figure 3 and Bluestein, 1993). These annual winter conditions over the Great Lakes

191 result in the highest average seasonal snowfall totals recorded in the US apart from
192 mountain locations (Climate Source, 2015). In Michigan specifically, Figure 4
193 demonstrates the influence of steady lake effect snow on average annual snowfall,
194 with many areas along Michigan's western coast receiving over double the snowfall
195 of inland locations just 50 to 100km farther east. The effects of this continuous
196 snowpack were outlined by a study of 5cm soil temperatures in Michigan over the
197 course of five climatologically disparate winters (Isard and Schaetzl, 1998): most of
198 western Michigan's topsoil layers remained unfrozen during all or nearly all of the
199 winters, while more inland and southern locations (i.e. beyond the influence of lake
200 effect snow) experienced hard freezes every year.

201 Analyses of empirical and modeled climate and soil data in Michigan
202 specifically show that soil temperature is more dependent upon snowpack depth
203 and persistence than upon air temperature (Isard and Schaetzl, 1998). Schaetzl and
204 Tomczak (2001) found that two barren sites in central Michigan experienced soil
205 freezing to depths greater than 20cm, but two nearby sites protected by leaf litter
206 and a thin but continuous snowpack in a forest setting did not freeze below 3cm.
207 Isard and Schaetzl (1995) modeled the forty-year average minimum monthly soil
208 temperature in the Lower Peninsula of Michigan and found it to be 1.7°C warmer at
209 the lake effect snowbelt site than at the non-snowbelt site along the same latitude
210 less than 42km apart. Enhanced snowfall also contributes to a favorable increase in
211 soil moisture recharge at the beginning of the temperate growing season (Johnsson
212 and Lundin, 1991; Hinkel et al., 1997; Sutinen et al., 2008). This augmented,
213 continuous infiltration of snowmelt also aids in the decomposition of residue from

the previous year,delivering an increase in nutrients to the soil below (Schaetzl et al., 2005).

1.4 Objective

It has been asserted that cold temperatures during the winter of 2008–2009 led to the mass mortality of *M. × giganteus* at experimental sites in Champaign, Illinois and Arlington, Wisconsin (Heaton et al., 2010; Zeri et al., 2011; G. Sanford, personal communication, 2015). However, *M. × giganteus* crops in southwest Michigan experienced near total survival during this time period despite being established in the same manner (Zeri et al., 2011; D. Pennington, unpublished data, 2015). This study seeks to use observations to explore and test the hypothesis that the prevalence of lake effect snow in the Lower Peninsula of Michigan may reliably insulate the 0-10cm soil layer and meaningfully reduce the local wintertime mortality of *M. × giganteus* rhizomes. This possible preferential survival, coupled with low opportunity costs of land, would render southern Michigan a favorable area for future propagation of *M. × giganteus*.

2. Methodology

2.1 *M. × giganteus* sites, observations, and analysis

Four experimental *M. × giganteus* sites were analyzed during the winter of 2008–2009 and the winter of 2013–2014. The details of each site are presented in Table 1 and their locations shown in Figure 5. Each of the four sites, in addition to having an experimental first-year *M. × giganteus* crop, has an automated weather station either collocated or within 5km that measures 2m air temperature and 5cm

237 soil temperature (soil heat flux plates [Illinois, Michigan; Zeri et al., 2011] and
 238 chromel-constantan thermocouples [Wisconsin; Kucharik et al., 2013]). While 10cm
 239 is the standard planting depth of *M. × giganteus* rhizomes, analysis at these sites was
 240 at a depth of 5cm to maintain consistency, since not all stations have soil
 241 temperature measurements at 10cm. All hydrometeorological data at each site have
 242 undergone quality control and gap-filling according to the methods of each
 243 collection agency (Zeri et al., 2011; Bland and Wayne, 2015; Olsen et al., 2015), and
 244 data availability ranges from 2008 to the present at the Wisconsin and Michigan
 245 stations and from 2008-2013 at the Illinois station. For this reason, the Illinois
 246 station was analyzed only during the winter of 2008-2009. Snow cover data from
 247 the state climatologists of Illinois and Wisconsin (Angel, 2015; Young, 2015), as well
 248 as assimilated satellite and ground observations (SNODAS) in Michigan developed
 249 by the National Oceanic and Atmospheric Administration (NOAA) National
 250 Operational Hydrologic Remote Sensing Center (NOHRSC, 2004), were used as a
 251 proxy for station snowfall data since snowfall is not measured automatically. A
 252 synoptic weather analysis was also undertaken to further explain snow cover and
 253 soil temperature observations in the winter of 2008-2009.

Site	Winters Analyzed	Survival >70%	Data: Weather/Soil	Data: Snow Depth
Champaign, Illinois (40.06°N, 88.20°W)	2008-09	No ¹	Energy Biosciences Institute: Champaign ¹	in situ ⁸
Arlington, Wisconsin (43.31°N, 89.38°W)	2008-09 2013-14	No ^{2,3,4} Yes ⁴	University of Wisconsin Extension Ag. Weather station: Arlington ⁶	in situ ⁹
Hickory Corners, Michigan (42.41°N, 85.37°W)	2008-09 2013-14	Yes ^{1,5} Yes ⁵	Enviro-weather station: Hickory Corners ⁷	SNODAS ¹⁰
East Lansing, Michigan	2008-09	Yes ^{1,5}	Enviro-weather station: East Lansing ⁷	SNODAS ¹⁰

(42.67°N, 84.49°W)	2013-14	Yes ⁵		
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Table 1: *M. × giganteus* site data: location, timeframe, survival, and hydrometeorological observation sources. References: [1] Zeri et al., 2011 and Zeri et al., 2013; [2] Thelen et al., 2009; [3] Heaton et al., 2010; [4] G. Sanford, personal communication, 2015; [5] D. Pennington, unpublished data, 2015; [6] Bland and Wayne, 2015; [7] Olsen et al., 2015; [8] Angel, 2015; [9] Young, 2015; [10] Snow data assimilation System (SNODAS): NOHRSC, 2004.

The hourly time series of air and soil temperatures at the four stations was compared during times of snow cover greater and less than 2.5cm (1in) during the winters of 2008-2009 and 2013-2014. Additionally, in order to test the degree that snow cover insulated the soil at these sites, the average absolute hourly difference of soil and air temperature during snow cover and no snow cover was calculated along with 5th and 95th percentile hourly values. To test if the two datasets were statistically different, two-sample t-tests were performed after avoiding autocorrelation by appropriately reducing the temporal frequency of the temperature data by a factor of the e-folding time of the time series. Since the snow vs. no snow temperature datasets were assumed to be of different size and variance, normalization via the central limit theorem was employed followed by Welch's *t*-test. The dataset pairs were expected to pass at a level of $\alpha=0.01$ or lower to be considered statistically significant.

2.2 Additional observations and analysis in Michigan

To assess on a greater spatial scale the effects of lake effect snow cover on soil insulation in the Lower Peninsula of Michigan, air and soil temperature analysis was expanded to include data from the Enviro-weather (EW) Michigan observation network (Olsen et al., 2015). 12 EW stations were selected (Figure 6) for comparison of time series differences in 2m air temperature and 5cm soil temperature during periods of snow cover and no snow cover (again, in order to maintain consistency,

5cm data was used instead of 10cm [standard *M. × giganteus* rhizome depth], since 10cm soil temperature is not measured at all sites). These 12 specific stations were selected due to their data availability 2008-present, as well as their diversity in location: four stations within 10km of Lake Michigan (“lakeside”), six stations 10–100km from Lake Michigan (“near-lake”), and two stations in southeast Michigan (“inland”) that are situated well beyond the principal lake effect snowbelt.

 In order to expand the comparison of soil temperatures during times of snow cover vs. no snow cover to include the 12 EW sites during DJF 2008-2015, areal snow cover data of a higher spatial resolution than climatologist and airport observations were needed. In this analysis, data from the NOHRSC SNOw Data Assimilation System (SNODAS) were used (NOHRSC, 2004). These data, available over the timeframe of study at a resolution of 1km in the US, incorporate downscaled predictions from numerical weather prediction models into a physically-based, energy- and mass-balanced snow model, also assimilating satellite, aircraft, and ground observations, to predict various snow cover parameters including snow water equivalent and snow depth. EW stations were matched to their corresponding NOHRSC data grid cell and were subsequently binned by snow depth in increments of 2.5cm. The mean soil temperature, 1st and 99th percentile temperatures, and outliers were calculated from the observations within each of these snow depth bins. The results from these seven consecutive winters in Michigan broaden the spatial and temporal range of evidence as to whether increased snow depth may lead to a robust, decreased likelihood of 5cm soil temperature reaching each experimental mortality threshold of *M. × giganteus*: –3°C

(Clifton-Brown and Lewandowski, 2000; hereafter referred to as **CL2000**) and -6°C (rounded from -6.5°C ; Peixoto et al., 2015; hereafter referred to as **PFS2015**).

3. Results

3.1 Climate and meteorological observations

Both the winters of 2008–2009 and 2013–2014 had below average temperatures and above average snowfall across most of the Midwest, although Champaign recorded below average snowfall during 2008–2009 (US NOAA National Climatic Data Center 1981–2010 U.S. climate normals: Arguez et al., 2012). Table 2 summarizes the 1981–2010 average winter temperatures and snowfall in Champaign, Arlington, and East Lansing alongside in situ observations from the winters of 2008–2009 and 2013–2014.

	<i>Avg. DJF temp. ($^{\circ}\text{C}$)</i>	08–09 DJF temp. ($^{\circ}\text{C}$)	13–14 DJF temp. ($^{\circ}\text{C}$)	<i>Avg. DJF snow (cm)</i>	08–09 DJF snow (cm)	13–14 DJF snow (cm)
Champaign, IL	-2.3°C	-3.7°C	-4.2°C	67	42	110
Arlington, WI	-7.4°C	-9.8°C	-12.8°C	130	209	132
E. Lansing, MI	-3.5°C	-6.2°C	-7.3°C	130	213	173

Table 2: December through February (DJF) temperature/snowfall averages and observations at three *M. × giganteus* sites (Arguez et al., 2012).

Champaign, Illinois, the location of the experimental cropping site of the UIUC Energy Farm in the east-central part of the state, has an average December through February (hereafter DJF) temperature of -2.3°C and an average seasonal snowfall of 67cm. The winter of 2008–2009 was the 28th coldest on record in

Illinois; Champaign recorded an average DJF temperature of -3.7°C (1.4°C below average) and a total seasonal snowfall of 42cm (25cm below average). The winter of 2013–2014 was the 9th coldest on record in Illinois; Champaign recorded an average DJF temperature of -4.2°C (1.9°C below average) and a total seasonal snowfall of 110cm (43cm above average).

Arlington, Wisconsin, the location of the experimental cropping site of the Great Lakes Bioenergy Research Center, is located in southern Wisconsin, 30km north of Madison. Arlington's average DJF temperature is -7.4°C and average seasonal snowfall is 130cm. The winter of 2008–2009 was the 18th coldest on record in Wisconsin; Arlington recorded an average DJF temperature of -9.8°C (2.4°C below average) and a total seasonal snowfall of 209cm (79cm above average). The winter of 2013–2014 was the 4th coldest on record in Wisconsin; Arlington recorded an average DJF temperature of -12.8°C (5.4°C below average) and a total seasonal snowfall of 132cm (2cm above average).

East Lansing, Michigan, the location of one of the experimental *M. × giganteus* cropping sites of Michigan State University (MSU), is located along the eastern fringe of the southern Michigan lake effect snowbelt. East Lansing has a similar climate to Hickory Corners, Michigan, which lies 80km to the southwest and is another MSU experimental *M. × giganteus* site. East Lansing's average DJF temperature is -3.5°C and average seasonal snowfall is 130cm. The winter of 2008–2009 was the 20th coldest on record in Michigan; East Lansing recorded an average DJF temperature of -6.2°C (2.7°C below average) and a total season snowfall of 213cm (83cm above average). The winter of 2013–2014 was the 10th coldest on

record in Michigan; East Lansing recorded an average DJF temperature of -7.3°C (3.8°C below average) and a total season snowfall of 173cm (43cm above average). East Lansing also broke its own record for most consecutive days of snow cover during this winter, with 110 consecutive days with at least 2.5cm (1in) of snow on the ground from late December 2013 to late March 2014 (Hoepner, 2014).

3.2 Time series of air temperature, soil temperature, and snow cover

The following time series show hourly 2m air temperature, hourly 5cm soil temperature, and hourly presence (binary) of at least 2.5cm snow cover from January to early March of 2009 (Figure 7) and 2014 (Figure 8) at the four stations. Figure 8 does not include data from Champaign due to lack of data availability at this particular *M. x giganteus* site. In all of these diagrams, blue shading indicates time periods of snow cover greater than or equal to 2.5cm.

At Champaign in 2009, the temperature remained above the CL2000 threshold of -3°C with snow cover on the ground except for a short interval in early February. Outside of these windows of snow cover, the 5cm soil temperature dropped below -3°C on ten separate occasions, but never dropped below the PFS2015 threshold of -6°C . In Arlington, snow cover persisted from January 1 to February 10 in 2009 and the 5cm soil temperature, while below freezing, remained at or above -3°C during this stretch. However, in the four intervals from February 10 onward during which there was no snow cover at Arlington, soil temperatures dropped well below -6°C at night and typically rebounded to above-freezing soil temperatures during the day despite below-freezing air temperatures. Additionally, despite uninterrupted snow cover during the same timeframe in 2014 at Arlington,

the soil temperature dropped below -6°C on seven separate occasions. It is possible that these variations, unseen in the Michigan time series in January through March of 2014, were due to instrument error, however no data quality control issues were reported by the Wisconsin State Climatology Office during this time frame (Young, 2015).

In 2009 at Hickory Corners, MI, insulating snow cover during most of January and early February caused the 5cm soil temperature to remain near 0°C despite air temperatures that were often below -20°C . This snow cover persisted until February 9, at which point a stretch of above-freezing temperatures caused the snow to melt. Two days later the phase change to liquid water was complete to a depth of 5cm, allowing the additional heat input from the unseasonably warm surface air to contribute to warming the soil rather than to the latent heat absorption that accompanies melting. Schaetzl and Tomczak (2001) likewise observed this phenomenon of shallow soil temperature lagging behind atmospheric temperature due to the latent heat requirements of the phase changes of water, manifested by a “flatlining” of temperature until all water at that depth is either completely liquid or completely frozen. Once this is achieved, the temperature can more freely fluctuate with the atmospheric temperature, assuming no snow cover and minimal residue. Another weeklong snowfall event at Hickory Corners in late February brought the 5cm soil back to the freezing point but no further, at which point the heat loss to the atmosphere was balanced by heat transfer from the relatively warmer ground below. However, with no snow cover at Hickory Corners in early March 2009, the 5cm soil temperature dropped below freezing and approached -3°C , the CL2000

laboratory mortality temperature of *M. × giganteus*. At Hickory Corners in 2014 the scenario was quite different: despite the winter being much colder than average, the 5cm soil temperature remained at or above freezing for the duration of the timeframe of study.

In East Lansing, conditions were similar to Hickory Corners during both winters. In early March 2009, East Lansing recorded 5cm soil temperatures slightly below -3°C due to cold temperatures and no protective snow cover, however, the crop almost completely survived. In addition to the 5cm soil temperature not dropping below the -6°C PFS2015 mortality threshold in 2009, it is also a possibility that the slightly deeper but unobserved 10cm (standard rhizome depth) soil temperature remained above the -3°C CCL2000 mortality threshold as well.

Table 3 shows the average absolute difference between 2m air temperature and 5cm soil temperature at each of the four sites from January 1 to March 8, 2009 during times of snow cover and no snow cover. Also included are the 5th and 95th percentile absolute difference values, i.e. 90% of the absolute temperature differences lie between these two values. It can be seen that there was a greater average difference between air and soil temperature during periods of snow cover. The soil-air absolute differences were also greater during extreme cold events with snow on the ground, seen in the 95th percentile values. Each of the four dataset pairs presented (two snow cover scenarios at four sites) are calculated to pass Welch's *t*-test with a *p*-value lower than the significance level $\alpha = 0.01$, indicating that the means of the absolute soil-air temperature differences are statistically different.

This suggests that snow cover provided a meaningful insulating effect at each of these four sites during this timeframe.

Site	$ T_{\text{soil}} - T_{\text{air}} $ (°C), 2.5+ cm snow cover	$ T_{\text{soil}} - T_{\text{air}} $ (°C), < 2.5cm snow cover	Difference in means passed <i>t</i> - test at $p < 0.01$?
Champaign, IL	7.6 (0.8, 16.8)	3.9 (0.3, 8.7)	Yes
Arlington, WI	9.5 (1.1, 19.3)	2.8 (0.3, 10.7)	Yes
Hickory Corners, MI	9.0 (1.7, 20.5)	5.7 (0.6, 13.2)	Yes
East Lansing, MI	8.3 (1.6, 19.3)	4.8 (0.4, 10.1)	Yes

Table 3: Average absolute difference of 5cm soil and 2m air temperature with and without snow cover from January 1 to March 8, 2009. Numbers in parentheses are the 5th and 95th percentile absolute differences, respectively, i.e. 90% of the absolute temperature differences lie between these two values. Each pair of complete datasets is calculated to pass Welch's *t*-test with a *p*-value lower than $\alpha = 0.01$, indicating that absolute soil-air temperature differences during periods of snow cover were statistically higher than during periods of no snow cover over this timeframe.

3.3 Synoptic analysis

At all four of these experimental *M. × giganteus* sites in early 2009, the timing of snowfall and cold air masses appears to play a large role in crop survival. The majority of cold temperature events in boreal winter in the US Midwest are associated with high-pressure systems that originate in Canada and move southward behind low-pressure systems that sweep northeastward across the eastern half of the US (Bluestein, 1993). These low-pressure systems are accompanied by a southward-stretching cold front and precipitation centered on the low-pressure system, extending in bands southward along the front. If temperatures are cold enough, this precipitation falls as snow. It is this snow cover that often protects against the cold temperatures that follow behind such frontal passage.

A series of surface weather maps in Figure 9 and Figure 10 show two mid-latitude systems that brought precipitation and cold temperatures to the Upper

Midwest in early 2009. During the first event (13–16 January 2009), 5cm soil temperatures at each of the four *M. × giganteus* sites of focus remained above the CL2000 *M. × giganteus* mortality temperature of -3°C . During the second event (25 February – 3 March 2009), 5cm soil temperatures at all sites but one (Hickory Corners) did not, and at Arlington the soil temperature reached below the PFS2015 mortality threshold of -6°C . Figure 9 extends from 13–16 January 2009 during and after the passage of a cold front in the eastern half of the US. The dashed light blue line represents the location of the 0°C surface isotherm at 0700 Eastern Standard Time (EST). A low-pressure system moved through the Upper Midwest on January 13 followed by another faster-moving low on January 14, which brought significant snow to the region. Over the following two days, cold, high-pressure air from Canada moved southward across the region. This onset of snow cover and subsequent cold temperatures can be seen in the meteorological data of the four experimental *M. × giganteus* sites in Figure 7. The shallow soil layers remained above -3°C likely due to the snow cover during this time period.

In contrast, Figure 10 is a series of surface maps from 25 February to 3 March 2009: during 25 – 27 February a much slower-moving low-pressure system traversed the Upper Midwest, providing additional time to advect warmer air from the south northward ahead of the front, which caused significant melting and also caused the majority of the associated precipitation to reach the surface as rain, not snow. Figure 11 shows CoCoRaHS observations of this melting and lack of subsequent snow cover in southern Michigan. Behind this cold front, a high-pressure system once again moved in, which led to a series of three clear, cold

nights. With no protective snow cover, enhanced radiative cooling of the surface led to the coldest 5cm soil temperatures of the year from 1 – 4 March at each of the sites despite nighttime low air temperatures during this timeframe remaining much warmer than the coldest air temperatures experienced in 2009. It is this latter type of system, with complete snowmelt immediately succeeded by a snow-less cold front and subsequent high-pressure regime, that may pose the biggest wintertime threat to *M. × giganteus* crops in the US Midwest.

3.4Enviro-weather stations time series and averages

Figure 12 shows the time series of 5cm soil data from each of the 12 stations plotted against the same data from Champaign from January 1 to March 8, 2009, with the EW station time series color-coded by proximity to the lake (see Figure 6). It can be seen that Champaign's shallow soil temperature was colder and more variable than any of the EW sites. In fact, throughout the timeframe of focus only one EW site (an inland site) reached a temperature below the CL2000 *M. × giganteus* mortality threshold of -3°C . The time series average 5cm soil temperatures for the lakeside stations, near-lake stations, inland stations, and Champaign, respectively, were 0.98°C , 0.85°C , 0.07°C , and -0.51°C . The average difference between soil temperature and air temperature was virtually identical across the three EW regimes: between 5.7°C and 6.0°C . Meanwhile, the average soil-air temperature difference in Champaign was much lower, at 2.3°C .

Figure 13 is a box-and-whisker diagram of 5cm soil temperature vs. snow depth in seven consecutive winters (DJF) 2008-2015 at the 12 EW stations. Soil temperatures are binned in increments of 2.5cm of snow cover and there are at least

50 soil temperature observations at each of the snow depths shown. The mean soil temperature was 2.5°C with no snow cover, 2.2°C with 2.5cm of snow cover, and between 0.6°C and 1.1°C for every other snow depth. None of the sites recorded a 5cm soil temperature below -3°C from 0-12.5cm of snow cover, but from 15-32.5cm of snow cover there were multiple instances of 5cm soil temperature dropping below -3°C. It should be noted that the soil temperature sensor at each of the EW sites used in this study is located beneath a surface cover of grass (Olsen et al., 2015), which may have also led to a positive temperature bias when compared to the *M. × giganteus* sites with varying amounts of post-harvest residue. It should likewise be considered that these data were taken at 5cm as opposed to the standard rhizome planting depth of 10cm. No 5cm soil temperatures at or below -6°C were observed at any of these sites during this time frame.

4. Discussion

In Champaign, cold air temperatures during periods of no snow cover during the 2008–2009 winter contributed to soil temperatures dropping below the CL2000 mortality threshold of -3°C, potentially triggering the mass mortality of the *M. × giganteus* crop at this site. Arlington experienced approximately the same amount of days with snow cover as the two Michigan sites during the 2008-2009 winter but had slightly lower air temperatures and recorded much lower extreme cold soil temperatures during periods of no snow cover, which led to mass mortality of *M. × giganteus*. In Michigan, first-year *M. × giganteus* crops experienced near total survival in both years. Additionally, at each of Champaign, Arlington, and East

Lansing, the winter of 2013–2014 was colder than the winter of 2008–2009. In Arlington and East Lansing, the winter of 2013–2014 was also less snowy than the winter of 2008–2009. Given that colder air temperatures and shallower depths of snow cover are physically expected to contribute to colder shallow soil temperatures, it is concomitantly expected that the winter of 2013–2014 experienced higher first-year *M. × giganteus* mortality than the winter of 2008–2009. But in fact, at Arlington, while air temperatures dropped below -6°C frequently in both winters, *M. × giganteus* planted in 2008 experienced a near total die-off due to cold exposure during the winter of 2008–2009 but *M. × giganteus* planted in 2013 experienced little to no loss during the winter of 2013–2014.

In this study there were two instances when the observed 5cm soil temperature dropped below the CL2000 -3°C threshold and yet the first-year *M. × giganteus* crop experienced greater than 70% survival entering the growing season that immediately followed. In East Lansing, this threshold was reached during the high-pressure event of early March 2009. One possible explanation for this is that the PFS2015 experimental *M. × giganteus* mortality threshold of -6°C was never reached, and perhaps this threshold is more representative of the ability of rhizomes to tolerate cold soil temperatures. Another possible explanation for this discrepancy is that *M. × giganteus* rhizomes are typically planted at a depth of 10cm, but in this study, only the 5cm temperatures were analyzed, since the Champaign observations were only taken at that depth. It is typically expected that deeper soil temperatures are warmer than shallower temperatures in the winter, and as expected the 10cm soil temperature at East Lansing in the winter of 2009 never

dropped below -3°C , reaching an absolute minimum of -1.6°C on the morning of March 3, 2009. In Arlington, despite uninterrupted snow cover during the winter of 2014, the measured 5cm temperature dipped below the PFS2015 threshold of -6°C multiple times. This also occurred at a depth of 10cm, with a seasonal minimum of -7.2°C observed on the morning of January 9, 2014. The possible conclusions are that the sensor or sensor placement was errant, the new *M. × giganteus* rhizomes in 2013 were planted deeper than 10cm, or that this particular strain of *M. × giganteus* can tolerate colder soil temperatures than previously tested. The manner in which the mortality temperature is superseded might also matter, as delineated in Peixoto et al. (2015). For example, in Arlington in 2014, the observed temperatures below -6°C were reached more gradually, whereas at the same site in 2009 there were eight diurnal episodes of rapid thawing and subsequent refreezing to well below -6°C .

It is shown here and in past studies that snow cover insulates shallow soil layers. It would follow that areas that receive more annual snowfall (such as the lake effect snowbelt of Lower Michigan) are more likely to provide cold insulation throughout the winter, an important consideration for rhizomatous perennial crops such as *M. × giganteus* that do well in warm continental climates but are susceptible to cold mortality. However, other factors that may also contribute to the preferential wintertime survival of first-year *M. × giganteus* rhizomes at these sites are the establishment practices (Pennington, 2011; Plazek et al., 2011; Boersma and Heaton, 2014) and also residual winter surface cover at each site. That is, since bare soil is more influenced by atmospheric temperature fluctuations than soil covered by vegetation or crop residue, *M. × giganteus* stands that have been established for

three or more years typically produce more above-ground biomass (Heaton et al., 2010) that may be left on the ground post-harvest to help insulate the soil (Kucharik et al., 2013). Because none of the four sites discussed in the present study have available data from side-by-side replicate plots of *M. × giganteus* of different age and winter crop residue amounts, the effects of stand age on winter survival is beyond the scope of this research but would be an intriguing area of future study.

An additional factor beyond snow cover that may influence the extent to which soil temperature is affected by extreme cold soil temperature is soil water content. Due to the higher heat capacity of water and the latent heating/cooling associated with the phase change of water, soil with higher water content will take a longer amount of time to respond to changes in air temperature (Schaetzl and Tomczak, 2001). This “flatlining” can be seen in parts of the time series of soil temperature in Figure 7, when air temperature oscillated above and below 0°C during periods of no snow cover. In general, this means that moister soils will have a decreased likelihood of reaching extreme cold temperatures at 10cm. Of the four *M. × giganteus* sites of the present study, only the Champaign, Illinois site had available soil moisture data at an adequate temporal resolution; therefore, a detailed soil moisture analysis is beyond the scope of this study. However, a facet of soil water content to note is that during the harsh winter of 2013-2014, while first-year *M. × giganteus* survived at all four sites, experimental stands of first-year *M. × giganteus* in Iowa suffered severe mortality (Boersma and Bonin, 2014). Figure 14 shows modeled surface soil moisture percentages in January 2009 and January 2014 in the Eastern US. It can be seen that in 2009, the areal surface soil moisture near each of

the present sites was ample and thus may not explain the variability in mortality. However, in 2014, Iowa was much drier than Michigan and southern Wisconsin, which may have contributed to the mortality of *M. × giganteus* in Iowa during that winter. This would be another intriguing area of future replication and study.

The soil and air temperature versus snow depth data shown in Figure 13 provide another refutation to the hypothesis that increased snow depth and persistence in Michigan's Lower Peninsula lake effect snowbelt will alone lead to a decreased likelihood of *M. × giganteus* cold mortality. Increased snow depth at the 12 selected EW stations did not predict shallow soil temperatures. In fact, with little or no snow depth, the average soil temperature was actually higher, likely an artifact of pre-snowfall and post-snowmelt warm air events. Additionally, it is extreme cold soil temperature events, not the average of all events, that directly lead to cold-induced rhizome mortality of *M. × giganteus*, and soil temperatures below -3°C occur were recorded seven times from 2008-2015 across the 12 EW stations, each one of these instances occurring with between 15cm and 32.5cm of snow cover. This is in conflict with the idea that increased snow cover directly leads to a decreased likelihood of extreme cold soil temperatures.

Good management practices can be followed that leave enough residue to help shelter the otherwise bare soil, however this comes at the expense of losing marketable biomass, thus increasing the breakeven price of *M. × giganteus*. Another option could be to harvest and remove the entire *M. × giganteus* plant (leaving bare soil) but afterwards continuing to monitor snow depth, soil temperature, and the threat of cold-air, high-pressure systems (synoptic analysis) throughout the winter.

If a complete snowmelt is forecasted to be quickly followed by a hard freeze, small acreage *M. × giganteus* farms could have enough warning time to apply an insulating layer of miscellaneous stover in preparation.

5. Conclusions

Lake Michigan's lake effect snowbelt is an intriguing option for large-scale expansion of *M. × giganteus* agriculture because the opportunity cost of land is low and the annual moisture supply is ample. The prevalence of orchards, another form of perennial agriculture along the Lower Peninsula of Michigan's western coast, demonstrates this preference of perennial growth along Lake Michigan's lake effect snowbelt (Kiefer, 2015). This study used observations to explore and test the hypothesis that the prevalence of lake effect snow in the Lower Peninsula of Michigan may reliably insulate the 0-10cm soil layer and meaningfully reduce the local wintertime mortality of *M. × giganteus* rhizomes. This hypothesis was here disproven that snow cover in the western Lower Peninsula of Michigan categorically decreases the likelihood of soil temperatures lower than the *M. × giganteus* mortality threshold. Each of the four experimental sites exhibited an absolute difference in 5cm soil temperature and 2m air temperature that was statistically greater during times of at least 2.5cm snow cover than times of no snow cover. However, there were still multiple instances of the 5cm soil temperature dropping below -6°C at these *M. × giganteus* sites despite ample snow cover. The rapid melting, varying snowfall totals, and subsequent intense cold often associated with the passage of synoptic-scale systems in Michigan likewise contribute to the volatility of depending

solely on snow cover to prevent *M. x giganteus* mortality. Analysis of observations at 12 additional Enviro-weather stations in Michigan over seven consecutive winters also showed instances of soil temperatures dropping below -3°C (although never below -6°C), despite being covered with 15-32.5cm of snow. These results together indicate that snow should not be exclusively relied upon to insulate shallow soil layers and improve the wintertime survival of *M. x giganteus*.

The precise instances and circumstances of past cold mortality events of *M. x giganteus* in the US Midwest will be valuable in the future parameterization of crop and land surface models in this region and in similar areas such as Southern Ontario (Canada), which has little empirical information to help test model results of the productivity and biogeophysical effects of *M. x giganteus* on a regional scale. However, due to the lack of organized observations and dissemination of *M. x giganteus* winter survival statistics, it remains difficult to assign a universal explanation for the preferential *M. x giganteus* survival in Michigan during the winter of 2008–2009 compared to the affected Wisconsin and Illinois crops. By continuing to organize and publish the details of *M. x giganteus* sites, including establishment practices, stand age, wintertime residue, soil moisture, and mortality statistics, the circumstances of cold-induced *M. x giganteus* mortality can be more rigorously analyzed on a site-by-site level and the most favorable geographic zones for future *M. x giganteus* propagation properly adjusted.

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Figures and Captions

Figure 1: Three past proposals of favorable regimes for *M. x giganteus* propagation. A) US DoE, 2006 (*M. x giganteus* zone in red); B) Miguez et al., 2002 (*M. x giganteus* zone in orange and dark yellow); C) Song et al., 2014 (*M. x giganteus* zone in blue and dark green). [2 column]

Figure 2: Yearlong time series from an idealized model of 2m air temperature (thin solid line), 10cm soil temperature (dashed line), and presence of snow cover (thick solid line). Soil temperature is modeled to remain warmer than the sub-freezing air temperature during periods of snow cover. Bonan, 2013. [1 column]

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817 **Figure 3: Visible satellite imagery of lake effect convection over Michigan on November 30, 2004.**

818 **Nemiroff and Bonnell, 2015. [1 column]**

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822 [Figure 4: 1951–1980 mean annual snowfall \(cm\) in Michigan. Lake effect snowbelt is shaded in gray.](#)

823 [Isard and Schaetzl, 1998. \[1 column\]](#)

Figure 5: Four experimental *M. × giganteus* monitoring sites: Champaign, Illinois (University of Illinois), Arlington, Wisconsin (University of Wisconsin), and East Lansing and Hickory Corners, Michigan (Michigan State University). In 2009, the sites at Champaign and Arlington suffered near complete mortality while the sites in Michigan experienced near complete survival. [1 column]

Figure 6: Location of selected stations from Michigan State University's Enviro-weather network. Blue dots represent lakeside stations, black dots represent near-lake stations, and green dots represent inland stations chosen for this study. [1 column]

Figure 7: Hourly time series of soil and air temperature from January 1 to March 8, 2009 at each of the four experimental *M. x giganteus* sites. “Windows” of blue shading represent at least 2.5 cm of snow cover on the ground. Dotted black lines indicate -3°C, and -6°C, the laboratory mortality temperatures of *M. x giganteus* observed by CL2000 and PFS2015, respectively. Near-complete mortality occurred at the sites of the first two time series, while near-complete survival occurred at the last two. It can be seen that soil

temperature more readily fluctuated with air temperature during periods of no snow cover. Only the second time series (Arlington, WI) registered soil temperatures below the -6°C threshold of PFS2015. [1 column]

Figure 8: Hourly time series of soil and air temperature from January 1 to March 8, 2014 at Arlington, Hickory Corners, and East Lansing. “Windows” of blue shading represent at least 2.5cm of snow cover on the ground. Dotted black lines indicate -3°C , and -6°C , the laboratory mortality temperatures of *M. x giganteus* observed by CL2000 and PFS2015, respectively. Snow cover persisted for the entirety of each of these time series, and all sites experienced complete survival, although the Arlington time series still shows that soil temperatures dropped below both mortality thresholds. [1 column]

Figure 9: Surface weather maps over the contiguous US, 13–16 January 2009. The southernmost dashed light blue line represents the 0°C surface isotherm. Passage of a low pressure system in the US Midwest is seen, immediately followed by a high pressure system which brought well below-freezing air to the region. [2 column]

Figure 10: Time series of surface weather maps over the contiguous US 25 February to 3 March 2009. The southernmost dashed light blue line represents the 0°C surface isotherm. Passage of a low pressure system in the US Midwest is seen, ahead of which the surface temperatures were warm enough to melt existing snow cover. Following this passage, a high pressure system set in, which brought well below-freezing temperatures to the region.

Figure 11: CoCoRAHS observations of snowfall depth in Michigan on 25 February and 27 February 2009.

Snowmelt caused by the southerly surge of warm air ahead of the low pressure system is reflected in diminished snow depths on 27 February, with white dots representing zero snow cover. [1 column]

Figure 12: Time series of soil temperature at 12 Enviro-weather stations in Michigan and at the experimental *M. x giganteus* plot in Champaign, Illinois from January 1 to March 8, 2009, color coded by proximity to Lake Michigan. While the soil temperatures of every lakeside and near-lake station remained well above the CL2000 -3°C mortality threshold throughout the winter, both of the inland stations and the Champaign *M. x giganteus* site experienced soil temperatures below this threshold on at least three separate occasions during this time period.[1 column]

Figure 13: Distributions of hourly observed soil temperature (12 selected Enviro-weather stations) by snow depth (NOHRSC) during seven consecutive winters (DJF 2008-2015) in Michigan. There at least 50 soil temperature observations of each snow depth shown. At each depth, the box represents soil temperatures within the 1st and 99th percentile, the red bar represents the mean soil temperature, and '+' markers represent outliers. Also plotted as horizontal lines are 0°C (solid; freezing temperature of water) and -3°C (dashed; CL2000 laboratory mortality temperature of *M. x giganteus*). From 2008-2015 at the 12 stations, seven instances of the 5cm soil temperature dropping below -3°C were recorded with 15-32.5cm of snow cover, while zero such instances were recorded under 0-12.5cm snow cover. Zero instances of 5cm soil temperature dropping below -6°C (PFS2015 laboratory mortality temperature of *M. x giganteus*) were recorded. [1 column]

Figure 14: Areal surface soil moisture content in the Eastern US on January 10 of 2009 (top) and 2014 (bottom). Percentages were calculated using a two-layer soil moisture model, Penman-Monteith evapotranspiration, and FAO soil classification.(WMO, 2015). Soil moisture percentages in January 2009 were close to 100% throughout the majority of the area of study, while percentages in January 2014 were as low as 40% in southern Minnesota and 20% in Iowa, which allowed for soil temperatures to fluctuate more freely with the air temperature. [1 column]